Texas Water Resources Institute
Annual Technical Report
FY 2010

Introduction

The Texas Water Resources Institute (TWRI), a unit of Texas AgriLife Research, Texas AgriLife Extension Service and the College of Agriculture and Life Sciences at Texas A&M University, and a member of the National Institutes for Water Resources, provides leadership in working to stimulate priority research and Extension educational programs in water resources. Texas AgriLife Research and the Texas AgriLife Extension Service provide administrative support for TWRI and the Institute is housed on the campus of Texas A&M University.

TWRI thrives on collaborations and partnerships and in fiscal year 2010 managed 92 active projects with $28,577,104 in funds. Those projects involved over 127 Texas A&M University System faculty members, and 177 faculty from other universities across the state. The Institute maintained joint projects with 16 Texas universities and four out-of-state universities; more than 87 federal, state and local governmental organizations; more than 20 consulting engineering firms, commodity groups and environmental organizations; and numerous others. In 2010 the Institute was awarded 51 new TWRI-lead projects with direct funding of $10,234,235.

TWRI works closely with agencies and stakeholders to provide research-derived, science-based information to help answer diverse water questions and also to produce communications to convey critical information and to gain visibility for its cooperative programs. Looking to the future, TWRI awards scholarships to graduate students at Texas A&M University through funding provided by the W.G. Mills Endowment and awards grants to graduate students from Texas universities with funds provided by the U.S. Geological Survey.

Research Program Introduction

Through the funds provided by the U.S. Geological Survey, TWRI funded 10 research projects in 2010-11 conducted by graduate students at Texas A&M University (5 projects), the University of Texas (2 projects), Texas A&M University-Kingsville (2 projects), and the University of Texas at El Paso (1 project). Additionally, through funds provided by the U.S. Geological Survey, TWRI facilitated the continuation of three competitive research programs at Texas A&M University, another at Texas State University, and a multi-state, international project.

Meghan Gallagher, of Texas A&M University, studied the biological treatment of wastewater contaminated with estrogenic compounds.

Qiao (Amy) Gao, of the University of Texas, examined the effect of photovoltaic nanomaterial roofing on harvested rainwater quality.

Ricardo Marmolejo, of the University of Texas at El Paso, researched low impact development (LID) structures for groundwater management and watershed protection in the AMRC10 watershed in El Paso Texas.

Nathan Matlock, of Texas A&M University, studied whether native freshwater vegetation from Texas affect golden algae, Prymnesium parvum, bloom dynamics.

Kyna McKee, of Texas A&M University, worked on watershed protection plan development for the Geronimo Creek Watershed.

Carolina Mendez, of The University of Texas, researched trihalomethane formation potential in rainwater harvested from different roofing materials.

Xubin Pan, of Texas A&M University-Kingsville, examined the design and evaluation of best management practices (BMPs) for urban stormwater quality improvement in South Texas.

Sa'd Shannak, of Texas A&M University, researched rainwater harvesting as a stormwater best management practice.

Catherine Simpson, of Texas A&M University-Kingsville, studied the impact of saline irrigation water on citrus rootstocks in the Lower Rio Grande Valley.

Bailey Sullivan, of Texas A&M University, examined anthropogenic influence on tetracycline resistance in a rapidly urbanizing Texas stream.

Dr. Vijay P. Singh, of the department of biological and agricultural engineering at Texas A&M University, continued researching hydrological drought characterization for Texas under climate change, with implications for water resources planning.

Dr. Benjamin F Schwartz, of the department of biology at Texas State University, continued examining the role of epikarst in controlling recharge, water quality and biodiversity in karst aquifers – comparing Virginia and Texas.

Dr. Ron Griffin, of the Department of Agricultural Economics at Texas A&M University, continued researching institutional mechanisms for accessing irrigation district water.

Dr. Steve Whisenant, Ecosystem Science and Management Department Head at Texas A&M University, continued working to enhance the livestock early warning system (LEWS) with NASA Earth-sun science data, GPS and RANET technologies, a collaboration with USGS/EROS.

Finally, the other competitive research grant is a multi-state, international effort that involves the collection and evaluation of new and existing data to develop groundwater quantity and quality information for binational aquifers between Arizona, New Mexico, Texas and Mexico. The United States-Mexico Transboundary Aquifer Assessment Program is in the first year of the five-year program.

USGS Grant No. 07HQAG0077 - Enhancing the Livestock Early Warning System (LEWS) with NASA Earth-Sun Science Data, GPS and RANET Technologies

Basic Information

Title:	USGS Grant No. 07HQAG0077 - Enhancing the Livestock Early Warning System (LEWS) with NASA Earth-Sun Science Data, GPS and RANET Technologies
Project Number:	2007TX318S
Start Date:	6/1/2007
End Date:	5/31/2010
Funding Source:	Supplemental
Congressional District:	08
Research Category:	Climate and Hydrologic Processes
Focus Category:	Drought, Agriculture, Climatological Processes
Descriptors:	
Principal Investigators:	Steve Whisenant

Publications

There are no publications.

Enhancing the Livestock Early Warning System (LEWS) with NASA Earth-Sun Science data, GPS and RANET Technologies: A Collaboration with USGS/EROS

Annual Report
March 2010 to February 2011

Texas Agrilife Research
Texas A&M University System
2147 TAMU
College Station, Texas 77843-2147
Phone: 979-845-4761

Principal Investigator:
Dr. Steven G. Whisenant
Department Head
Dept. of Ecosystem Science and Management
Texas A&M University
College Station, Texas 77843-2126
Phone: 979-845-5579

Enhancing the Livestock Early Warning System (LEWS) with NASA Earth-Sun Science data, GPS and RANET Technologies: A Collaboration with USGS/EROS

Project Description

A study was initiated in 2007 to enhance the Livestock Early Warning Systems (LEWS) decision support system (DSS) by using NASA Earth-Sun Science data by adding water resources monitoring and herd migration tools that are disseminated to pastoral communities using RANET technologies. The existing LEWS project had recognized a need to improve the existing DSS to better identify situations where water becomes a limitation to pastoral use of forage supplies in a given region. The region identified for study provides a rich environment where the technology would greatly enhance water resource monitoring and provide high impact on the national livestock sector. Monitoring the status of waterholes and rivers is important not only to the pastoralists but also for better management of the environment in terms of land degradation brought about by excessive concentration of livestock during droughts.

The project was located in a transboundary site in East Africa where pastoralism is a significant component of the economy (Abule et al., 2005). The study area traverses an ecologically, ethnically and institutionally heterogeneous transect of approximately 750 kilometers, from Yabello in southern Ethiopia south through Baringo, Marsabit, Isiolo, Wajir, Mandera and Samburu districts in northern Kenya. The spatial extent of the study area is approximately 150,000 km^2. This study area was chosen not only because of the international nature of its extent (i.e., Ethiopia and Kenya) but also to capture variation in ecological potential, market access, livestock mobility and ethnic diversity across the region. It is also an area characterized by a growing number of conflicts between pastoralist communities over land, water and pasture.

The study area is inhabited by several main pastoral ethnic groups: the Boran, Gabbra, Somali, Rendille, Samburu and others. Climatically, southern Ethiopia is semi-arid to arid. The main pastoral group in this zone is the Boran people who are pure pastoralists. Somali clans are also found in this zone. Northern Kenya can also be characterized as semi-arid to arid with the major pastoral groups in this region being the Samburu, Turkana, Borana and Somali. All these groups are pure pastoralists and practice transhumance (i.e. the practice of moving between seasonal base camps throughout the year to optimize use of forage resources). Their livelihoods depend on herds of cattle, sheep, goats and camels for food security. They move their livestock seasonally in order to exploit grazing in areas away from their permanent settlement sites. The animals owned are used for milking, slaughtered for meat, sold for cash or bartered for other commodities.

Pastoralism by definition is an extensive system of livestock production in which a degree of mobility is incorporated as a strategy to manage production over a heterogeneous landscape characterized by a precarious climate. Because of the need to take full advantage of the landscape, pastoralism is poorly fitted to the rigid structure of national and international boundaries. The pastoral strategy of mobility therefore underscores the need for a regional perspective, especially since other impacts such as resource access conflict, spread of disease and livestock rustling are side effects of pastoral mobility. For this study, we are conducting four integrated activities that will provide a prototype application for arid regions in East Africa that will greatly improve the scope and effectiveness of the LEWS DSS. These four activities/objectives are as follows:

1) Characterization and verification of water resources identified with NASA Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER), Shuttle Radar Topography Mission (SRTM) data to add a water resource mapping component to the LEWS DSS;
2) Improvement of the forage mapping component of the LEWS DSS using Moderate Resolution Imaging Spectroradiometer (MODIS) Vegetation Continuous Fields (VCF) data to extend field collected data to other unsampled areas;
3) Mapping of seasonal migration patterns and resource utilization of pastoral lands using GPS technology;
4) Operational monitoring of water resources with NASA Tropical Rainfall Measuring Mission (TRMM) data.

For each of these activities, the current status and results of each of these activities will be provided.

Activity 1: Characterizing water resources with ASTER and SRTM data

The main objective of this activities is to create a regional water resources inventory through the construction of a geo-database of waterholes, land cover and their drainage areas using spectral analysis of Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) and Moderate Resolution Imaging Spectroradiometer (MODIS) satellite imagery and applying watershed delineation tools on the 90m Shuttle Radar Topography Mission (SRTM) data. In May 2007, the USGS/EROS Data Center conducted the spectral analysis of the study area using ASTER imagery acquired during the period from 2000 to 2006. A total of 70 scenes were acquired that covered almost 85% of the study area. The analysis by USGS EROS identified 88 possible waterholes in the study area. For these, 52 were in Ethiopia, 34 in Kenya and 2 in Sudan. Only cloud free areas of the images were used to identify these waterholes, which could imply the possible existence of more waterholes that were not visible in the image due to clouds and cloud shadows.

Starting in August 2007, field surveys were conducted to verify the satellite-based classifications of water holes delineated by USGS-EROS and to acquire further ancillary data for incorporation into the geodatabase on water resources in the study area. This data will include characterization of the general hydrology of the water hole (rain-fed or subsurface), flow regimes as well as technical details and locations of other water schemes such as boreholes, ponds, dry river beds, shallow wells, *birkas*, earth dams and other watering points, including those that were not identified during the ASTER imagery/SRTM analysis. The field inventory emphasized temporal characteristics on prevailing patterns of seasonal water availability as used by pastoralists and was be particularly focused on those regions where water becomes limiting during dry periods of the year.

During this reporting period, field data collection was completed and data were used for production of a Validation and Verification report (V&V). The verification and validation report documented the performance of the various NASA data, methods and tools for water resource monitoring and pasture characterization activities of the LEWS DSS, as per the stated objectives of the project. Data were summarized by the Texas A&M team and submitted to USGS for final analysis. Model sensitivity analysis, field verification, validation techniques and results were included in the report produced by USGS.

Benchmarking Surveys

Benchmark surveys were established to addresses the utility of LEWS-DSS as an information tool for monitoring resource conditions and mitigating for drought. The purpose of the surveys were to evaluate the usefulness or value of the information provided by the LEWS-DSS for decision making with regard to livestock grazing management and mitigating for drought, and suggested improvements. Unfortunately, several extant factors affected the operation of the system during 2009 and early 2010 which affected the delivery of the early warning products in a timely manner. These factors include the ending of funding for the Global Livestock Collaborative Research and Support Programs in June 2009 and the subsequent changeover in personnel and institutionalization of the system. In 2010, the problem with the scan motor on the NOAA-17 satellite, suspension of AVHRR-NDVI image production, and the long delay in resuming production of AVHRR NDVI from NOAA-18 has limited the ability to produce regional forage maps which also hindered system operations. Therefore it was expected that stakeholder might be limited.

The first survey was administered on-line in April 2008 with the follow-up survey being available in July 2010. For each survey, stakeholders in Kenya and Ethiopia were notified via email that the survey was being conducted and instructions were provided on how to access the system. Stakeholders were reminded again after the initial email. Twenty-seven stakeholders took part in the initial survey, whereas only 10 participants were recorded for the follow-up survey. Unfortunately, many survey questions were either only partially answered or skipped all together during the process of completing both surveys, and more so for the second effort. Therefore, statistical analysis of the survey data was not practical. However, generalizations about the data received are made and summarized below.

Usefulness or Value of the LEWS Forage Products. Respondents in 2008 indicated universally (100%) that the LEWS-forage monitoring products were valuable to their decision-making process; this was also supported by a 100 percent positive response rate by respondents in 2010. When asked to rate whether the forage conditions products (i.e., current and historic forage conditions, and forage forecasts, etc.) that are provided by the LEWS-DSS were valuable for decision making regarding where to graze animals or to sell livestock when shortage of forage is predicted, respondents indicated that this information was valuable or somewhat valuable for all products provided (Figure 1). This finding was supported by results of the follow-up survey administered in 2010 (Figure 2).

Regarding increased confidence in decision making due to the information provided by LEWS, 50 percent of respondents' indicated that this data increased their confidence in the decisions they make “greatly” and the remaining 50 percent indicated that their confidence was increased “moderately”. Findings of the 2010 follow-up survey indicated a slight increase in confidence (60 percent “greatly” and 40 percent “moderately”, respectively) due to information provided by LEWS.

Likewise, when ranking the value of data related to water resources, respondents ranked this information as valuable to very valuable to their decision-making. The one exception to this trend was regarding runoff amounts and flood hazard data, where informants ranked these data as only moderately valuable. Furthermore, when asked if the addition of data/information related to water resources monitoring would improve the LEWS product the majority of respondents indicated that this information would either “greatly” or “moderately” improve the forage condition data provided. Current surface water availability, historic water availability, rainfall data, and historic evapotranspiration data were all indicated to be a valuable asset to them. Respondents to the 2010 follow-up survey provided support for this by indicating that the addition of information pertaining to surface water availability and water related information was very useful to somewhat useful to their decision making, strategy development, and planning.

As a herd migration management tool, 50 percent or more of respondents indicated that the additional water related data helps to reduce overgrazing and land degradation, to reduce potential for conflicts over resources, and improves their confidence in making resource management decisions (Figure 3). The findings of the 2010 follow-up survey corroborate this finding.

Generally, respondents indicated that they would like to continue receiving the LEWS forage condition data at the prescribed time intervals (i.e., monthly reports for the current condition reports, every 3 months for forecast data, etc.) currently in effect. The preferred format for receiving this data is via radio broadcasts, written materials (monthly reports, flyers, briefs etc.) and to a lesser degree, oral communication to the individual or through the Chiefs of the communities.

Suggested Improvements to the System. Survey respondent provided suggestions on ways to improve the system that included:

- Linking the LEWS-DSS web-site to other providers of early warning systems information (i.e., FEWSNET, Arid Lands Resource Management Project, etc.)
- Make the information more readily available/accessible to pastoralist communities at the village level
- Make maps a selectable download item so that those with limited computing or internet capacity can choose which ones they want/need to speed up download processing times
- Encourage openness among the livestock sector actors to promote use of the product
- Provide training or “short courses on data collection, analysis and also monitoring and evaluation.”
- Include discussions or evaluations of the contributions of trees/shrub to the forage base. Specifically, on the invasion of *Prosopis juliflora* and how this species contributes or not to the forage base especially during periods of drought.

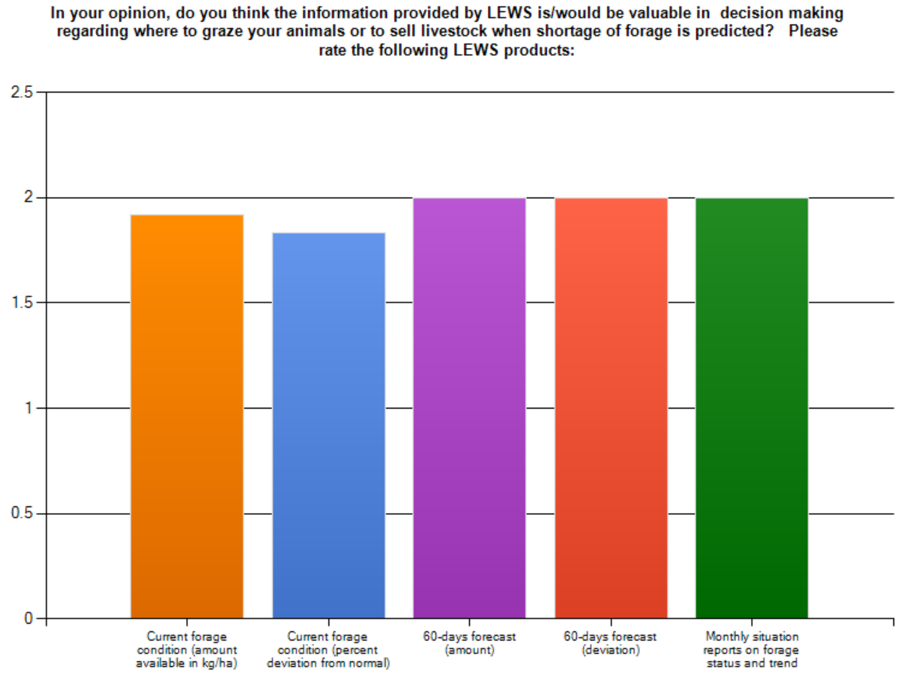


Figure 1. Summary Chart indicating Rank of Value of Each Product Indicated to Respondents Decision Making. The Rank Values are as follows: 2 = "Valuable", 1 = "Somewhat Valuable" and 0 = "Not Applicable". Derived from the Initial on-line Survey Administered (http://www.surveymonkey.com/) in 2008.

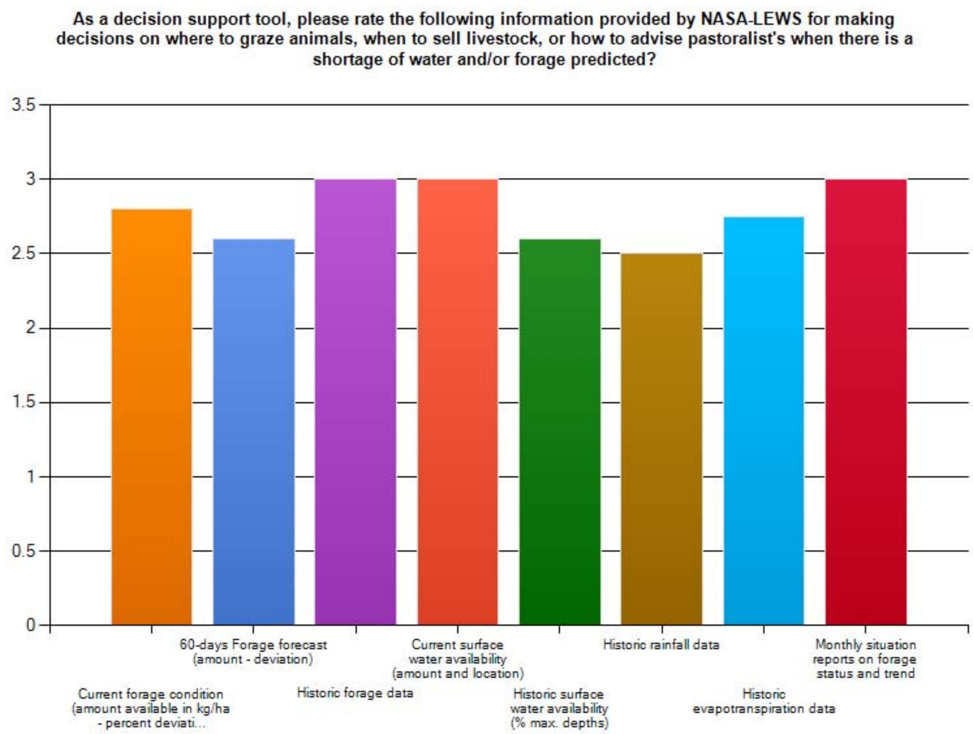


Figure 2. Summary Chart indicating Respondents Ranking of the Value of LEWS Forage Condition Information. Derived from the Follow-up Survey Administered on-line (http://www.surveymonkey.com/) in 2010. Rank Values are as follows: 3 = "Valuable", 2 = "Somewhat Valuable" and 3 = "Not Valuable" to their Decision Making.

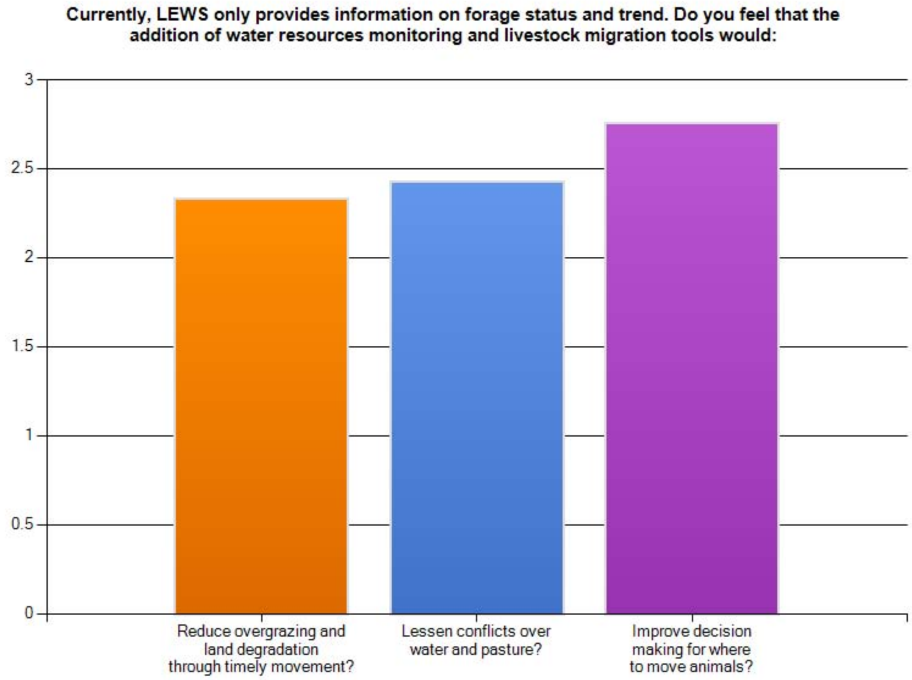


Figure 3 - Effect of Adding Information on Water Resources to the LEWS Forage Condition Database provided by LEWS-DSS. Derived from the Initial Survey Administered on-line (http://www.surveymonkey.com/) in 2008. Rank Values are as follows: 3 = "Greatly", 2 = "Moderately", and 3 = "No Effect" on each Factor Indicated.

Benchmarking Workshops

Two workshops were held in east Africa in an effort to introduce a new NASA/LEWS Decision Support System (DSS) product to key stakeholders and decision makers on 24th and 25th March in Nairobi, and on 29th and 30th March in Addis Ababa, Ethiopia. The primary purpose of the workshops was to engage stakeholders in discussion about (i) incorporation of key components from the forage monitoring component of the livestock early warning system (LEWS) (http://glews.tamu.edu/africa) (ii) the livestock market information system (LMIS) associated with the Livestock Information Network and Knowledge System (LINKS) project (http://www.lmiske.net and http://www.lmiset.net for Kenya and Ethiopia, respectively) (iii) the new water-monitoring tool developed by USGS (http://watermon.tamu.edu) to enhance the existing LEWS DSS. Ultimately, the intent was to create a new enhanced early warning system DSS called the Livestock Vulnerability Index (LVI). The NASA/LEWS team was composed of: Gabriel Senay (USGS), Jay Angerer (Texas AgriLife Research), Manohar Velpuri (SDSU/USGS), Gatarwa Kariuki (ILRI-Kenya), Sintayehu Alemayehu (ILRI-Ethiopia), and Steven Huckett (Texas AgriLife Research).

The objectives for the workshop were to: 1) discuss existing early warning products and gather stakeholder feedback; 2) evaluate this feedback and discuss how we might develop final products; 3) identify who the target audience should be and how best to disseminate information to them, and; 4) to explore options for combining data/tools to assist other development efforts in arid and semi-arid lands. The proposed LVI was envisioned to provide producers, marketers, pastoral communities and decision makers' access to early warning information regarding water and forage in an easy to use one-stop shopping format. This format would provide near real-time data regarding forage and water conditions by combining data from existing information systems to enhance the ability to pinpoint areas of vulnerability, and thus, to better protect livelihoods. Ultimately, the LVI would be a valuable tool for addressing food security issues related to livestock, conflict management, and provide important information for livelihood improvement efforts throughout East Africa.

The first workshop, held in Nairobi Kenya at the Jacaranda Hotel, had 19 participants in attendance. The second workshop was held in Addis Ababa, Ethiopia on the International Livestock Research Institute campus where 31 individuals participated. These participants represented a range of institutions (attendee lists for both workshops are attached). Topics of discussion included an introduction to NASA technologies available to identify waterholes (surface water resources) in semi-arid east Africa using remotely sensed data and imagery, and an introduction and demonstration of a simulation model designed for processing this information into a user friendly format.

The hands-on demonstration of the Water Monitoring website (http://watermon.tamu.edu) online demonstration was enthusiastically received by all participants in both workshops and generated many discussions about how it could be adapted to fill specific needs for various projects. The consensus was that this was a very good product with many applications ranging from livestock movement and livelihood improvement to conflict zone mitigation efforts.

After the online demonstration, a survey was conducted using four questionnaires that focused on 1) the usefulness of the waterhole monitoring data for livestock early warning, 2) the waterhole monitoring product, 3) on the performance of the waterhole monitoring website, and 4) on evaluating the improved-performance of the project compared to existing methods.

After demonstration of the water monitoring product, an overview of the existing LEWS and LMIS systems was presented on the second day of the workshop. These deliberations then turned to the introduction of the Livestock Vulnerability Index (LVI) concept. The primary focus of the second day of the workshop was to engage stakeholders in a discussion about the LVI concept to elicit ideas for how best to develop the LVI to maximize its utility as a DSS. The audience proved to be quite interested in such a product and joined in animated discussion and debate about how best to develop the product, who would be the primary audience and users of this information, and how best to disseminate the product to stakeholders. Feedback from participants included their observations of major strengths and weaknesses of the proposed LVI systems and suggestions for improving the concept. These major points were:

Strengths

- The LVI would provide a "one-stop" shopping portal for early warning information related to livestock and livelihoods that rely on livestock
- Combined several key data sources to provide better and integrated early warning information
- Near-real time information for decision makers

    - Presentation is simple and easy to use/understand
    - Ability to model trends in waterholes and range vegetation through time
    - Provides a tool to monitor effects of with climate change, land use and degradation
- Relevancy for the pastoralists, real users
- Important to involve users in consultations and collective decision-making
- potential to inform trans-boundary issues on trade and animal health

Weaknesses

- The need to include borehole and well monitoring
- Need to increase coverage area to include more waterholes; expansion to other pastoral areas
- Concern that small waterholes are not captured
- Need to assess or account for water volume at waterholes
- Need to improve the vegetative cover to maintain livestock and link to status of the water points
- Need to work on dissemination so as to maximize the utility of the DSS
- The need develop capacity to forecast water conditions at least one month into future
- Literacy among pastoralists and lack of access will reduce its use
- Need to get input of private sector or other stakeholders

An important consideration discussed was how to disseminate the information produced with the LVI and the water monitoring products. Several mediums such as radio, ministry bulletins, news outlets, traditional communications (word of mouth) were discussed. A second important discussion point was the issue of institutionalization. Because of past challenges of maintaining project-based activities beyond termination of the project, it is our intent to develop the system and institutionalize it as soon as possible so that "ownership" of the LVI system becomes embedded in the host countries. Adoption of the system is envisioned to be by a willing national government agency, regional non-government organization, or other appropriate institution, and be technically supported by Texas A&M/Texas AgriLife Research or USGS. This of course will depend primarily on how rapidly local capacity to operate and maintain the LVI is developed.

The LVI concept was enthusiastically received by stakeholders at both workshops, as a way to amalgamate several existing early warning products into an efficient and useful DSS for improving management of livestock resources throughout the East Africa region. This model is intended to serve as an affordable clearinghouse of key information for governments, NGOs and pastoral communities to enhance their decision making ability for livelihood improvement and policy development more holistically than has been the case in the past. Information derived from LVI can be easily integrated with existing programs within regional governments, USGS-Famine Early Warning Systems Network (FEWS NET), Intergovernmental Authority on Development's (IGAD) Conflict Early Warning and Response Mechanism (CEWARN), and livestock market information systems (LMIS), to name a few.

Due to its near real-time GIS-based platform, pastoral communities will have an effective tool for planning livestock movement based on availability of water and forage. Other tangible uses of this product include early warning information for alleviating effects of drought (water and forage conditions), policy development, conflict mitigation between different groups over issues pertaining to access to water and grazing resources, early warning to assist with marketing decisions, and future research and feasibility studies for new waterhole locations. It was felt that existing ministries of livestock or water resources would have a comparative advantage with its extensive structure of extension and network of field monitors at local levels. It is the intent of the U.S. partners to continue providing technical back-stopping of the product. Potential consumers and partners of the LVI identified in the workshop include the following:

- Pastoral Communities
- Regional Governments, Ministries of Water Resources / Livestock
- Ministries of Northern Kenya, Southern Ethiopia, and other Arid Areas
- Disaster Risk Management and Food Security Sector (DRMFSS) – Early Warning and Response Directorate
- NGOs: CARE International, VSF Consortium, JICA, GAA, CordAID, GTZ, Acted, OCHA, Save the Children, CARE Pastoralists Coordination Program, UNICEF – Emergency Water Cluster, OXFAM (GB, USA, Spain), ACF, Global Water Initiative (GWI) - Regional Program
- World Bank, African Development Bank, DFID, ASERACA, UN-WFP Vulnerability Analysis and Mapping (VAM) and FAO - Emergency and Recovery Unit
- Regional Universities
- Famine Early Warning Systems Network (FEWSNET)
- Pastoral Community Development Program, Arid Lands Resource Management Program,
- Consultants and other private livestock groups

A central, under-lying theme of these workshops was to facilitate more collaboration among research and development institutions which takes steps toward more effective livelihood improvement efforts throughout East Africa and beyond.

Activity 2: Mapping forage baseline with MODIS Vegetation Continuous Fields

The Moderate Resolution Imaging Spectroradiometer (MODIS) Vegetation Continuous Fields (VCF) product was analyzed for its use in extending LEWS DSS field collected vegetation data to other unsampled areas. The objective of this activity was to verify whether MODIS VCF data could be useful in providing improved delineation of areas experiencing drought or low forage conditions compared to the current method of geostatistical analysis using forage model output and AVHRR NDVI data.

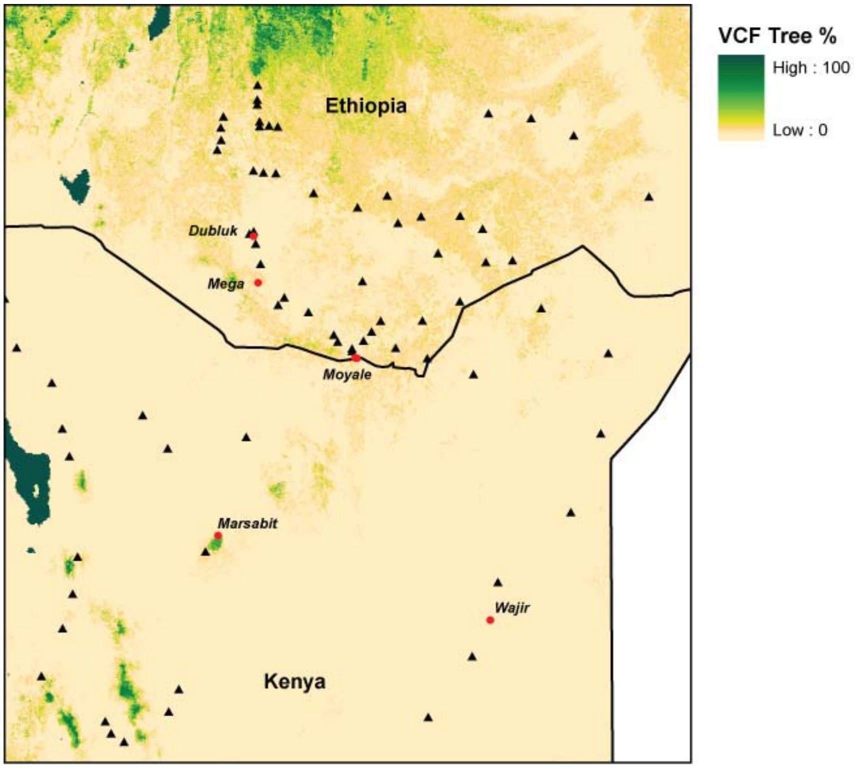
As part of the implementation of the forage monitoring simulation model for the LEWS DSS, baseline plant community information was determined by a ground sampling approach in which selected sites were visited by the LEWS teams to characterize vegetation community parameters to gather data to parameterize the biophysical simulation model (PHYGROW) (Stuth et al. 2003a; Stuth et al 2003b; Ryan 2005; Stuth et al. 2005). PHYGROW is capable of simulating forage growth and the consumption of forage by multiple grazers with varied preferences for the vegetation present. The simulation model runs are parameterized for each of the sampling sites using the field information and near real-time climate data as driving variables. Modeling results for the sampling sites are then geostatistically interpolated to unsampled areas using NDVI data to produce regional maps of forage conditions.

For this activity, we began the assessment on whether we could use MODIS Vegetation Continuous Fields (VCF) data to assist in forage model parameterization at new sites to alleviate the need for additional field data collection for model parameterization. We also sought to assess whether the higher density of sampling points would improve the delineation of drought stricken areas over that of the geostatistically interpolated (cokriging) methodology.

Methods. For the VCF analysis, we chose the MODIS VCF collection 3 data that contains proportional estimates for vegetative cover types (tree vegetation, herbaceous vegetation, and bare ground) within a 500 x 500 m pixel (Hansen et al. 2003). The tree cover type reflects the tree canopy cover (i.e., amount of skylight obstructed by tree canopies) for trees greater than 5 m in height. The herbaceous canopy cover component represents grasses, forbs and shrubs less than 5 meters in height. For the study area, the MODIS VCF data were processed to extract the herbaceous and tree cover layers (Figure 1). The PHYGROW model uses cover measurements for defining the relative differences between plant proportions in different plant communities. For this analysis, we chose to use the VCF values as the plant proportion values in PHYGROW. No data were collected to assess how well the VCF plant proportions matched the field collected data at the monitoring sites.

Because of the relatively high resolution of the VCF data (500 m) compared to the RFE rainfall (Herman et al. 1997) data (~11 km) that is used to drive the PHYGROW simulation model, we chose to use an 8 x 8 km grid cell for the VCF analysis. This would also allow us a more direct comparison with the interpolated model output that has a resolution of 8 km to match the NDVI data that is used as a covariate in the geostatistical analysis. For each 8 x 8 km grid cell, the cover percentages for the VCF tree and herbaceous cover were individually averaged for all of the 500 m pixels within the 8 x 8 km cell (excluding water and null values). Because shrubs make up a large component of the landscape in this region and because their water use and use by livestock is quite different from forbs and grasses, we developed a simple methodology to partition out a shrub component from the overall herbaceous component for each cell. We used the MODIS Land Cover product (Figure 5) to assign a dominant land cover class to each 8 x 8 km grid cell. We chose to use the IGBP land cover product which identified 6 different dominant land cover classes across the study region (Table 1). These included closed shrublands, open shrublands,woody savannas, savannas, grasslands, and barren lands. For each of these land cover classes, there are general definitions of the cover type which provide a guideline on the percentage of shrubs in each cover class. We used this definition to allocate the proportion of the herbaceous component that would be split into grasses and shrubs (Table 1). For example, if the majority of the land cover type in an 8 x 8 pixel was woody savanna, we partitioned out the VCF herbaceous value into 70% grass and 30% shrubs (Table 1). Therefore, if the VCF herbaceous value for the 8 x 8 cell was 50%, then the grass component would be 35% and the shrub component would be 15%.

Once the percent grass, shrub and tree were determined for each grid cell, simulation model runs were prepared for each of the grid cells. For the plant growth parameters, the grass, shrub and tree plant parameters were derived from the dominant grass, shrub, and tree species at the nearest



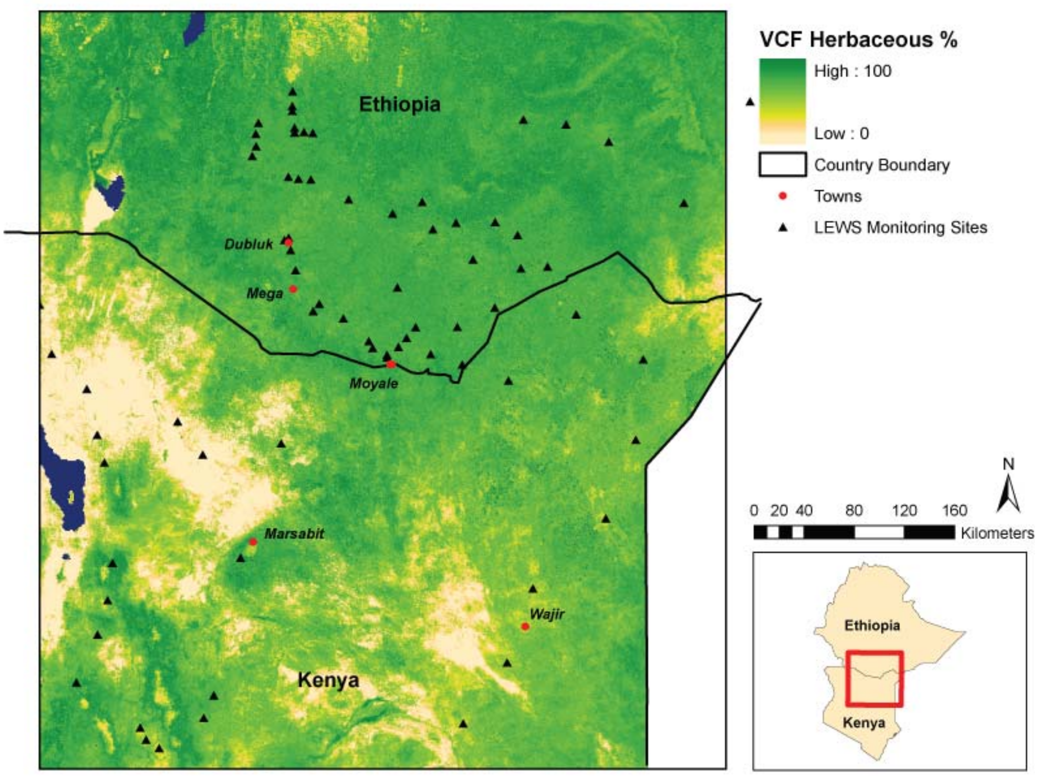


Figure 4. Tree canopy cover (%) and herbaceous canopy cover percent for the MODIS VCF data with the study area region. The triangular symbols represent the location of field monitoring sites for the Livestock Early Warning System where data were collected for parameterizing the PHYGROW simulation model.

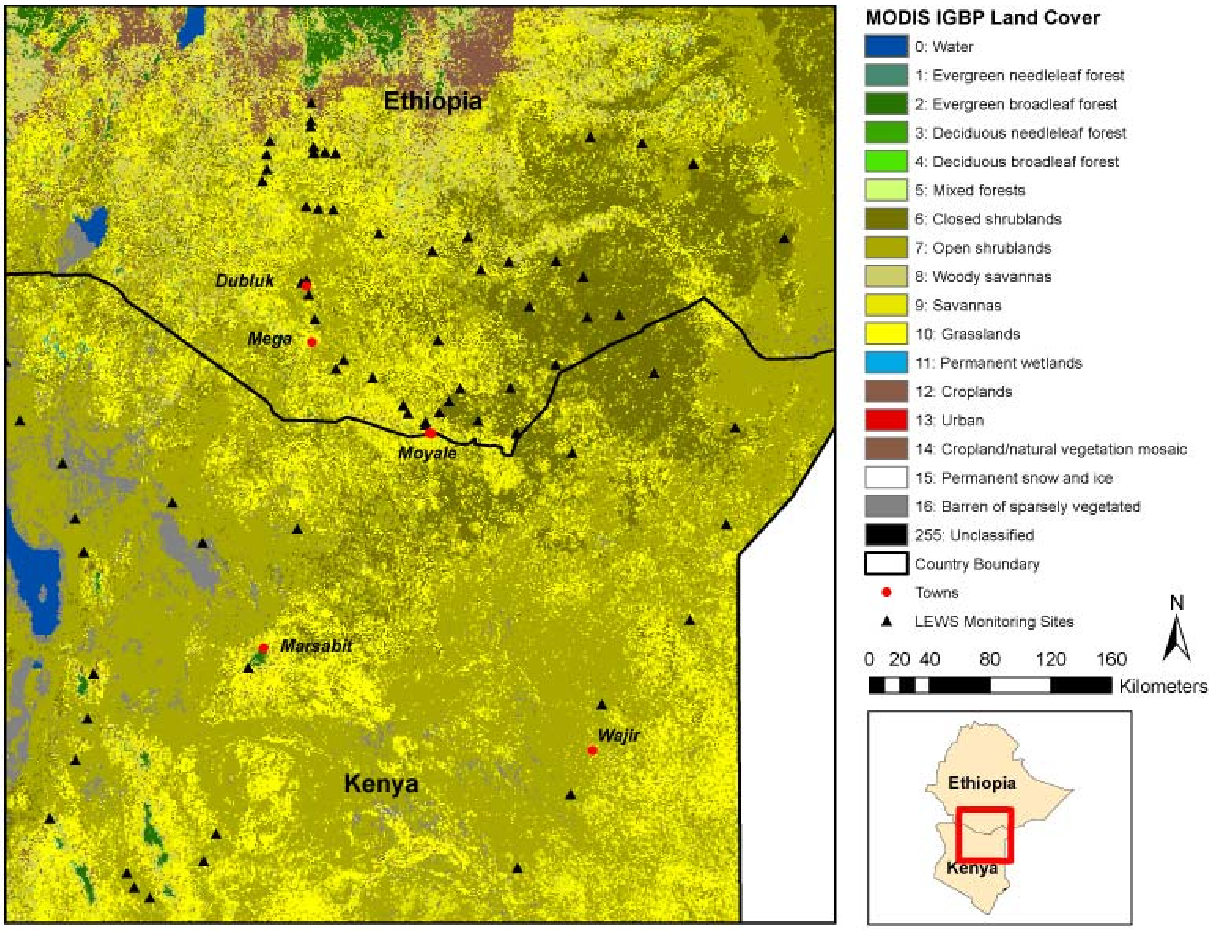


Figure 5. MODIS IGBP land cover classes within the study region. The triangular symbols in the map represent LEWS monitoring sites that were used to provide plant parameters for the VCF analysis.

Table 1. MODIS IGBP Cover class designation and the percentage breakdown of the herbaceous VCF value for grass and shrub components of the herbaceous class.

Class Number	IGBP Land Cover Class	Herbaceous Class Breakdown	
		Percent Grass	Percent Shrub
6	Closed shrublands	0.4	0.6
7	Open shrublands	0.65	0.35
8	Woody savannas	0.7	0.3
9	Savannas	0.8	0.2
10	Grasslands	0.95	0.05
16	Barren	1	0

LEWS monitoring site. Soils parameters were derived from digital soil maps and soil profile data gathered during previous LEWS efforts. Grazing parameters which included kinds of grazers present, the general stocking rates, and grazing preferences for the grass, shrub, and tree components were derived from the nearest LEWS monitoring site. The climate data used to drive the simulation model runs included the RFE rainfall and surface temperature data provided by NOAA Climate Prediction Center through the Famine Early Warning System program. The Collaborative Historical African Rainfall Model (CHARM) (Funk et al. 2003) data were used for historical rainfall data to produce long-term averages of forage production.

Simulations for each grid cell were conducted and data stored in the central LEWS database. After runs were completed, a weighted average of the total forage available to the grazers was calculated. Total forage available represents the amount of forage that is available to be eaten for each of the different kinds of grazers and is dependent on the plant species on the landscape and the preference the grazer has for those species on the landscape. For example, on grassland, the total forage available for cattle will generally be much higher than that of goats because cattle tend to be grass eaters and the goats tend to be browsers. A weighted average of the total forage available across grazers allows the use of a representative forage value that is weighted toward the dominant grazer on the landscape. Therefore, changes in total forage available can be a signal of vulnerability of the dominant kinds of animals in a region when drought hits. The weighted average total forage available was used as model output variable to compare the VCF derived maps versus that derived from the traditional geostatistical interpolation that LEWS has been using previously.

Results. The VCF analysis resulted in 3364 unique simulation runs within the study area. The total forage available for each simulation was extracted for each month beginning in May 2009 to February 2010 and attached to a shapefile of the 8 x 8 km grid in the GIS. The grid was then converted to a raster to allow comparison with the interpolated LEWS maps. The period from May 2009 to February 2010 was chosen because it represents a period of severe to extreme drought in portions of the study area, so it offers the opportunity to examine the delineation of these areas by the different products.

In a comparison of the VCF derived maps of total forage available to that derived from the traditional LEWS approach of geostatistical modeling (cokriging), the VCF derived maps do a much better job of delineating local areas of low forage conditions (Figure 6). Because the cokriging analysis has a tendency to smooth boundaries between changing forage conditions, it does not do as great a job of delineating local conditions. Also, the ability of cokriging to provide finer delineation of forage conditions is dependent on the number of monitoring points and the proximity of the points. The triangular region between Marsabit, Moyale, and Wajir in Kenya (Figure 5) provides a good example of the lack of variation in the cokriging maps for this area and this is likely driven by the low number of LEWS monitoring points in this region (Figure 6). The VCF analysis does a much better job of displaying the variability in conditions across this region.

For the majority of the months during the period from May 2009 to May 2010, the VCF derived product predicted much higher forage in the northwestern portion of the study region and lower forage in the western and southern portions of the study region when compared to the cokriging map (Figure 6 for August 2009). The lower forage predictions in the western portion of the study area are due the VCF values for tree and herbaceous being very low (< 10% total cover over larger portions of the region) and some areas were estimated as completely barren. Because there are very few LEWS monitoring sites in this area, the cokriging estimation of forage is likely too high and is driven by the forage predictions for sites in slightly better condition.

An examination of the deviation from long term average maps for August 2009 reveals that the VCF derived maps are depicting much worse drought conditions than the LEWS cokriging product (Figure 7). August 2009 was one of the peak months of the drought in Kenya, and in the northern Kenya there were reports of livestock losses and migration from the area because of the lack of water and forage (http://www.nytimes.com/2009/09/08/world/africa/08kenya.html). During the August 2009 period, the LEWS cokriging map depicts poor to scarce conditions (-10 to -50% below average) for much of northern Kenya (Figure 4). However, the VCF derived map depicts conditions of scarce to disaster (-30 to -100% below average) for the majority of Northern Kenya (Figure 7). As discussed previously, the VCF map also does a much better job of delineating local differences in forage conditions with greater definition of the boundaries were drought and disaster conditions are predicted.

An examination of the February 2010 results (Figure 8) of the forage predictions for both products indicates that there were similar predictions of forage amounts in the eastern portions of the study area in Kenya. However, as was seen in August 2009, the VCF product predicts much higher forage amounts in the northwester portion of the study area portion of the study area and lower amounts in the west and southwest (Figure 8). The VCF product also delineates some areas of very low forage east and southeast of Marsabit that the LEWS cokriging map does not pick up (Figure 8). A differencing of the VCF derived map and the cokriging map revealed that the cokriged map predicted 700 to 900 kg/ha higher forage in these areas.

A comparison of the VCF and cokriging products for February 2010 with regard to forage deviations shows differences in the depiction of drought versus non drought areas between the two products (Figure 9). By February 2010, rain had been received in Northern Kenya and recovery from the drought had begun. The VCF map predicted that much of the southern and eastern portions of the study area were in scarce forage to drought conditions (-30 to -70% below average) (Figure 9). The cokriging map predicted that much of this area was in normal conditions. Both maps identify an emergence of below average forage in Ethiopia in the northern portion of the study area (Figure 9). However, the cokriging map depicts it as being much less severe than the VCF map.

Conclusions. The mapping of total forage available on landscapes in Ethiopia and Kenya using plant community parameters derived from the MODIS VCF product appears to hold promise for delineating areas of drought conditions and for examining departures from long-term average. The product does a good job of representing and delineating areas of local drought compared to the LEWS cokriging product and has a tendency to depict droughts as more severe than the LEWS cokriging product.

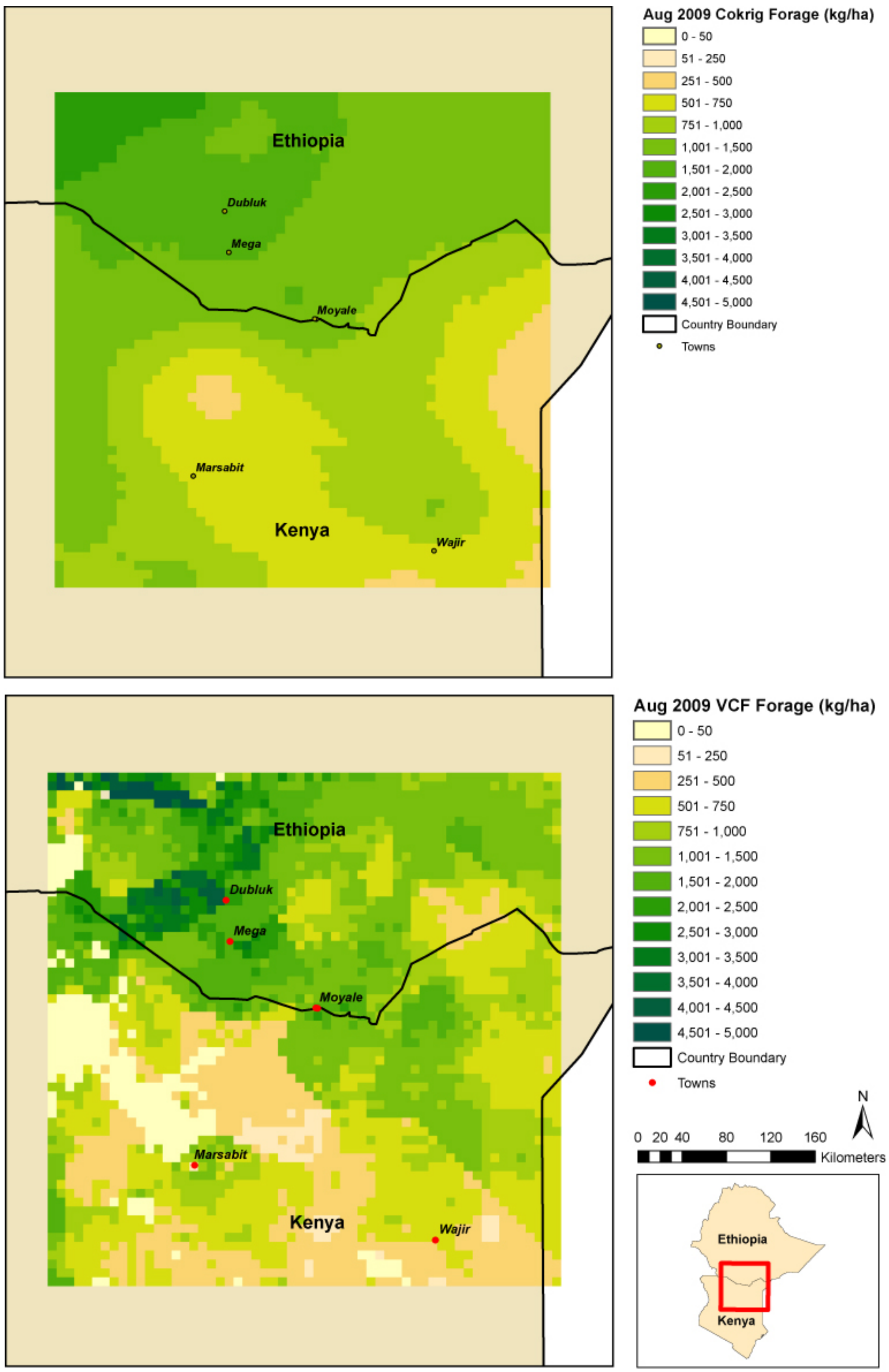


Figure 6. A comparison of total forage available maps for Livestock Early Warning System outputs using the geostatistical method of cokriging (top map) versus that derived using VCF data (bottom) for August 2009 during the peak of the drought.

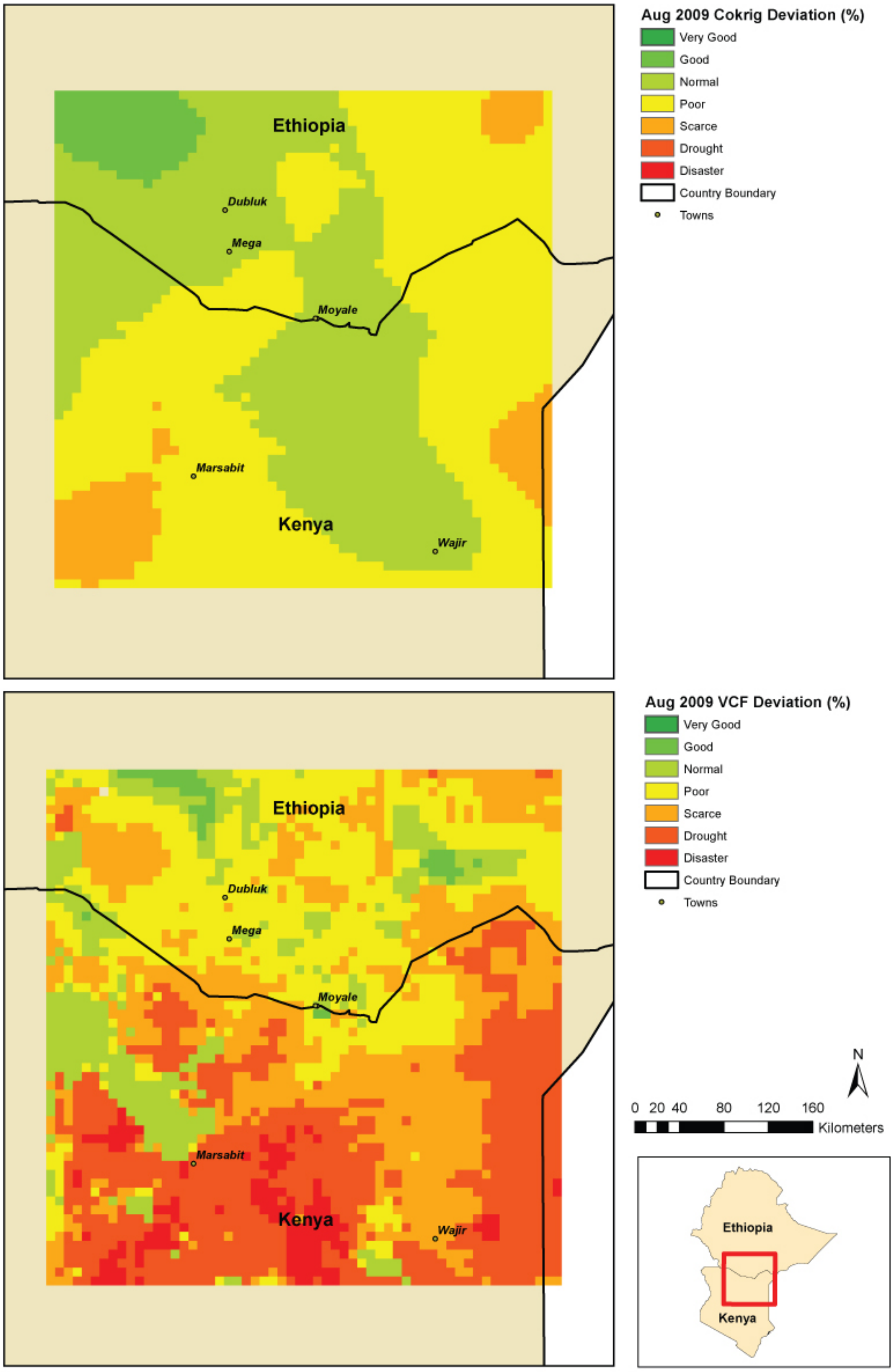


Figure 7. A comparison of forage deviation from long term average for LEWS maps derived from geostatistical analysis (cokriging) (top) versus that derived from VCF data (bottom) during the peak of the drought period in August 2009.

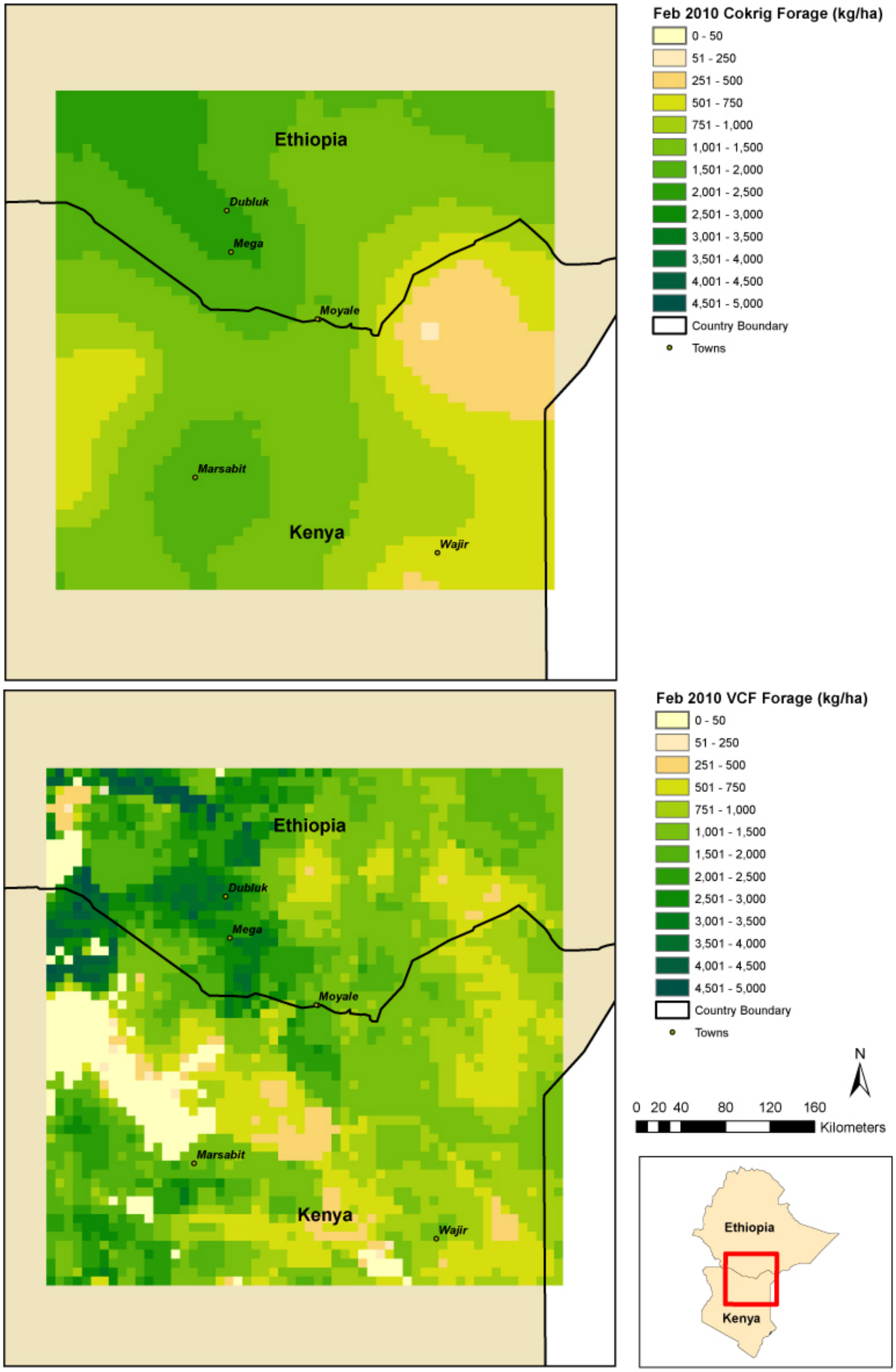


Figure 8. A comparison of total forage available maps for Livestock Early Warning System outputs using the geostatistical method of cokriging (top map) versus that derived using VCF data (bottom) for February 2010 during recovery from the 2009 drought.

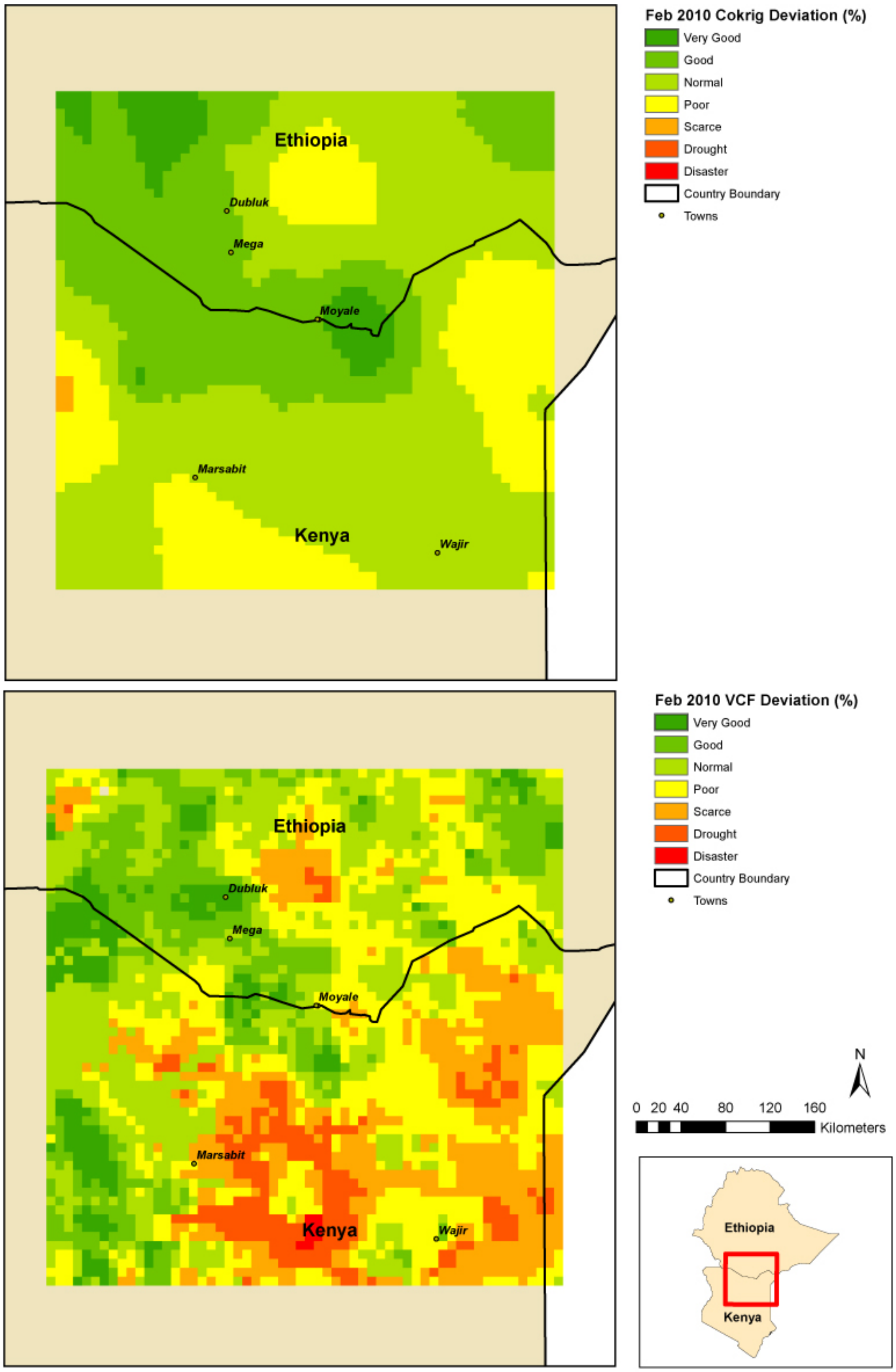


Figure 9. A comparison of forage deviation from long term average for LEWS maps derived from geostatistical analysis (cokriging) (top) versus that derived from VCF data (bottom) during the period of recovery after the 2009 drought.

The accuracy of the predictions for forage available by the VCF product needs to be evaluated before large scale use. The accuracy of the LEWS products has been evaluated at the monitoring site locations in the past, but both products need ground-truthing at distances away from the LEWS monitoring points to properly validate the product. However, the VCF product appears to do very well at anomaly detection (i.e. deviation from long-term average) for drought, and in the short term, this may be its best use until it can be properly validated with field data.

The initial overhead with regard to computing requirements and data storage for setting up the VCF analysis is quite high and will require much planning if one tries to implement this for all of East Africa. One needs to have large database stores for the weather and data output associated with doing large numbers of simulations. Another consideration is the number of days that it would take to conduct all of the runs in a timely fashion. Distributed computing system is extremely useful for this task and will likely be needed to make a VCF mapping system operational for all of East Africa.

Activity 3: Mapping seasonal migration patterns with GPS technology

One of the objectives of the NASA LEWS DSS project was to perform migratory route survey to study the movement patterns of pastoralists and their livestock herds in response to changing forage and water supply needs in the study area using GPS technology. However, due to difficulties in training pastoralists in the use of GPS technologies and with managing the GPS units (data downloads, batteries, etc.), this approach was abandoned. Instead, information on the migration was gathered through interviews with strategically located key informants who were representative of the major pastoral communities in each of the countries.

Under this activity, we set out to determine the movement patterns of pastoralists and their livestock herds in response to changing forage and water supply. Our findings provide valuable insights to compare various communities' mobility and grazing management behaviors and provided insights into the decision processes of pastoralist. The addition of these insights will improve the quality of information produced by the Water Monitoring and LEWS products and facilitate a more effective early warning system for pastoral communities.

Broadly, it was indicated by the people and groups interviewed that weather patterns and biophysical feature are the key drivers of livestock movements throughout the study area. Migration patterns can be generally described as the movement of animals from lower elevations during the rainy seasons to higher elevations during the drier seasons. Lowland range may produce excellent quality and quantity of forage but the reliability of surface water resources is a limiting factor. Conversely, rangelands at higher elevations tend to receive higher rainfall amounts, have a higher probability of adequate surface water resources, and produce forage over longer periods of time. In essence, pastoralists take advantage of elevation differences in rainfall, surface water availability, and forage production and to spread the impact of grazing over larger areas both temporally and spatially, giving them a degree of wealth and food security. Of course there are exceptions to this generalization which may be explained by local conditions and constraints.

Regional Migration Patterns

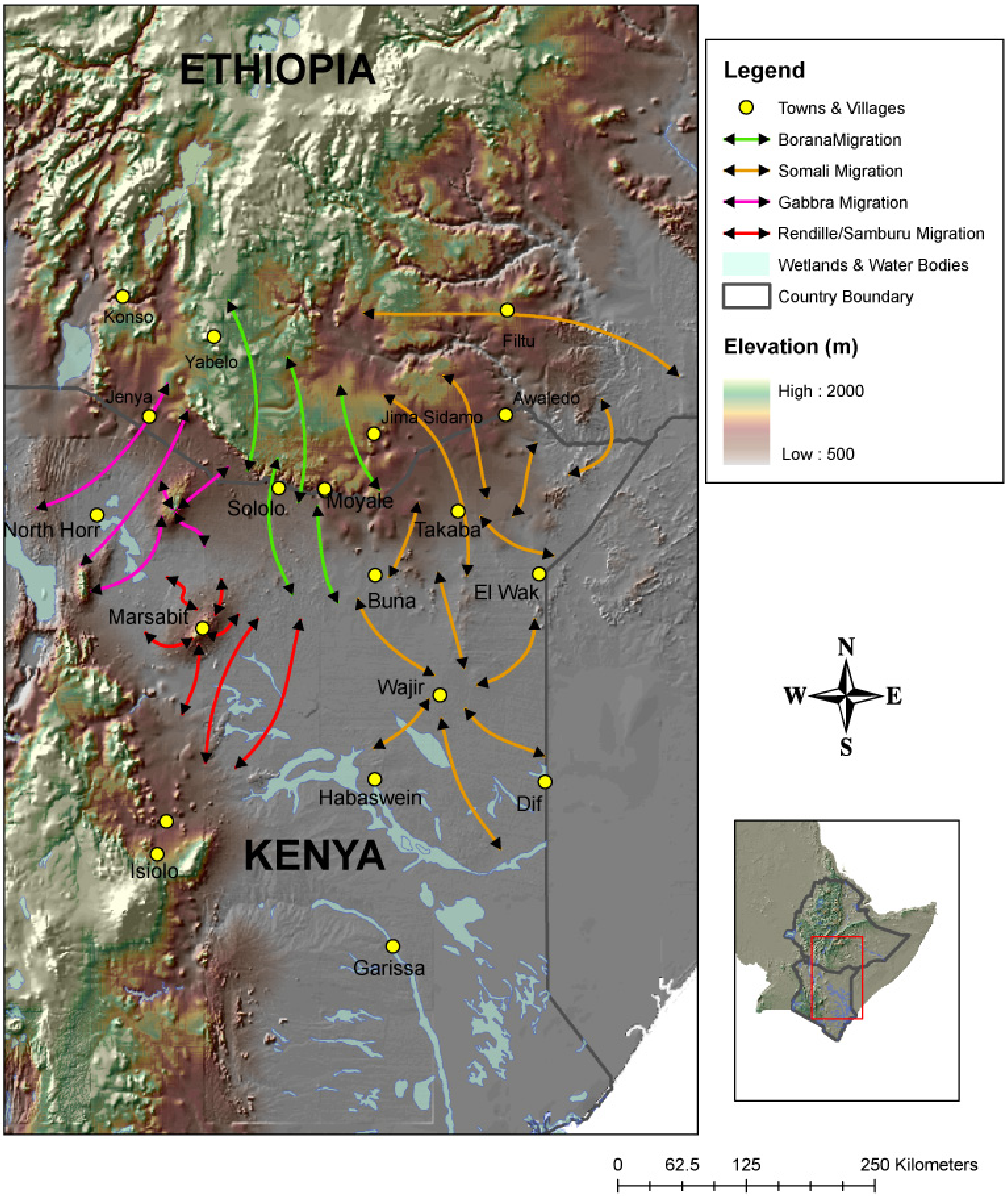


Figure 10. Illustration of Regional Livestock Movements in the Arid and Semi-Arid Rangelands of northern Kenya and southern Ethiopia

In all regions, management of migrating livestock herds are almost universally shaped by the warra/forra herd management system, whereby herds are divided into a home bound warra herd and a migratory forra herd. The timing and distance of the movement of animals is dictated by the availability of water first, and by forage second. Since both water and forage resources are heavily dependent on seasonal weather patterns, which can vary greatly locally and regionally, these resources are typically unevenly available over large areas making the size and direction and distance forra herds are moved difficult to define.

Under the NASA LEWS DSS project, information on the migratory patterns of the pastoralists has been collected that has never been published before. Figure 10 shows the migration patterns of major pastoral communities within the study site. Such comprehensive information on the migratory patterns within the study site has never been made and thus this information will be published in the peer-review journal.

Activity 4: Operational monitoring of water resources with TRMM

In this activity, new water resources monitoring products were added into the LEWS DSS. These new products are essential for monitoring the conditions of water resources that are vital in decision making by the user community of herders. In particular, daily water availability monitoring products have been developed for individual waterholes for use by stakeholders.

The majority of tasks for this activity were conducted by the USGS/EROS team in association with the ASTER imagery analysis under Activity 1. USGS-EROS developed daily rainfall estimates subsetted from the NASA TRMM dataset for Africa. A modeling framework for modeling daily catchment runoff for the contributing areas around waterholes using the TRMM dataset has been developed and is fully operational. Daily water level changes (whether positive or negative) were validated for sixteen (16) major waterholes identified under Activity 1 of this study using similar techniques by Senay and Verdin (2004).

The Texas AgriLife Research team has worked with USGS and their subcontractor South Dakota State University to develop a web portal for displaying the water monitoring activities. The website can be viewed at http://watermon.tamu.edu. This website offers users the ability to monitor and download waterhole depth information from 1998 to present. Currently, 42 representative waterholes in the region are being operationally monitored (with a day lag) for variations in waterhole depths. The site provides the current status of depths for each waterhole (daily depth variation information) which would enable pastoral communities to make appropriate decisions on their migratory movements in search of water and forage. It also allows users to examine the median water levels along with past years data.

During this reporting period, the site has been enhanced to provide a low-bandwidth version to allow easier access of information in rural areas of Ethiopia and Kenya with slow internet connections. The site was also enhanced to provide near real-time tracking of the status of the waterhole conditions by color coding the indicators on the Google map interface (Figure 11). The help and information components were also improved to make the site more user-friendly.

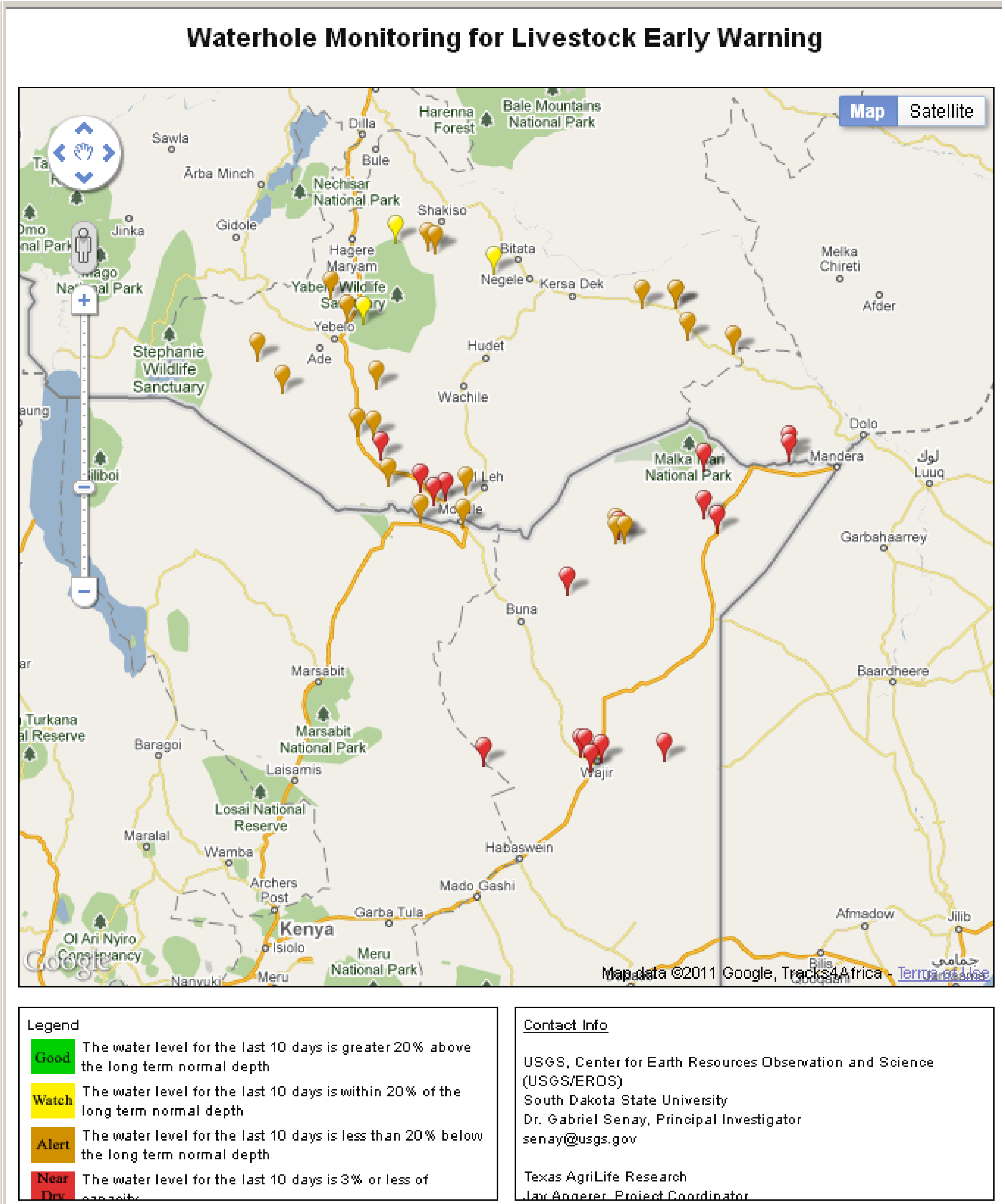


Figure 11. Map interface for waterhole status on water monitoring website (http://watermon.tamu.edu).

Literature Cited

Abule, E., H.A Snyman and G.N Smit. 2005. Comparisons of pastoralists' perceptions about rangeland resource utilisation in the Middle Awash Valley of Ethiopia. J. Environ. Manage. 75, 21–35.

Funk, C., J. Michaelsen, J. Verdin, G. Artan, G. Husak, G. Senay, H. Gadain, and T. Magadazire, 2003: The Collaborative Historical African Rainfall Model: Description and Evaluation. International Journal of Climatology, 23, 47-66

Hansen, M., R. DeFries, J.R. Townshend, M. Carroll, C. Dimiceli, and R. Sohlberg (2003), Vegetation Continuous Fields MOD44B, 2001 Percent Tree Cover, Collection 3, University of Maryland, College Park, Maryland, 2001.

Herman A, Kumar VB, Arkin PA, Kousky JV (1997) Objectively determined 10-day African rainfall estimates created for famine early warning systems. International Journal of Remote Sensing 18: 2147-2159.

Ryan Z (2005) Establishment and evaluation of a livestock early warning system for Laikipia, Kenya. Thesis, Texas A&M University: College Station, Texas.

Senay, G.P. and J.P. Verdin, 2004. Developing index maps of water-harvest potential in Africa. *Applied Engineering in Agriculture, American Society of Agricultural Engineers*, 20(6): 789-799.

Stuth JW, Angerer J, Kaitho R, Zander K, Jama A, Heath C, Bucher J, Hamilton W, Conner R, Inbody D (2003a) The Livestock Early Warning System (LEWS): Blending technology and the human dimension to support grazing decisions. Arid Lands Newsletter, University of Arizona. Available from http://cals.arizona.edu/OALS/ALN/aln53/stuth.html (accessed 7/1/2007).

Stuth JW, Schmitt D, Rowan RC, Angerer JP, Zander K (2003b) PHYGROW Users Guide and Technical Documentation. Texas A&M University. Available from http://cnrit.tamu.edu/phygrow/PHYGROW_userguide.pdf (accessed June 1, 2007).

Stuth JW, Angerer J, Kaitho R, Jama A, Marambii R (2005a) Livestock early warning system for Africa rangelands. *In* Boken VK, Cracknell AP and Heathcote RL (eds), Monitoring and predicting agricultural drought : a global study. Oxford University Press, New York, pp. 283-294.

Award No. 08HQAG0118 Transboundary Aquifer Assessment Program

Basic Information

Title:	Award No. 08HQAG0118 Transboundary Aquifer Assessment Program
Project Number:	2008TX353S
Start Date:	3/31/2008
End Date:	4/30/2011
Funding Source:	Supplemental
Congressional District:	
Research Category:	Ground-water Flow and Transport
Focus Category:	Groundwater, Models, Hydrology
Descriptors:	
Principal Investigators:	Ari Michelson

Publications

There are no publications.

UNITED STATES – MEXICO TRANSBOUNDARY AQUIFER ASSESSMENT PROGRAM
ANNUAL REPORT 2010–2011
New Mexico and Texas Water Resources Research Institutes in Collaboration with USGS NM and TX State Offices

Description: This is a Congressionally-authorized program, Public Law 109-448, to conduct bi-national, scientific research to systematically assess priority transboundary aquifers. The results of this program will provide a scientific foundation for state and local officials to address pressing water resource challenges in the United States–Mexico border region. Investigations will be conducted in partnership with the U.S. Geological Survey (USGS), Texas and New Mexico Water Resources Research Institutes and in collaboration with appropriate state agencies and Mexican counterparts.

Relevance and Background: In the desert region of the border surface water is scarce and unreliable, making groundwater the primary—and in some areas, the only—water source. Declining aquifers and increasing use of border groundwater resources by municipal and other water users have raised serious concerns about long-term availability of this supply. Water quantity and quality are determining and limiting factors that ultimately control future economic development, population growth, and human health along the United States–Mexico border. However, knowledge about the extent, depletion rates, quality, and solute movement of transboundary aquifers is inadequate.

Objectives: The *United States–Mexico Transboundary Aquifer Assessment* Program objectives are to collect and evaluate new and existing data to develop high-quality, comprehensive groundwater quantity and quality information, and to develop groundwater flow models for selected priority binational aquifers in Arizona, New Mexico, Texas, and Mexico. This bi-national information is essential for understanding the extent of these aquifers and quantifying water availability, water quality, and use of these aquifers. Based on stakeholder input, the primary initial focus of the New Mexico and Texas assessment program is the Mesilla Basin aquifer in the El Paso, TX, Southern New Mexico and Ciudad Juarez, MX regions because of the reliance, rapidly expanding use, and immediate need for information regarding this aquifer. Through this program, scientists from New Mexico State University, The Texas A&M University System, University of Arizona, U.S. Geological Survey, state agencies, and Mexican counterparts are working in partnership to collect, share, and evaluate new and existing data to develop high-quality, comprehensive, groundwater quantity and quality data and groundwater flow models for bi-national aquifers. This information is needed to understand availability and use and to evaluate strategies to protect water quality and enhance water supplies for sustainable economic development on the United States–Mexico border.

Project Activity and Accomplishments: (need to add Arizona)

Accomplishments and activities include:

a. Development of research plans in collaboration with stakeholders;
b. Review and evaluation of approximately 800 publications and previous studies on the Mesilla Basin and development of a database for bibliographical searches and sharing;

c. Review and assessment of existing geological, hydrogeologic monitoring data, ancillary databases, and geographic information systems (GIS) for the Mesilla Basin from different sources, such as U.S. Geological Survey, New Mexico Office of State Engineer, Texas Water Development Board, Paso del Norte Watershed Council as well as available Mexico data and information;
d. Evaluation and further development of existing hydrogeologic framework models;
e. Review of seven existing independent groundwater models for the Mesilla Basin aquifer to select which one/ones to use for bi-national aquifer modeling;
f. Identification of data gaps and additional information needed for hydrogeologic model development;
g. Development of a data sharing and program coordination agreement with Mexico through the U.S. and Mexico International Boundary and Water Commissions;
h. Preparation of a scope of work and funding proposal for research to be conducted in Mexico.

Partners: (need to add other NM and AZ)
Texas Water Development Board, El Paso Water Utilities, New Mexico State University, University of Arizona, USGS Texas State Office, Water Science Center, USGS New Mexico State Office Water Science Center, International Boundary and Water Commission–United States and Mexican Sections, and many others, including numerous water management agencies and organizations.

Hydrological Drought Characterization for Texas under Climate Change, with Implications for Water Resources Planning and Management

Basic Information

Title:	Hydrological Drought Characterization for Texas under Climate Change, with Implications for Water Resources Planning and Management
Project Number:	2009TX334G
Start Date:	9/1/2009
End Date:	8/31/2012
Funding Source:	104G
Congressional District:	17th, TX
Research Category:	Climate and Hydrologic Processes
Focus Category:	Drought, Surface Water, Climatological Processes
Descriptors:	None
Principal Investigators:	Vijay P Singh, Ashok Kumar Mishra

Publications

1. Singh, V. P., 2010, Entropy theory for derivation of infiltration equations, Water Resources Reseach, 46, W03527, doi:10.1029/2009WR008193.
2. Singh, V. P., 2010, Entropy theory for movement of moisture in soils, Water Resources Research, 46, W03516, doi:10.1029/2009WR008288.
3. Mishra, A. K., and V. P., Singh, 2010, Changes in extreme precipitations in Texas, J. Geophysical Research, American Geophysical Union, (In Press). Manuscript no: 2009JD013398.
4. Mishra, A. K., M., Özger, and V. P., Singh, 2010, Association between uncertainty in meteorological variables and water resources planning for Texas, Journal of Hydrologic Engineering, ASCE, (in press).
5. Ozger, M., A. K., Mishra, and V. P., Singh, 2010, Scaling characteristics of wet and dry spells of precipitation data, Journal of Hydrologic Engineering, ASCE, (In press).
6. Ozger, M., A. K., Mishra, and V. P., Singh, 2010, Long lead time drought forecasting using a wavelet and fuzzy logic combination model, Water Resources Research (Submitted after first review), American Geophysical Union, Manuscript no:2009WR008794.
7. Mishra, A. K., and V. P., Singh, 2010, A review on drought concepts, Journal of Hydrology, (Submitted after first review), Manuscript no: HYDROL 8529.
8. Mishra, A. K., and V. P., Singh, 2010, Drought modeling: A review, Reviews of Geophysics, (Submitted).
9. Mishra, A. K., M., Özger, and V. P., Singh, 2010, Seasonal streamflow extremes in Texas River basins: Uncertainty, trends and teleconnections under climate change scenarios, Journal of Geophysical Research, (Submitted).
10. Singh, V. P., 2010, Entropy theory for derivation of infiltration equations, Water Resources Reseach, 46, W03527, doi:10.1029/2009WR008193.
11. Singh, V. P., 2010, Entropy theory for movement of moisture in soils, Water Resources Research, 46, W03516, doi:10.1029/2009WR008288.

12. Mishra, A. K., and V. P., Singh, 2010, Changes in extreme precipitations in Texas, J. Geophysical Research, American Geophysical Union, (In Press). Manuscript no: 2009JD013398.
13. Mishra, A. K., M., Özger, and V. P., Singh, 2010, Association between uncertainty in meteorological variables and water resources planning for Texas, Journal of Hydrologic Engineering, ASCE, (in press).
14. Ozger, M., A. K., Mishra, and V. P., Singh, 2010, Scaling characteristics of wet and dry spells of precipitation data, Journal of Hydrologic Engineering, ASCE, (In press).
15. Ozger, M., A. K., Mishra, and V. P., Singh, 2010, Long lead time drought forecasting using a wavelet and fuzzy logic combination model, Water Resources Research (Submitted after first review), American Geophysical Union, Manuscript no:2009WR008794.
16. Mishra, A. K., and V. P., Singh, 2010, A review on drought concepts, Journal of Hydrology, (Submitted after first review), Manuscript no: HYDROL 8529.
17. Mishra, A. K., and V. P., Singh, 2010, Drought modeling: A review, Reviews of Geophysics, (Submitted).
18. Mishra, A. K., M., Özger, and V. P., Singh, 2010, Seasonal streamflow extremes in Texas River basins: Uncertainty, trends and teleconnections under climate change scenarios, Journal of Geophysical Research, (Submitted).
19. Mishra, A. K., Singh, V. P., and Özger, M., (2011). Seasonal streamflow extremes in Texas River basins: uncertainty, trends and teleconnections. Journal of Geophysical Research, AGU,116, D08108. doi:10.1029/2010JD014597.
20. Mishra, A. K., and Singh, V. P. (2011), Drought modeling: A review, J Hydrology, (In Press).
21. Ozger, M., Mishra, A. K., and Singh, V. P. (2011), Long lead time drought forecasting using a wavelet and fuzzy logic combination model. J Hydrometeorology (Submitted after first review), AMS. Manuscript no: JHM-D-10-05007.
22. Ozger, M., Mishra, A. K., and Singh, V. P. (2010), Scaling characteristics of precipitation data in conjunction with wavelet analysis. Journal of Hydrology, 395(3-4), 279-288.
23. Ozger, M., Mishra, A. K., and Singh, V. P. (2010), Predicting Palmer Drought Severity Index using meteorological variables. International Journal of Climatology, DOI: 10.1002/joc.2215.
24. Ozger, M., Mishra, A. K., and Singh, V. P. (2010), Predicting Palmer Drought Severity Index using meteorological variables. International Journal of Climatology, DOI: 10.1002/joc.2215.
25. Mishra, A. K., and Singh, V. P. (2010), A review of drought concepts. Journal of Hydrology, 391(1-2), 202-216.
26. Z. Hao., and V. P. Singh. (2011), Single-site monthly streamflow simulation using entropy theory, Water Resources Research (Resubmitted)
27. Long, D., and Singh, V.P. (2011), A two-source trapezoid model for evapotranspiration from satellite imagery, Remote Sensing of Environment (Under review).
28. Long, D., and Singh, V.P. (2011), How sensitive is SEBAL to changes in input variables, domain size and satellite sensor? Journal of Geophysical Research (Under review).
29. Long, D., and Singh, V.P. (2011), A Modified Surface Energy Balance Algorithm for Land (M-SEBAL) based on a trapezoidal framework, Water Resources Research (Under review).
30. Long, D., and Singh, V.P. (2011), Addressing the scale dependencies of remote sensing-based triangle models, Agricultural and Forest Meteorology (Under review).
31. Rajsekhar, D., Mishra, A. and Singh, V.P. (2011), Regionalization of annual hydrological drought severity for Neches river basin, IPWE, Singapore, Jan 4-6,2011.
32. Rajsekhar, D., Mishra, A. and Singh, V. P. (2011), Drought Regionalization of Brazos River using an entropy approach, Symposium on Data driven approaches to drought, Purdue University, West Lafayette, Indiana, June 21-22, 2011.

Hydrological drought characterization for Texas under climate change, with implications for water resources planning

Project number: 2009TX334G

Progress report (June 2010 to May 2011)

Vijay P. Singh and Ashok K. Mishra
Department of Biological and Agricultural Engineering
Texas A and M University
Scoates Hall, 2117 TAMU
College Station, Texas 77843-2117, U.S.A.

Contents

Hydrological drought characterization for Texas under climate change, with implications for water resources planning

1. Basic information

Title:	Hydrological drought characterization for Texas under climate change, with implications for water resources planning
Project number:	2009TX334G
Start Date:	September 1, 2009
End Date:	August 31, 2012
Funding source:	104G
Congressional District:	17th TX
Research Category:	Climate and Hydrologic Processes.
Focus Categories:	Drought (DROU), Surface water (SW), Climatological processes (CP)
Descriptors:	Hydrological drought, Climate change, Critical basin, Teleconnection.
Principal investigator(s):	Vijay P. Singh and Ashok K. Mishra

2. Publications

Mishra, A. K., Singh, V. P., and Özger, M., (2011). Seasonal streamflow extremes in Texas River basins: uncertainty, trends and teleconnections. Journal of Geophysical Research, AGU,116, D08108. doi:10.1029/2010JD014597.

Mishra, A. K., and Singh, V. P. (2011), Drought modeling: A review, *J Hydrology*, (In Press).

Ozger, M., Mishra, A. K., and Singh, V. P. (2011), Long lead time drought forecasting using a wavelet and fuzzy logic combination model. *J Hydrometeorology (Submitted after first review*), AMS. *Manuscript no: JHM-D-10-05007.*

Ozger, M., Mishra, A. K., and Singh, V. P. (2010), Scaling characteristics of precipitation data in conjunction with wavelet analysis. Journal of Hydrology, 395(3-4), 279-288.

Ozger, M., Mishra, A. K., and Singh, V. P. (2010), Predicting Palmer Drought Severity Index using meteorological variables. International Journal of Climatology, DOI: 10.1002/joc.2215.

Mishra, A. K., and Singh, V. P. (2010), A review of drought concepts. Journal of Hydrology, 391(1-2), 202-216.

Z. Hao., and V. P. Singh. (2011), Single-site monthly streamflow simulation using entropy theory, Water Resources Research (Resubmitted)

Long, D., and Singh, V.P. (2011), A two-source trapezoid model for evapotranspiration from satellite imagery, Remote Sensing of Environment (Under review).

Long, D., and Singh, V.P. (2011), How sensitive is SEBAL to changes in input variables, domain size and satellite sensor? Journal of Geophysical Research (Under review).

Long, D., and Singh, V.P. (2011), A Modified Surface Energy Balance Algorithm for Land (M-SEBAL) based on a trapezoidal framework, Water Resources Research (Under review).

Long, D., and Singh, V.P. (2011), Addressing the scale dependencies of remote sensing-based triangle models, Agricultural and Forest Meteorology (Under review).

Rajsekhar, D., Mishra, A. and Singh, V.P. (2011), Regionalization of annual hydrological drought severity for Neches river basin, IPWE, Singapore, Jan 4-6,2011.

Rajsekhar, D., Mishra, A. and Singh, V. P. (2011), Drought Regionalization of Brazos River using an entropy approach, Symposium on Data driven approaches to drought, Purdue University, West Lafayette, Indiana, June 21-22, 2011.

3. Problem and Research objectives

Droughts in the United States result in an estimated average annual damage of $6 to 8 billion (Wilhite, 2000). The estimated loss from the 1988 drought was $40 billion (American Meteorological Society, 1997) and the estimated loss for the state of Texas alone from the 1996 drought was $6 billion (Wilhite, 2000). Like other western states, Texas is a water deficient state and is highly vulnerable to droughts, and its vulnerability is being compounded by rapidly growing population. According to the Water Plan (*Water for Texas 2007*) developed by Texas Water development Board, water shortages during droughts could cost businesses and workers in the state about $9.1 billion by 2010 and $98.4 billion by 2060 and about 85 percent of the state's projected population would not have enough water by 2060 in drought conditions), if an additional 8.8 million acre-feet of water supplies are not developed. Further complicating the Texas water shortage is climate change, which is being much debated these days. The major concern arising from climate change is its effect on water resources in terms of droughts and the resultant impact on different sectors. The objective of the project is therefore threefold:

(i) Analysis of multivariate hydrologic droughts: Drought is characterized by severity, areal extent, and duration. Multivariate distributions of these characteristics are needed and they will be derived using copulas. Then, droughts will be characterized by constructing: (a) Severity – Duration – Frequency curves (SDF), (b) Severity – Area – Frequency (SAF) curves, and (c) Severity-Interarrival time Frequency (SIF) curves. These curves are important for water resources planning.

(ii) Assessment of drought risk under climate change: Climate change impact studies have been conducted using a top-down approach. First, outputs from Global Circulation Models (GCMs) are considered which are downscaled in a second step to the river basin scale using either a statistical/empirical or a dynamic approach. The local weather scenarios are then statistically linked to possible large-scale climate conditions that are available from GCMs. Finally the downscaled meteorological variables are used as input to a macro scale land surface hydrologic model (i.e., VIC model) for investigating future hydrological drought scenarios. Several questions will be addressed: (a) How much percentage of a basin will undergo a drought in year 2050? (b) What will be the severity of the 2050 drought? (c) Will the drought of 2050 be more severe than the 2020 or 2080 drought? (d) What will be the duration of the drought in 2050 or 2080? (e) How much will be the water deficit in a river in 2050, considering it as a hydrological drought? (f) How will drought properties vary, when compared to the past 50 years? This objective will also attempt to quantify uncertainties in drought characterization, considering primarily climate change and different water management strategies.

(iii) Understanding of low frequency climate variations in association with Southern Oscillation Index (SOI) and Nino indexes: These variations affect Texas and their understanding will help provide improved streamflow forecasting needed for reservoir operations and will aid water management decisions. The lead-time of forecasting will be annual.

4 A. Regionalization of annual drought severity for selected basins

1. Setting up of VIC model and simulation of streamflow in Texas basins

1.1 Introduction

The VIC model is a large scale hydrological model and it is a semi-distributed macroscale hydrological model which balances both the water and surface energy budgets within the grid cell and its sub-grid variations are captured statistically (Liang et al. 1994; Cherkauer and Lettenmaier 1999). Distinguishing characteristics of the VIC model include: subgrid variability in land surface vegetation classes and the soil moisture storage capacity, drainage from the lower soil moisture zone (base flow) as a nonlinear recession and inclusion of topography that allows for orographic precipitation and temperature lapse rates resulting in more realistic hydrology in mountainous regions. Each of the cells is simulated independent of each other. Land surface is divided into different vegetation covers in such a way that multiple vegetation classes can exist within a cell. To simulate streamflow, VIC results are typically post-processed with a separate routing model (Lohmann, et al., 1996; 1998a; b) based on a linear transfer function to simulate streamflow. In this routing scheme, the surface runoff simulated by VIC in each grid cell is transported to the outlet of the grid cell using a unit hydrograph approach. Then, runoff from each grid cell is routed through the channel using a linearized Saint-Venant equation. The VIC model can be run in either a water balance mode or a water-and-energy balance mode. The water balance mode does not solve the surface energy balance where it assumes that the soil surface temperature is equal to the air temperature for the current time step. By eliminating the ground heat flux solution and the iterative processes required to close the surface energy balance, the water balance mode requires significantly less computational time than other model modes (Gao et al., 2010).

1.2 Data Requirements

The VIC model for streamflow simulation was run at 1/8th degree resolution and hence all the input files including forcing files, soil and vegetation parameters have this resolution. The model needs climatic forcing data at a daily temporal scale, and the forcing variables commonly used are daily precipitation, wind speed and air temperature extremes. The time period of data used was for the latter half of the 20th century: 1949-2000. The gridded forcing data at 1/8th degree resolution required for driving the model was obtained from Maurer et al. (2002) who has provided a data base for 15 delineated basins over the United States, Canada and Mexico. From this, a subset for Neches basin was derived for this study. Apart from forcing data, soil and land cover data is also required by the VIC model. Vegetation parameters needed were also obtained from LDAS. The leaf area index (LAI) needed was obtained from Moderate Resolution Imaging Spectroradiometer (MODIS) data.

The data needed in the routing scheme includes a fraction file, flow direction file, Xmask file, flow velocity and diffusion files, and unit hydrograph file. ArcMap was used for the preparation of the files, and the DEM files needed for creating the required files were obtained from the USGS hydro1k datasets.

1.3 Study Area

The following basins were chosen to demonstrate the results obtained from the VIC model: Neches, Brazos and Cypress river basins located in Texas. The DEM of the basins along with the location stations used for validating the model results are given in Figure 1.

1.4 Calibration and Validation of the model

Since VIC model involves a number of parameters, calibration of the same can become quite tedious. The recommended parameters along with the plausible range of values for each of them are given in Table 1. In this study, six soil parameters were considered for calibration purposes. As far as the calibration of the routing model is concerned, the suggested parameters for adjustment include velocity and diffusivity. If only monthly streamflows are required, velocity and diffusivity values of 1.5 m/s and 800 m^2/s are deemed acceptable. The simulated streamflow was then validated using the USGS observed streamflow (Figure 2). The chosen stations used for validation and their locational details are given in Table 2, and their performance evaluation are given in Table 3.

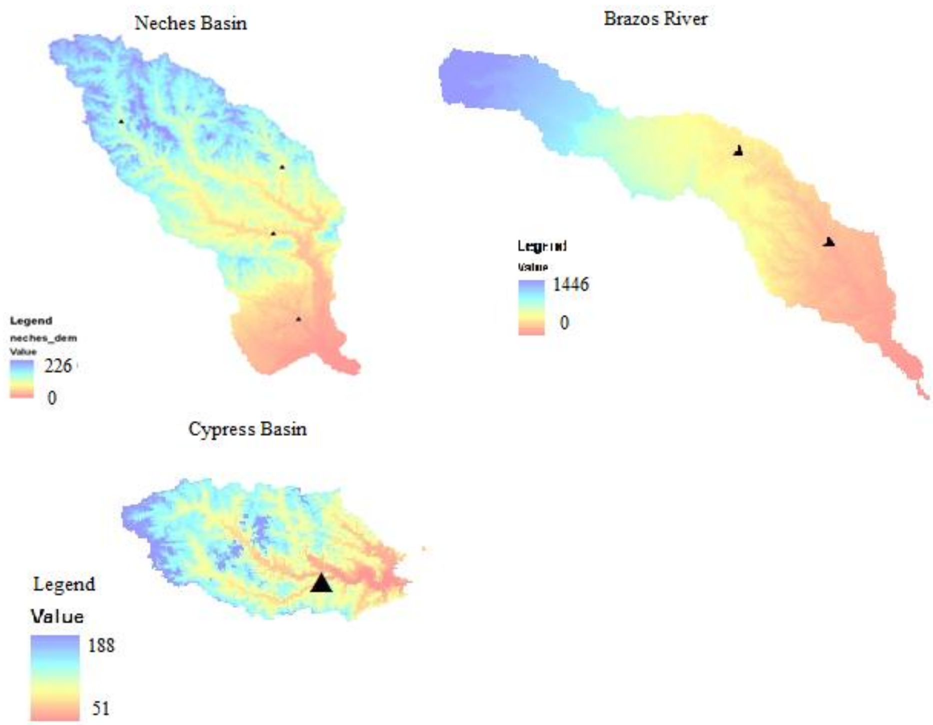


Figure 1. DEMs of selected basins with station locations

Table 1. Details of calibration parameters

Soil parameter	Unit	Range of values
Infiltration shape parameter (b_{inf})	None	0-0.4
Maximum sub-surface flow rate (Ds_{max})	mm/day	0-30
Fraction of Ds_{max} when non linear flow starts (Ds)	None	0-1
Depth of second soil layer (D_2)	meter	0.1-1.5
Depth of third soil layer (D_3)	meter	0.1-1.5
Fraction of maximum soil moisture when non linear flow starts	None	0-1

Table 2 Validation stations and their details

Station name	Latitude	Longitude	Drainage area (sq miles)
Brazos rv nr Waco	31.535	-97.073	19993
Brazos rv nr Southbend	33.024	-98.643	22673
Neches Rv Nr Neches	31.892	-95.431	1145
Neches Rv Nr Kountze	30.397	-94.263	860
Neches Rv Nr Rockland	31.025	-95.161	3636
Neches Rv Nr Chirena	31.504	-94.304	503
Little creek Nr Jefferson (Cypress)	32.713	-94.345	675

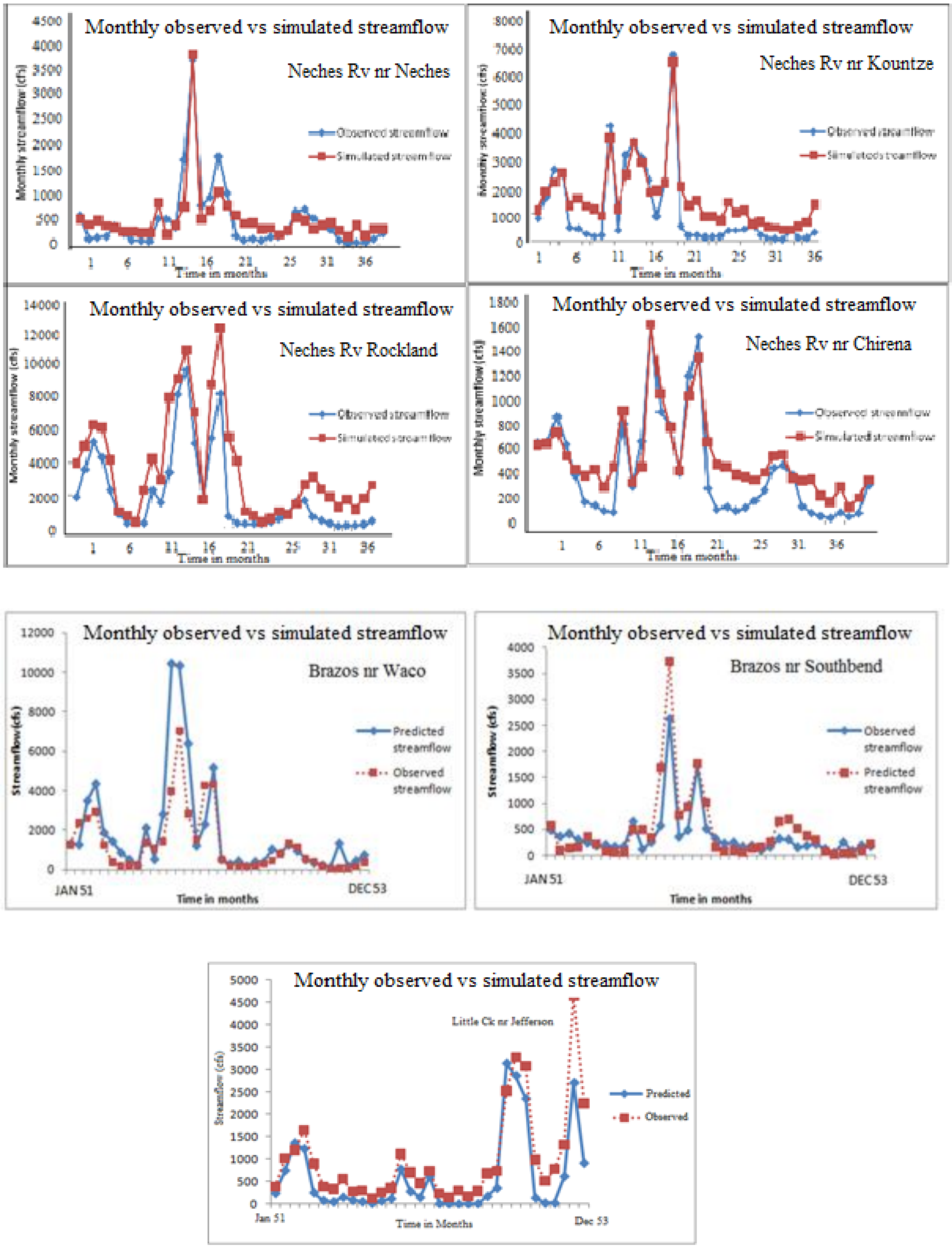


Figure 2. Monthly observed versus simulated streamflow validation results

Table 3. Validation results at the selected stations

Station	Correlation coefficient	MF ratio	NSE
Brazos nr Waco	0.90	1.27	0.62
Brazos nr Southbend	0.87	1.58	0.51
Neches Rv nr Neches	0.91	1.07	0.83
Neches Rv nr Kountze	0.95	1.39	0.78
Neches Rv nr Rockland	0.92	1.78	0.38
Neches Rv nr Chirena	0.94	1.27	0.77
Little Ck nr Jefferson	0.91	1.66	0.57

2. Calculation of standardized streamflow index

Theory of runs was used to derive drought severity from VIC simulated streamflow. A run is defined as a portion of time series of drought variable X_t in which all values are either above or below a threshold level X_0. Accordingly it can be called a positive or a negative run. The threshold level may be constant or it may vary with time. For this study, the drought variable X_t chosen was standardised streamflow index (SSFI). The concept of SSFI is based on the standardised precipitation index (SPI) by Mckee et al. (1993) and has been applied by Modarres (2007). It is statistically similar to SPI. SSFI for a given period can be defined as:

$$SSFI = \frac{F_i - \bar{F}}{\sigma}$$

where F_i is the flow rate in time interval i, $\bar{F}$ is the mean of the series and σ is the standard deviation of the series. The drought classification based on SSFI is similar to that based on SPI. Table 4 gives details of the SSFI classification. The SSFI values less than zero were considered for calculating the drought severity. The cumulative deficit gives the severity value. Figure 3 explains drought characterisation using the theory of runs. All the shaded portions indicate drought events. The annual severity value for all the VIC girds within the basin over the period 1949-2000 was calculated using this method.

Table 4. SSFI classification

SSFI value	Classification
2.0 or more	Extremely wet
1.5 to 1.99	Very wet
1.0 to 1.49	Moderately wet
-0.99 to 0.99	Near normal
-1.0 to -1.49	Moderately dry
-1.5 to -1.99	Severely dry

-2.0 or less	Extremely dry

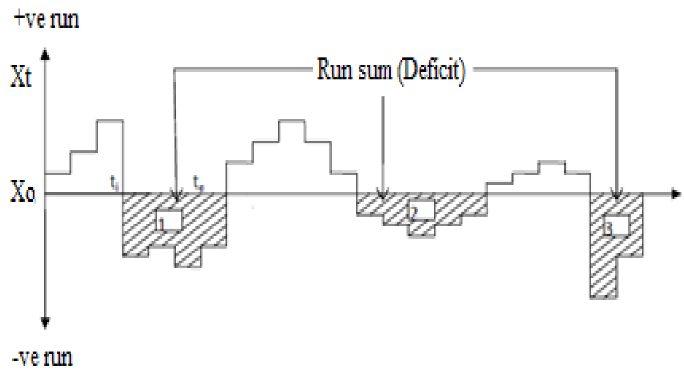


Figure 3. Theory of runs

3. Methodology used for regionalization

Out of various methods available for regionalization, clustering was chosen in this study. Clustering is considered to be one of the most important unsupervised learning techniques. It is the process of organizing similar members into clusters. A cluster can thus be defined as a collection of objects which are similar to each other and dissimilar to members of other clusters.

3.1 k-means clustering

Among the different types of clustering, K-means is a popular clustering technique used in hydrology. K-means is a hard clustering algorithm in which a collection of N vectors will be classified into K groups. The aim of the algorithm is to find the center of the clusters (also known as centroids) for each group. The algorithm minimizes the objective function which is essentially a dissimilarity function.

The steps in the algorithm includes: (1) Initialise the centroids, k_i = 1,2,...k, by randomly selecting k points from among all data points . (2) Determine the membership matrix U by equation: u_{ij} = 1 if $\|X_j - k_i\|^2 \le \|X_j - k_k\|^2$, for all k≠i, u_{ij} = 0 , otherwise. (3) Compute the dissimilarity function F = $\sum_{i=1}^{k}[\sum_{k,x_k \in G_i} \|x_k - k_i\|^2]$. Stop if its improvement over previous iteration is below a threshold. (4) Compute new centroids using $k_i = \frac{1}{|G_i|}\sum_{k,x_k \in G_i} x_k$ and go to step (2).

The performance of the algorithm depends on the initial position of centroids. Since we do not know the value of k apriori, cluster validity indices were employed to determine an estimate of k to be used. Out of the several cluster validity indices available, the Davies-Bouldin index, the Dunns index and the Calinski-Harabasz index are primarily used for hard clustering algorithms like k-means. The optimum k value can be selected based on any one of these indices such that it has the highest Dunns index and the Calinski-Harabasz index and the lowest Davies-Bouldin index. These indices give an idea about the initial value of k to be selected.

In hydrology, k-means algorithm and its variants have been used primarily as part of regionalisation of watersheds and some of the examples include: Bhaskar and O'Connor (1989), Burn and Goel (2000), Rao and Srinivas (2005), and Isik and Singh (2008).

3.2 Directional information transfer

An additional entropy based approach for clustering was also adopted for Brazos River basin and results were compared with the conventional k-means clustering. The concept of entropy was first used in the context of communication theory. In communication theory, entropy measures the uncertainty of a random event, or rather the information contained in it through the observations of it (Yang and Burn, 1994). Since there will be some kind of information transfer between different sites, the observations made at one site infer information about other sites too, to some extent. This information transfer among the stations is termed as ‘mutual information’.

If two random variables (X,Y) are considered, the mutual information or the measure of information transfer between them can be computed as (Lathi,1968):

$$T(X,Y) = H(X) - H(X/Y)$$

where H(X/Y) represents the information lost during transmission. It can be estimated as:

$$H(X/Y) = \sum_{i,j} p(X_i, Y_j) \log_2 \frac{p(X_i, Y_j)}{p(Y_j)}$$

Thus, entropy and mutual information provide a threefold measure of information at a station, information transfer and loss between stations, and description of relationships among stations according to the information transfer between them (Yang and Burn,1994). This makes it unique from other conventional similarity measures.

Directional information transfer is a standardized version of mutual information. It is the fraction of the information transferred from one site to another. The concept of DIT was introduced by Coombs et al. (1970) in the field of mathematical psychology as a coefficient of constraint (Fass, 2006). It is a normalized version of mutual information between two gauges to obtain the fraction of information transferred from one site to another as a value between 0 and 1. DIT is a much better index than mutual information because the upper bound of mutual information can vary from site to site, depending on the marginal entropy value at the respective station which makes the mutual information, a not so good index of dependence. DIT can thus be expressed as:

$$DIT_{xy} = \frac{T(X,Y)}{H(X)};\ DIT_{yx} = \frac{T(X,Y)}{H(Y)}$$

where DIT_{xy} describes the fractional information inferred by station X about Y, and DIT_{yx} is the fractional information inferred by station Y about X, T(X,Y) is the mutual information between X and Y, and H(X) and H(Y) are the marginal entropy values for X and Y, respectively. The marginal entropy values are calculated using the formula for Shannon entropy, the mutual information between X and Y can be calculated as T(X,Y) = H(X)-H(X/Y), where H(X/Y) is equivalent to the loss of information H_{lost}.

$$DIT = (H - H_{lost}) / H = 1 - (H_{lost} / H)$$

While using DIT for regionalization, those stations for which both DIT_{xy} and DIT_{yx} are high can be considered to be strongly dependent since information can be mutually inferred between them. If neither DIT is high, then the two stations should remain in separate groups. If only one DIT is high, say DIT_{xy}, then station Y, whose information can be predicted by X, can join station X if station Y does not belong to any other group; otherwise it stays in its own group. But, by no means can X enter station Y's group (Yang and Burn, 1994). DIT can be distinguished from traditional similarity measures like correlation coefficient, since it is based on the information connection between stations.

The number of groups formed is controlled by the threshold value of DIT. A higher threshold value will lead to a larger number of groups. However, the size of each group will be small. A lower threshold value will result in the formation of a small number of groups, but the size of each group will be larger.

3.3 Results of Regionalization

3.3.1 Neches Basin

Since we do not know the initial value of k apriori, the use of cluster validity indices was employed to get an idea in this regard. Figure 4 gives the estimates from the various cluster validity indices. Figure 5 shows the homogenous drought regions based on drought severity over the Neches basin. Figure 6 gives the annual average severity and percentage area for each region formed. The annual average drought severity and the percentage of area for each region within the basin is shown in Table 5.

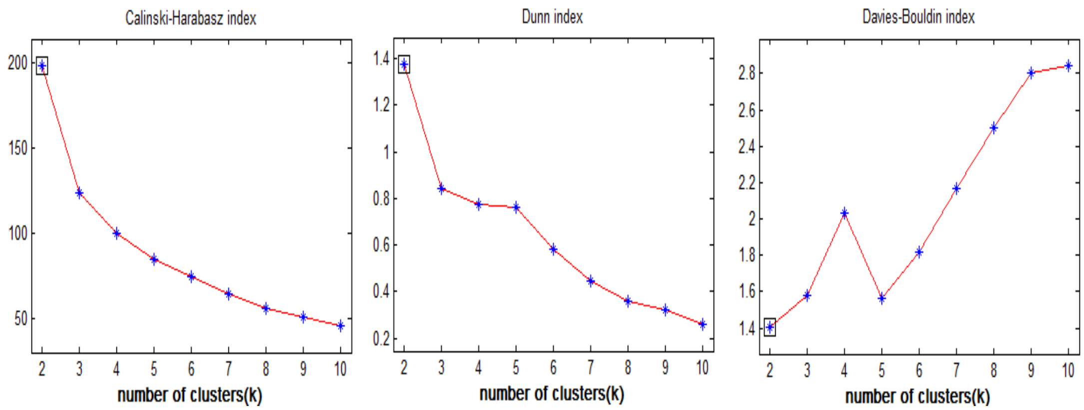


Figure 4. Initial estimate of k based on cluster validity indices for Neches basin

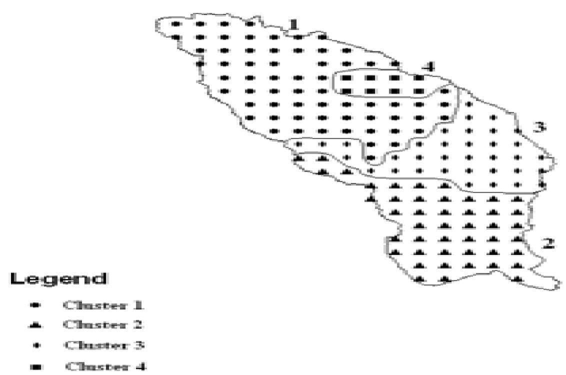


Figure 5. Homogenous regions formed within Neches River basin using k-means clustering

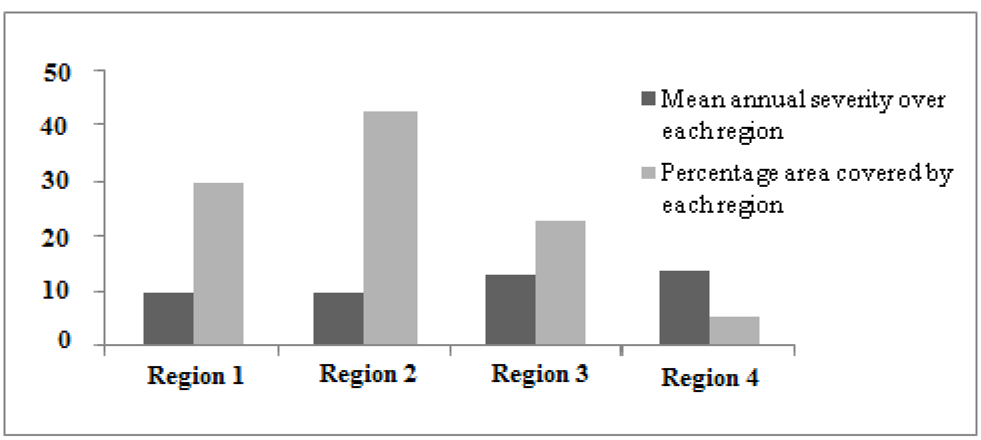


Figure 6. Annual average severity and percentage area of each region formed within Neches River basin

Table 5. Annual average severity and percentage area for each region within Neches basin

Region	Annual average severity	Percentage area	Climatic region
Region 1	9.44	29.7%	Sub tropical humid
Region 2	9.49	42.6%	Sub tropical humid
Region 3	13.63	22.6%	Sub tropical humid
Region 4	12.92	5.2%	Sub tropical humid

3.3.2 Brazos Basin

Figure 7 gives the initial estimate of the number of clusters for regionalization. Figures 8 and 9 gives the annual average severity and percentage area for each region formed using DIT and k-means clustering respectively. Figures 10 and 11 gives the final regions formed using DIT and k-means clustering respectively. Tables 6 and 7 gives the details of the regions formed using DIT and k-means clustering respectively.

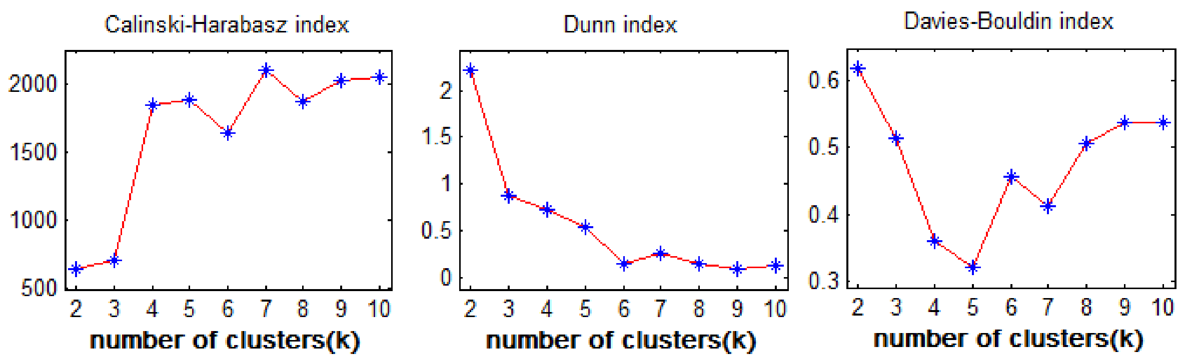


Figure 7. Initial estimate of k based on cluster validity indices for Brazos basin

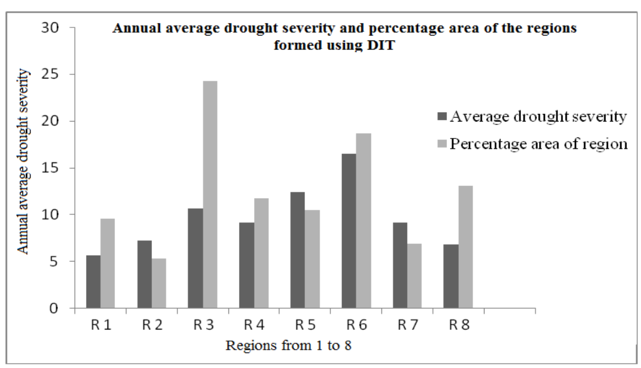


Figure 8. Average annual severity and percentage area for regions formed using DIT

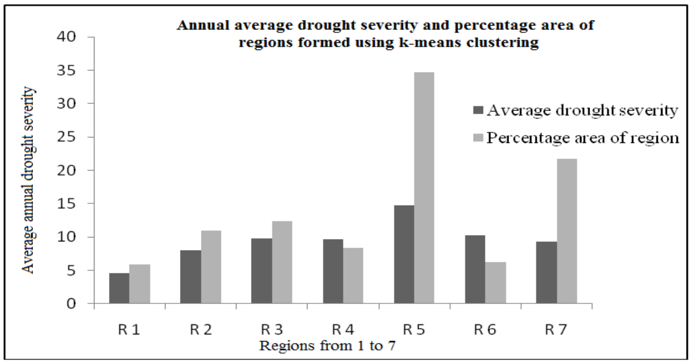


Figure 9. Average annual severity and percentage area for regions formed using k-means clustering

Table 6. Details of the regions formed using DIT

Region	Annual average severity	Percentage area	Climatic region
1	5.631	9.61	Subtropical humid
2	7.239	5.31	Subtropical humid
3	10.677	24.25	Subtropical humid
4	9.127	11.76	Subtropical subhumid
5	12.388	10.47	Subtropical subhumid
6	16.502	18.65	Subtropical subhumid
7	9.178	6.88	Continental steppe
8	6.838	13.05	Continental steppe

Table 7. Details of the regions formed using K-means

Region	Annual average severity	Percentage area	Climatic region
1	4.519	5.88	Subtropical humid
2	8.012	10.91	Subtropical humid
3	9.770	12.34	Subtropical humid
4	9.617	8.32	Subtropical humid
5	14.770	34.72	Subtropical subhumid
6	10.296	6.17	Subtropical subhumid
7	9.255	21.66	Continental steppe

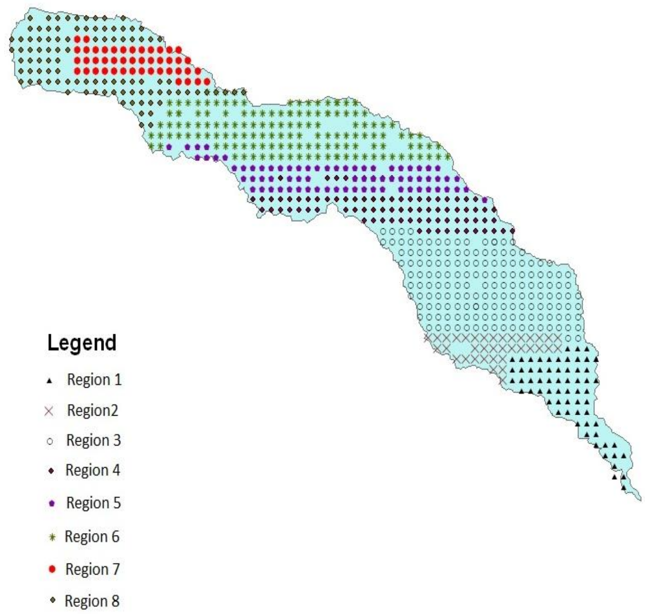


Figure 10. Homogenous regions formed within Brazos River basin using DIT

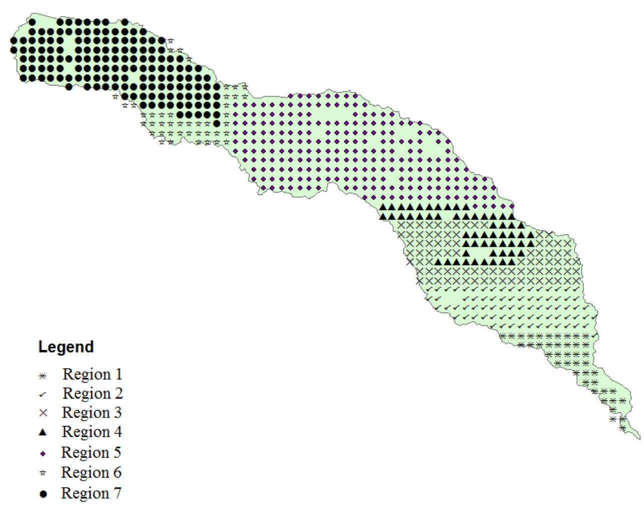


Figure 11. Homogenous regions formed within Brazos River basin using k-means clustering

3.3.3 Cypress basin

Figure 12 gives the initial estimate of the number of clusters for regionalization. Figure 13 shows the homogenous regions formed on the basis of drought severity. Table 8 gives the details of the regions formed and Figure 14 shows the annual average severity and the percentage area of each region within the Cypress basin.

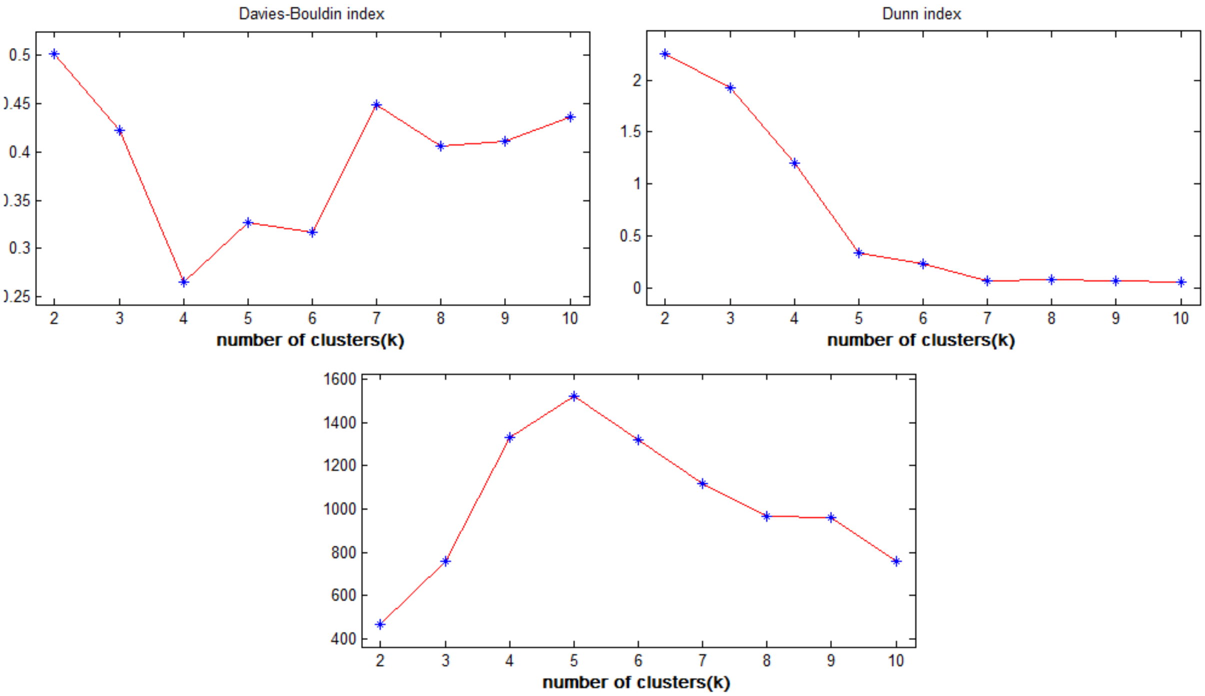


Figure 12. Initial estimate of k based on cluster validity indices for Brazos basin

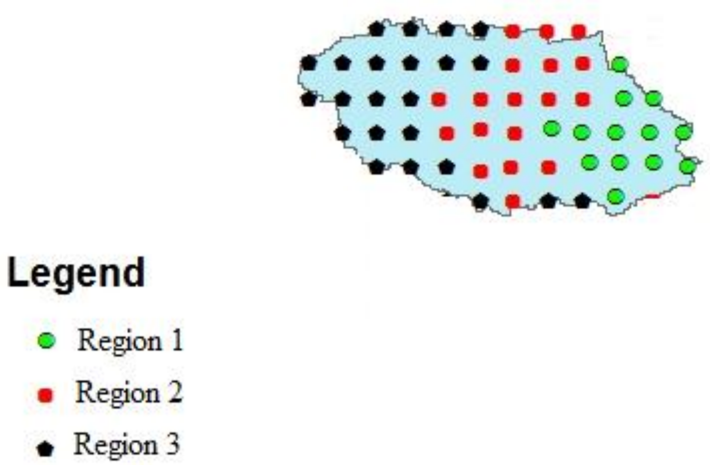


Figure 13. Homogenous regions formed within Cypress basin using k-means clustering

Table 8. Details of the regions formed using k-means clustering

Region	Annual average severity	Percentage area	Climate region
Region 1	10.68	24.1%	Sub tropical humid
Region 2	15.59	33.3%	Sub tropical humid
Region 3	13.17	42.6%	Sub tropical humid

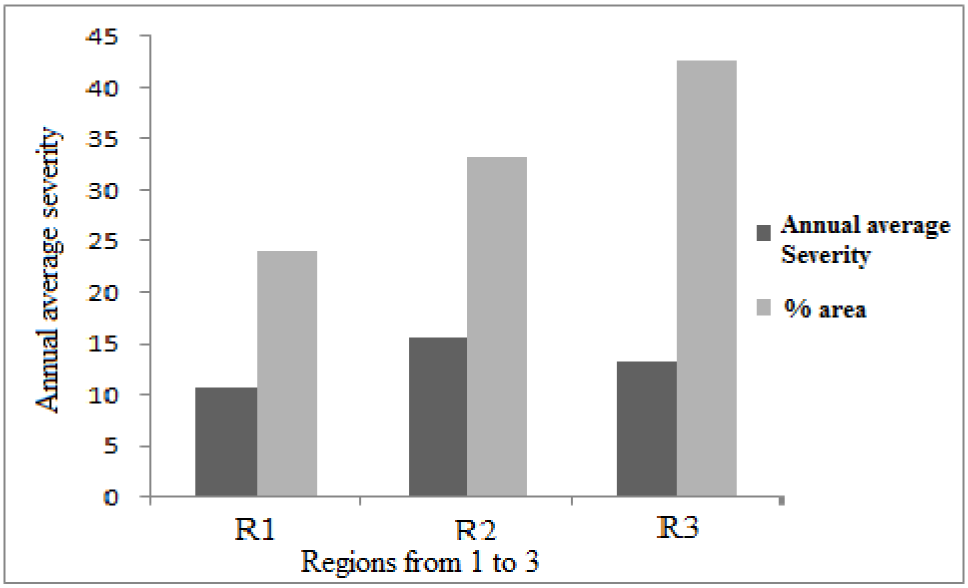


Figure 14. Annual average severity and percentage area for regions formed using k-means clustering

4. Severity-area calculation

The areal extend of drought events categorized as moderate and severe for each year from 1950-2000 within the three basins considered were calculated. The plots showing the percentage area within the basin affected by moderate or severe drought versus the year considered, is shown in Figure 15.

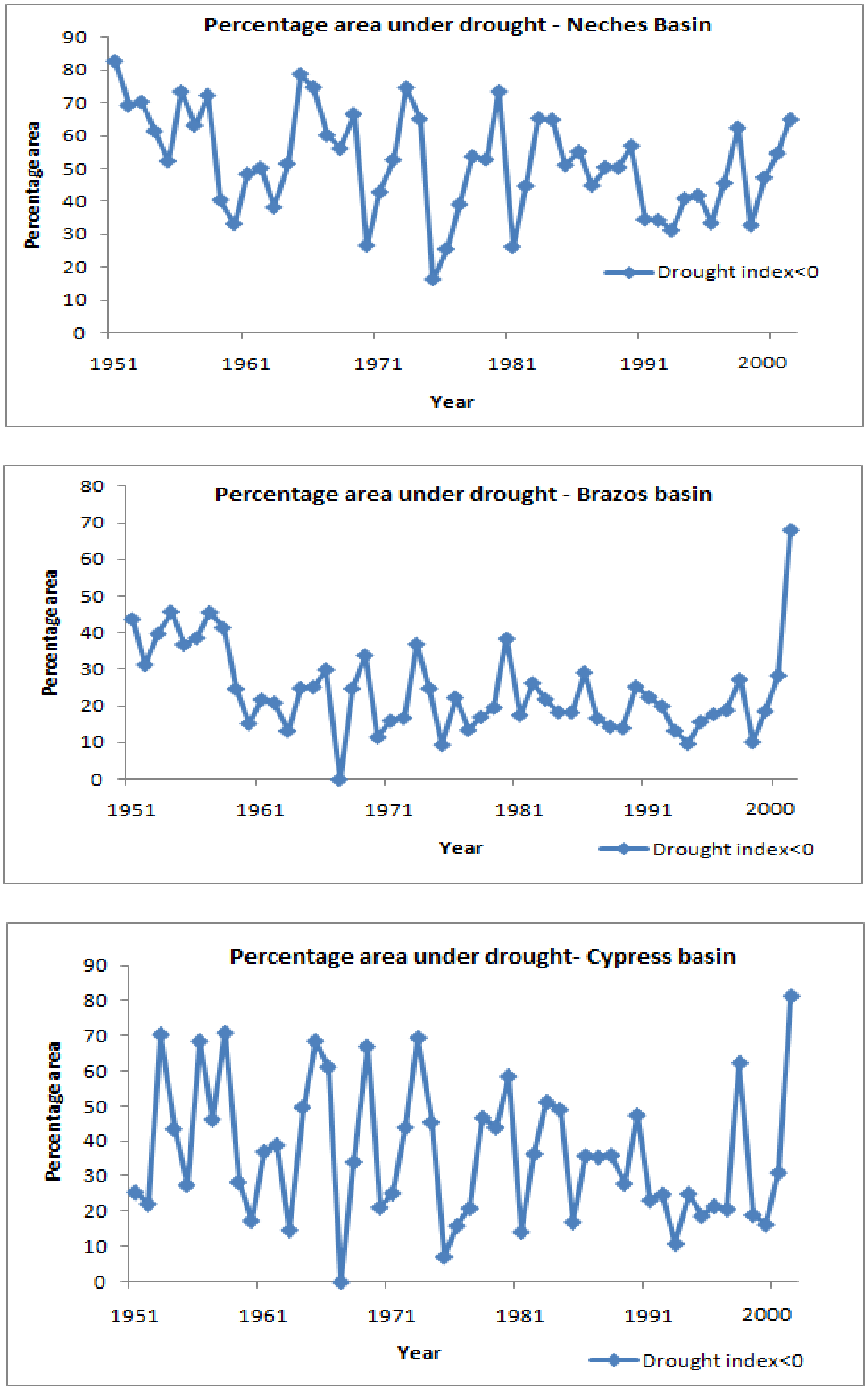


Figure 15. Percentage area under drought over the period 1950-2000 in Neches, Brazos and Cypress basins respectively

5. Conclusions

The importance of identifying homogenous regions based on the drought characteristic- severity is explored. Because of the impact of droughts on society, adequate monitoring and planning is required for effective mitigation of the same. Similar water management schemes and drought planning can be adopted for homogenous regions. Also, identification of homogenous drought regions is needed for regional frequency analysis of droughts. The severity patterns within the regions follow the general precipitation trends. The areal extend of severe droughts were considerably lesser than moderate or mild droughts for all three basin.

4B. Simulation of rainfall events

1. Objective

The objective of this study is to develop an efficient method for simulating both the low to moderate and extreme rainfall. To that end, the specific objectives are to: (1) examine if the existing distributions are reliable to model precipitation intensity exhibiting different patterns, (2) propose a hybrid distribution to simulate precipitation preserving extreme characteristics, (3) validate the hybrid distribution model, (4) couple the hybrid distribution with a Markov chain for daily rainfall simulation, and (5) validate the coupled rainfall simulator.

2. Literature review and methodology

Under the context of climate change, with the increase of the magnitude and frequency of hydrological extreme events, say drought and floods, simulating and downscaling the extreme precipitation events has since been attracting more and more attentions (*Solomon et al*., 2007). At the best of our knowledge, *Wilks* (1999) first studied the performance of different precipitation occurrence and amount submodels to represent the extreme value characteristics of synthetic precipitation sequence and concluded that the commonly used Gamma model is inferior to the mixture exponential model. *Semenov* (2008) assessed the skill of the LARS-GW to simulate the extreme weather events. *Qian et al*. (2008) evaluated the performance of LARS-WG and AAFC-WG for producing daily precipitation extremes. *Hashmi et al*. (2010) compared the SDSM and LARS-WG for simulation of extreme precipitation. On the other hand, some efforts have also been devoted to improving the accuracy of extreme precipitation event, say *Vrac* and *Naveau* (2007), *Furrer* and *Katz* (2008), *Hundecha et al*. (2009). One common place in these papers is that a compound distribution was used such that the low to moderate as well as extreme precipitation events could be equally and efficiently simulated. A dynamic mixture of Gamma and Pareto distribution was adopted to simulate and downscale heavy precipitation events by *Vrac* and *Naveau* (2007) and *Hundecha et al*. (2009). Based on a full comparison of other candidate precipitation intensity models, *Furrer* and *Katz* (2008) recommended a hybrid Gamma and generalized Pareto distribution to simulate extreme precipitation. In both the compound distributions, generalized Pareto distribution acts as one of the components whose probability density function is given as:

$$f_{\mathrm{GP}}(x;\mathbf{P}_{\mathrm{GP}}) = \frac{1}{\sigma}(1+\kappa\frac{x-\theta}{\sigma})^{-\frac{1}{\kappa}-1} \quad x>0 \quad \kappa \geq 0, \sigma > 0, \theta \geq 0$$

where $\mathbf{P}_{\mathrm{GP}} = [\ln\kappa, \ln\sigma, \ln\theta]$, κ, σ and θ are the shape, scale and location parameter, respectively.

The underlying reasons for the popularity of this model could be explained by the extreme value theory (EVT), see *Coles* (2001), *Castillo et al*. (2005). EVT states that the precipitation exceedances over a threshold μ can be asymptotically approximated by the generalized Pareto distribution given that the threshold and the number of observations are both large enough. Although the generalized Pareto distribution has been widely and successfully used to model heavy precipitation due to its attracting mathematical theory, it has a serious drawback of overlooking small values since the threshold should be sufficiently high and also since only the exceedances would be involved in the analysis, which would introduce information loss. Therefore it is not suitable for precipitation simulation or downscaling where the full range should be modeled.

The dynamic mixture of Gamma and Pareto distribution is the first compound distribution appeared in literatures which can model the full range of precipitation intensity. *Vrac* and *Naveau* (2007) used this distribution to downscale heavy precipitation events. *Hundecha et al*. (2009) used it to generate synthetic daily precipitation sequence. This distribution originates from the one proposed by *Frigessi et al*. (2002) where the Weibull and the generalized Pareto distribution were used as the two components. The density of the dynamic mixture distribution is given by

$$f_{\mathrm{DM}}(x; \mathbf{P}_{\mathrm{DM}}) = \frac{[1 - p(x; \mu, \tau)] f_{\mathrm{G}}(x; a, b) + p(x; \mu, \tau) f_{\mathrm{GP}}(x; \kappa, \sigma, 0)}{Z(a, b, \mu, \tau, \kappa, \sigma)} \quad x > 0 \quad a, b, \mu, \tau, \kappa, \sigma > 0$$

where $\mathbf{P}_{\mathrm{DM}} = [\ln a, \ln b, \ln \mu, \ln \tau, \ln \kappa, \ln \sigma]$, $p(x; \mu, \tau)$ is the mixing function expressed as

$$p(x; \mu, \tau) = \frac{1}{2} + \frac{1}{\pi} \arctan\left(\frac{x - \mu}{\tau}\right)$$

with location parameter μ and scale parameter τ. The mixing function increases from 0 to 1 monotonically as x increases from 0 to infinity such that the 'bulk' of the distribution is dominated by Gamma whereas the 'tail' is dominated by Pareto distribution. The other ingredients in this mixture model are the Gamma density function $f_{\mathrm{G}}(x; a, b)$, the generalized Pareto density $f_{\mathrm{GP}}(x; \kappa, \sigma, 0)$ and the normalization function $Z(a, b, \mu, \tau, \kappa, \sigma)$ such that the integral of the mixture density is unite.

The advantages of this distribution are: 1) it can model the full range of precipitation; 2) it circumvents the selection of threshold, which is a challenging task in practice. To estimate the parameters of the model, not only the normalization constant should be integrated but also the log-likelihood function should be maximized. Since there is no closed form for the integral appeared in the normalizing constant, numerical integration should be used whose accuracy thus determines the final goodness-of-fit of the estimated model. This model gained successes in model precipitation intensity. This distribution, however, is subjective to problems like expensive computation, numerical instability, data sensitivity and so on

Considering the defects of the dynamic mixture distribution mentioned above and the discontinuity at the threshold in the limiting case (mixing rate $\tau = 0$) and the difficulty of incorporating covariates, *Furrer* and *Katz* (2008) proposed a hybrid distribution where a generalized Pareto distribution is stuck to the tail of a Gamma distribution. For simplicity, we will use FK08 to denote this distribution. The probability density function is expressed as

$$f_{\mathrm{FK08}}(x; \mathbf{P}_{\mathrm{FK08}}) = f_{\mathrm{G}}(x; a, b) I(x \leq \theta) + [1 - F_{\mathrm{G}}(\theta; a, b)] f_{\mathrm{GP}}(x; \kappa, \sigma, \theta) I(x > \theta)$$

where I is the usual indicator function and $1 - F(\theta; a, b)$ is the normalization factor. This factor ensures that the integral of the hybrid density over its support is unit. To force the hybrid density be continuous at the threshold θ it is necessary that $f_{\mathrm{FK08}}(\theta_{-}) = f_{\mathrm{FK08}}(\theta_{+})$, which will lead to $\sigma = \frac{1 - F_{\mathrm{G}}(\theta; a, b)}{f_{\mathrm{G}}(\theta; a, b)}$

The performance of the distribution is determined by the selected threshold, which should be neither too large nor too small. A too mall threshold means over emphasis on the generalized Pareto distribution which will lead to an over heavy tail. A too large threshold indicates less emphasis on the generalized Pareto distribution which will result in an underrepresented tail. Even though a suitable threshold can model both the low to moderate and the extrema well, the threshold should be selected by a trial and error procedure which is a laborious work and often subjective to the preferences of different practitioners.

Since we want to model the full range of precipitation, since we want to circumvent the threshold selection and since we want to decrease the complexity of the model without losing its ability, we chose an eclectic way between the dynamic mixture distribution and the FK08 distribution to build a hybrid distribution by stitching a generalized Pareto tail to an exponential distribution. This hybrid distribution is originate from the one introduced by *Carreau* and *Bengio* (2009), where a Gaussian and a generalized Pareto were stitched together. The probability density function of the hybrid exponential and generalized Pareto distribution (hybrid exp/gp) is expressed as

$$f_{\mathrm{H}}(x; \mathbf{P}_{\mathrm{H}}) = \frac{1}{Z}[f_{\mathrm{E}}(x; \mu) I(x \le \theta) + f_{\mathrm{GP}}(x; \kappa, \sigma, \theta) I(x > \theta)]$$

The cumulative distribution function is given as

$$F_{\mathrm{H}}(x; \mathbf{P}_{\mathrm{H}}) = \frac{1}{Z}\{F_{\mathrm{E}}(x; \mu) I(x \le \theta) + [F_{\mathrm{E}}(\theta; \mu) + F_{\mathrm{GP}}(x; \kappa, \sigma, \theta)] I(x > \theta)\}$$

The *p*-quantile function is expressed as

$$x_p = [-\mu \ln(1 - pZ)] I\big(p \le F_{\mathrm{E}}(\theta)\big) + [\theta + \frac{\sigma}{\kappa}(\left(pZ - 2 + \exp\left(-\frac{\theta}{\mu}\right)\right)^{-\kappa} - 1)] I\big(p > F_{\mathrm{E}}(\theta)\big)$$

Finally, the hybrid exp/gp distribution was built into the two-state Markov model to simulate daily precipitation. A Markov chain based precipitation generator was developed using MATLAB. The developed precipitation generator has the following properties:

1) Different choice for Markov chain order up to a maximum order of 4.
2) Different choice for subperiod models: biweekly, monthly, seasonal and annual model.
3) Different choice for precipitation intensity distribution models: Gamma distribution, mixed exponential distribution, dynamic mixture of Gamma and Pareto model and the proposed hybrid exp/gp distribution.

3. Results and discussion

This model is used to simulation daily precipitation of different climate divisions of Texas. An ensemble of weather indices concerning the extreme behaviors of precipitation events was used to verify the validity of the proposed hybrid exp/gp distribution in reproducing the extreme rainfall events. These weather indices considered includes: 1) total rainfall amount (PT) – measures the total amount of significant precipitation over a given period, 2) highest 1 day precipitation amount (P1day) – measures the block extreme precipitation over a period, 3) highest 5 day precipitation amount (P5day) – measures the block extreme of consecutive 5 day precipitation over a period, 4) heavy precipitation days (P10mm) – quantizes the number of wet days whose precipitation is greater than 10 mm, 5) very heavy precipitation days (P20mm) – quantizes the number of wet days with precipitation greater than 20mm, 6) moderate wet days (P75p) – quantizes the number of wet days whose precipitation is greater than the 0.75 percentile of rainfall over a period, 7) precipitation fraction due to wet days whose rainfall is greater than the 0.90 percentile over a period (P90pF), 8) precipitation fraction due to wet days whose rainfall is greater than the 0.95 percentile over a period (P95pF), 9) precipitation fraction due to wet days whose rainfall is greater than the 0.99 percentile over a period (P99pF).

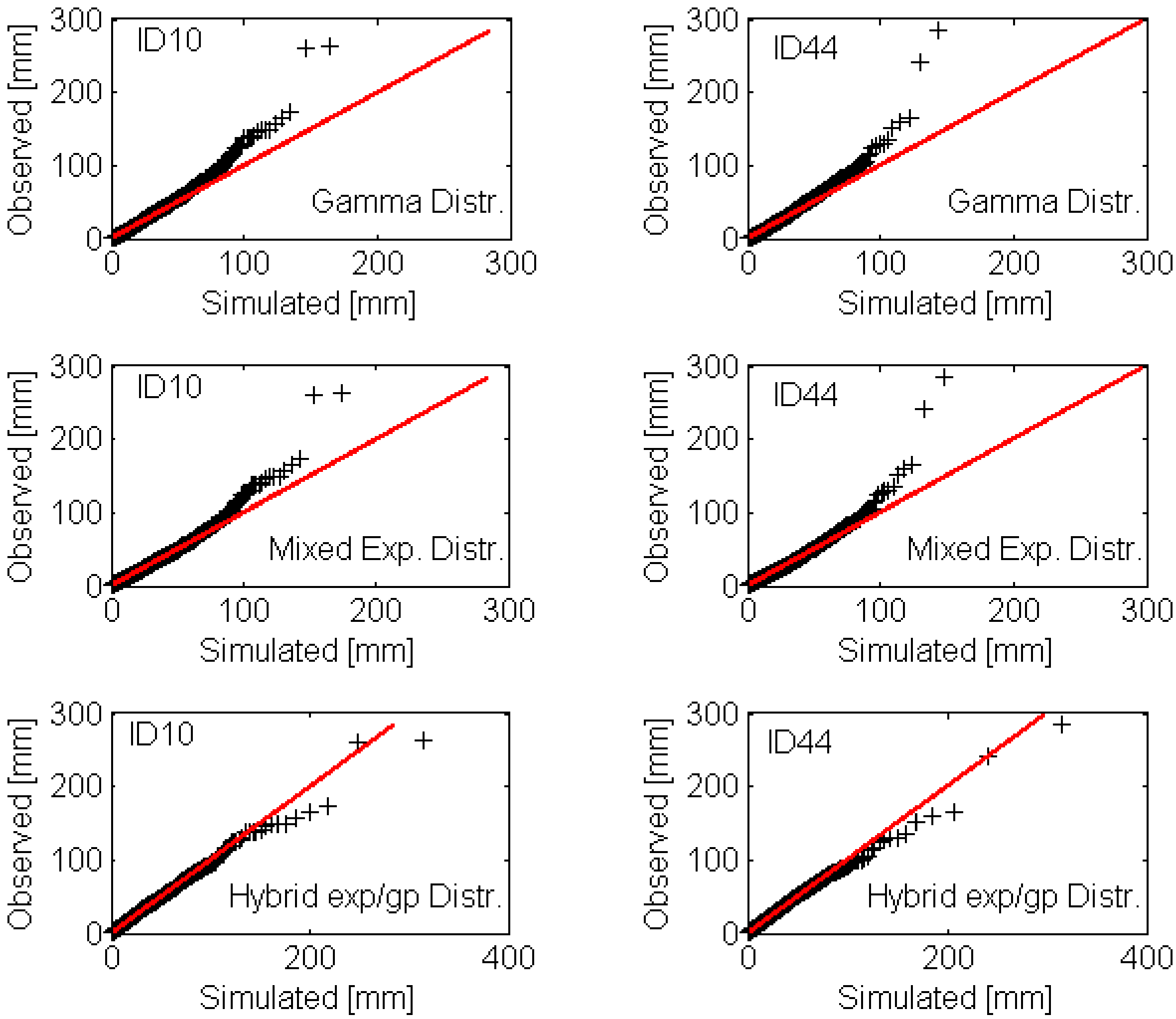
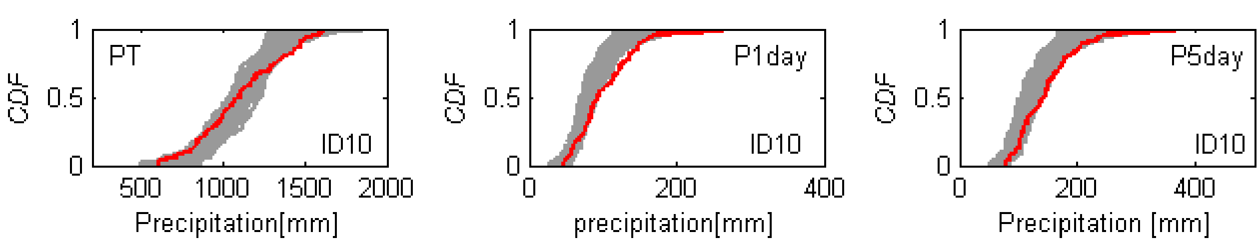


Figure 1. Empirical QQ Plots of Observed versus Simulated Quantiles of Precipitation Intensity Using Different Models, i.e. Upper Panel for Gamma Distribution, Middle Panel for Mixed Exponential Distribution and Lower Panel for Hybrid exp/gp Distribution. The Left and Right Columns are for the Station ID10 and the Station ID44, respectively.



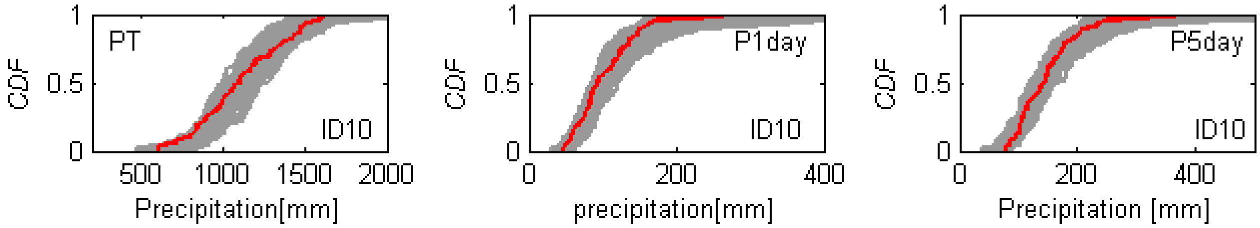


Figure 2. Empirical distribution function of the observed weather indices (red line) and the ensemble empirical distribution functions of the simulated weather indices (grey shaded area) for station ID10. The left panel is for PT. the middle panel is for P1day. And the right panel is for P5day. The upper and lower panels are related to the results obtained from Gamma distribution and hybrid exp/gp distribution, respectively.

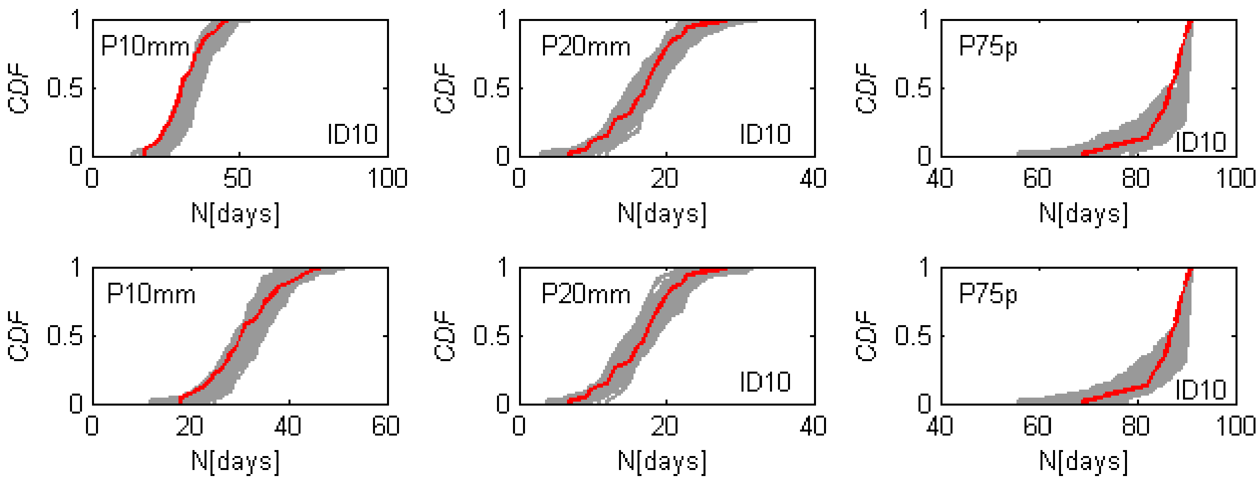
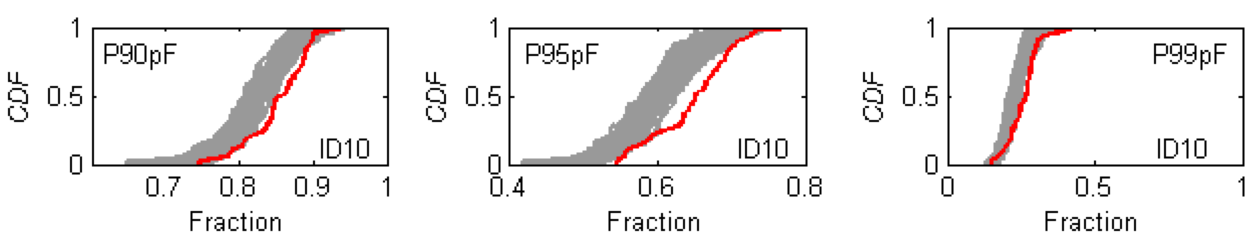


Figure 3. Empirical distribution function of the observed weather indices (red line) and the ensemble empirical distribution functions of the simulated weather indices (grey shaded area) for station ID10. The left panel is for P10mm. the middle panel is for P20mm. And the right panel is for P75p. The upper and lower panels are related to the results obtained from Gamma distribution and hybrid exp/gp distribution, respectively.



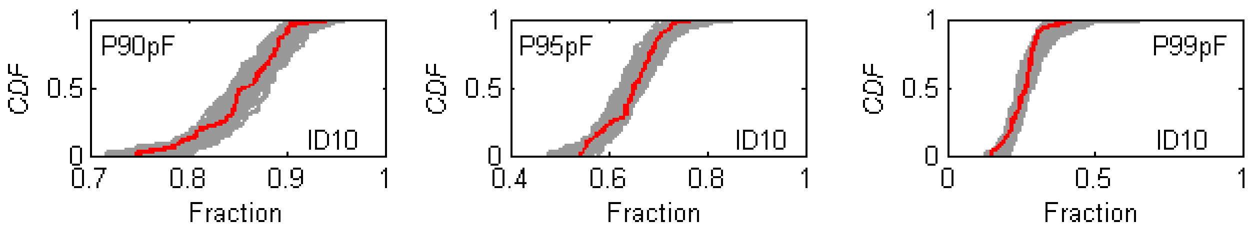


Figure 4. Empirical distribution function of the observed weather indices (red line) and the ensemble empirical distribution functions of the simulated weather indices (grey shaded area) for station ID10. The left panel is for P90pF. The middle panel is for P95pF. And the right panel is for P95pF. The upper and lower panels are related to the results obtained from Gamma distribution and hybrid exp/gp distribution, respectively.

Major conclusions could be draw:

1. Commonly used distributions, such as exponential, gamma, and mixed exponential, cannot capture the full range of the right-skewed and heavy-tailed daily precipitation, since the tails of these distributions are not heavy enough. Using any of these distributions, the extreme rainfall events are not captured in the synthetic sequence.
2. Compound distributions, such as dynamic mixture of gamma and generalized Pareto distributions and FK08 distribution, suffer from functional complexity, numerical instability, data sensitivity, supervised learning, and expensive computation.
3. The proposed compound distribution, the hybrid exp/gp distribution, stitching a generalized Pareto tail to an exponential distribution, is able to model the full range of precipitation. Due to its relative functional simplicity, its parameters can be estimated and the random number can be generated efficiently without numerical problems.
4. The hybrid exp/gp distribution, which satisfactorily models both the 'bulk' and the 'tail' of precipitation, can be incorporated into a stochastic weather generator to simulate and downscale extreme precipitation.
5. The hybrid exp/gp distribution is more flexible in selecting different model fitting approaches, since it has explicit and simple cumulative distribution function and quantile function. This is a desirable property, especially when the MLE estimator loses optimality.
6. The dynamic mixture distribution is always troubled with numerical problem not only because of the noisy sample data but also because sometimes it is difficult to get the

accurate normalization constant which is critical for its performance. The hybrid exp/gp distribution does not have such problems.

7. The hybrid exp/gp distribution learns the location parameter (threshold) of the generalized Pareto distribution in an unsupervised way. Considering the threshold as the junction point of the two component distributions, it builds the threshold selection implicitly into the model fitting procedure. Therefore, the subjectivity and laborious expensive property of traditional PoT analysis is no longer a problem.
8. Generally MLE is the best choice to fit the hybrid exp/gp distribution. Two different candidate approaches, i.e., 2-step QLS method and MGF method, can be good remedies when the MLE method has problems due to the generalized Pareto tail. For the dynamic mixture distribution, however, there is not good alternative fitting method again due to its functional complexity.
9. Discarding expensive computation, precipitation intensity fitting shows that sometimes the dynamic mixture distribution provides a better agreement between the fitted model and the data without showing any information about over-fitting. The intent, however, is not to replace the dynamic mixture distribution but to complement it and to provide a much more efficient way to fit the heavy-tailed precipitation intensity without losing the goodness-of-fit, if any.
10. Incorporation of the proposed hybrid exp/gp distribution into the chain-dependent higher order Markov chain model allows to generate synthetic daily precipitation while preserving extreme rainfall events.

REFERENCES

Bhaskar, N.R. and O'Connor, C.A. 1989. “Comparison of method of residuals and cluster analysis for flood regionalization”, *J. Water Res. Pl. and Mgmt.* 115(6),793–808.

Burn, D.H. and Goel, N.K. 2000. “The formation of groups for regional flood frequency analysis”, *Hydro. Sci. J.,* 45(1), 97–112.

Cherkauer, K. A., and D. P. Lettenmaier, 1999: “Hydrologic effects of frozen soils in the upper Mississipi River basin”. J. Geophys. Res., 104, 19 599–19 610.

Fass,D.M. 2006. Human sensitivity to mutual information.PHD dissertation, Rutgers state university of N.J., New Brunswick.

Gao, H., Q. Tang, X. Shi, C. Zhu, T. J. Bohn, F. Su, J. Sheffield, M. Pan, D. P. Lettenmaier, and E. F. Wood, 2010: Water Budget Record from Variable Infiltration Capacity (VIC) Model. In *Algorithm Theoretical Basis Document for Terrestrial Water Cycle Data Records* (in review).

Isik,S. and Singh,V.P. (2008). “Hydrologic Regionalization of watersheds in Turkey”, *J.Hydrol.Eng*., 13(9),824-834.

Lathi, B.P. 1968. “An introduction to Random Signals and Information Theory”, International Textbook Company, Scanton, Pennsylvania.

Liang, X., D. P. Lettenmaier, E. F. Wood, and S. J. Burges, 1994: A simple hydrologically based model of land surface water and energy fluxes for general circulation models. J. Geophys. Res., 99, 14 415–14 428.

Lohmann, D., Nolte-Holube,R. and Raschke, E. (1996). “A large-scale horizontal routing model to be coupled to land surface parametrization schemes”, *Tellus,* 48(A), 708-721.

Lohmann, D., Raschke, E., Nijssen, B. and Lettenmaier, D.P. (1998). “Regional scale hydrology: I. Formulation of the VIC-2L model coupled to a routing model”, *Hydrol. Sci. J.*, 43(1), 131-141.

Maurer, E.P., Wood, A.W., Adam, J.C., Lettenmaier, D.P. and Nijssen, B. (2002). “A Long-Term Hydrologically-Based Data Set of Land Surface Fluxes and States for the Conterminous United States”, *J. Clim.,* 15(22), 3237-3251.

McKee, T.B., Doesken, N.J., Kleist, J.1993. “The relationship of drought frequency and duration to time scales”, *Eight conf. App. Clim.,* Anaheim, CA.

Modarres, R. (2007). “Streamflow drought time series forecasting”, *Stoch. Environ. Res. Risk Assess.,* 22, 223-233.

Rao, A.R., and Srinivas, V.V.,(2005). “Regionalization of watersheds by Hybrid cluster analysis”, *J. Hydrol.*,318(1),37-56.

Yang,Y. and Burn, D.H. 1994. An entropy approach to data collection network design, *J.Hydrol*., 157,307-324.

The Role of Epikarst in Controlling Recharge, Water Quality and Biodiversity in Karst Aquifers: A Comparative Study between Virginia and Texas

Basic Information

Title:	The Role of Epikarst in Controlling Recharge, Water Quality and Biodiversity in Karst Aquifers: A Comparative Study between Virginia and Texas
Project Number:	2009TX335G
Start Date:	8/1/2009
End Date:	7/31/2011
Funding Source:	104G
Congressional District:	Texas District 25
Research Category:	Ground-water Flow and Transport
Focus Category:	Groundwater, Water Quantity, Hydrogeochemistry
Descriptors:	None
Principal Investigators:	Benjamin F Schwartz

Publications

There are no publications.

Title: The Role of Epikarst in Controlling Recharge, Water Quality and Biodiversity in Karst Aquifers: A Comparative Study between Virginia and Texas

Project Number: 2009TX335G

Start Date: 8/1/2009

End Date: 7-31-2011

Funding Source: 104g

Congressional District: 25

Focus Category: Groundwater, Water Quantity, Hydrogeochemistry

Descriptors: Epikarst, Karst, Recharge, Water Quality, Biodiversity

Principle Investigator: Benjamin F. Schwartz, Texas State University

Co-PIs: Madeline E. Schreiber, Virginia Polytechnic Institute and State University; and Daniel H. Doctor, U.S. Geological Survey.

Annual report for March 2009 – May 2010

<u>Progress Summary:</u>

Progress at the Texas site has been very good. Weather data collection and precipitation sampling have been ongoing at the surface above three in-cave sites in TX, and geochemical parameters have been measured in the caves at a variety of sites, including numerous drip sites with variable precipitation response times, an in-cave stream, and a nearby well. Due to the extreme drought of 2008-2009, few water samples were collected until October 2009. Now that the drought has ended, samples are being collected on a more frequent basis and are providing valuable information.

At the Virginia site, progress has also been very good. This funding allowed us to continue monitoring and sampling activities for a third year at the James Cave site where a stream, three drip sites, and precipitation is being monitored and sampled. Additionally, lysimeters were installed in soils above the in-cave sites and water samples are routinely being collected from them. A graduate student is nearly finished with his thesis and will soon be defending and publishing his work.

Work Summary:

Over the past 9 months, numerous visits have been made to install and maintain the equipment on the surface and underground. In Texas, since the end of the drought, weekly visits are being made to maintain equipment, download data and collect samples. In Virginia, trips to the surface site and into the cave are limited to once or twice each month due to logistics.

Detailed Summary of Preliminary Results:

Texas

In Headquarters Cave, McCarty Cave, and Cave Without A Name, drip rates slowed or nearly stopped during 2009, but have recovered since the rains in the fall season of 2009. Geochemical and drip data are currently too sparse to reach many conclusions about how the epikarst controls recharge quantity and quality. One tentative conclusion supported by some of our drip data (as well as previous studies) is that flow and storage in the epikarst at our TX sites is influenced by storage in the porous bedrock matrix. This storage component supports flow at drip sites for long periods of time and attenuates signals from precipitation events. In contrast, matrix storage appears to be much less important at the Virginia site and precipitation signals at drip sites are dominated by seasonality of ET.

Virginia

With this funding, we have extended our collection of long term records of hydrologic and geochemical data to examine the role of epikarst in controlling the quantity and geochemical evolution of recharge water as it passes through the epikarst.

Data collected from September 2007 to present are being used to identify trends in the temporal and spatial distribution of recharge to underlying aquifer. Results show that water-rock interactions and anthropogenic inputs (e.g., manure, fertilizer, and road salt) have impact on the water quality of recharge. Geochemical signatures of different water types (precipitation, soil water, epikarst drips, cave stream) are used to estimate the degree of evolution and residence time of recharge in epikarst. As is typical with karst systems, heterogeneity exists in the epikarst; however all sites share similar hydrologic and geochemical responses to recharge events. Drip rate patterns indicate that recharge primarily occurs during late winter/spring, and is almost negligible during the summer due to evapotranspiration. Analysis of water stable isotopes is being used to estimate retention time of water in epikarst.

By assessing the timing and quality of recharge, both during base flow conditions and in response to multiple recharge events of varying magnitudes, it is possible to use the results from James Cave as an analog for watershed managers to better characterize the role of epikarst in controlling recharge and water quality in similar karst aquifers.

Student involvement:

Three graduate students and three undergraduate students are involved with various aspects of the TX portion of this research, including thesis work for all three graduate students.

In Virginia, one graduate student is involved with the work and is completing his thesis this year.

Publications:

To date, one abstract has been published during this project. Several additional publications are expected to result from this work – in the form of journal articles, theses, and abstracts.

EPIKARST ROLE IN CONTROLLING THE QUALITY OF KARST AQUIFER RECHARGE

GERST, Jonathan, Geosciences, Virginia Tech, 4044 Derring Hall, Blacksburg, VA 24061, jgerst@vt.edu, SCHWARTZ, Benjamin F., Department of Biology, Texas State University - San Marcos, 601 University Drive, San Marcos, TX 78666, SCHREIBER, Madeline E., Department of Geosciences, Virginia Tech, 4044 Derring Hall, Blacksburg, VA 24061, and DOCTOR, Daniel H., U.S. Geol. Survey, MS 926A, Reston, VA 20192

Abstract

Epikarst, or the region of vegetation, soil, and weathered bedrock lying between the land surface and soluble bedrock, offers water retention capacity that does not exist in deeper, more mature sections of karst aquifers. Thus, the epikarst can act as a temporary reservoir for surface-applied contaminants and naturally-occurring chemical species. Long-term multi-parameter records of precipitation, soil water, epikarst drip water, and in-cave stream-water at James Cave in Dublin, VA, allow us to examine the role of epikarst in controlling the quality and geochemical evolution of recharge water as it passes through the epikarst.

Data collected since September 2007 are being used to identify trends in the temporal and spatial distribution of recharge to the karst aquifer. Drip rates indicate that recharge occurs during late winter/spring, but is minimized by evapotranspiration in summer. Precipitation over James Cave passes through the epikarst where its composition is modified by water-rock interactions. Chemical species such as Na, K, Cl, NO3, SO4, and DOC can serve as tracers to assess the timing and mechanisms of recharge. Geochemical differences between sites indicate that hydrologic and geochemical processes in the epikarst are spatially heterogeneous.

However, temporal variations in major ion concentrations can be correlated between sites as a function of recharge.

Specific conductance, pH, alkalinity, and major ion concentrations in epikarst drip water increase during low flow due to increased water-rock interaction. During high flow, however, younger recharge pushes older geochemically saturated water through the epikarst. High flow also inhibits the potential for natural attenuation of contaminants. The structural orientation of the epikarst, the presence of microbial activity, climate, and amount and timing of recharge are all factors in determining the extent to which epikarst controls the quality of recharge to the karst aquifer.

2009 Portland GSA Annual Meeting (18-21 October 2009)

Biological Treatment of Wastewater Contaminated with Estrogenic Compounds

Basic Information

Title:	Biological Treatment of Wastewater Contaminated with Estrogenic Compounds
Project Number:	2010TX354B
Start Date:	3/1/2010
End Date:	2/28/2011
Funding Source:	104B
Congressional District:	17
Research Category:	Water Quality
Focus Category:	Treatment, Wastewater, Water Quality
Descriptors:	None
Principal Investigators:	Meghan A Gallagher, R Karhikeyan

Publication

1. Gallagher, M. and R. Karthikeyan, 2011, Biological Treatment of Estrogenic Compounds in Wastewater, Poster Presentation at 2011 National Water Conference, Washington, D.C.

REPORT

Title: Biological Treatment of Wastewater Contaminated with Estrogenic Compounds

Project Number: 2010TX354B

Primary PI:

Meghan Anne Gallagher
2nd year Master of Science Student
Department of Biological and Agricultural Engineering
Texas A&M University
meghan.gallagher63@gmail.com
Cell: (210) 367-3905
325 Scoates Hall
2117 TAMU
College Station, TX77843 – 2117

Other PIs:

Dr. R. Karthikeyan
Assistant Professor
Department of Biological and Agricultural Engineering
Texas A&M University
karthi@tamu.edu
Office: (979) 845 - 7951
306 A Scoates Hall
2117 TAMU
College Station, TX 77843-2117

Abstract:

Currently there are no surface or groundwater regulations to address the concentrations of natural and synthetic hormones resulting from animal waste treatment processes and domestic wastewater treatment effluents. These emerging contaminants are endocrine disrupting compounds. Estrogen concentrations as low as 10 ng/L in wastewater have been known to alter the sex of fish. Biological treatment of estrogenic water will be studied in this research. Wastewater from various relevant sources will be collected and screened for organisms that are capable of degrading hormones. Enrichment culture based methods will be used during the initial screening process. Potential bacterial species capable of degrading hormones will be isolated, genomic DNA from the isolates will be extracted, and sequenced. Then various environmental factors that control and govern the biodegradation of hormones will be studied to design biological treatment processes. The results from this study will be presented here.

Problem and Research Objectives:

Emerging contaminants such as steroid hormones are not currently under regulation, yet field and lab studies show a potential for endocrine disruption in the aquatic environment (Tyler et al., 1998). Research was done 45 years ago to study the degradation of estrogenic compounds in the environment (Stumm-Zollinger and Fair, 1965). This study concluded that there would not be high enough concentration in the environment to cause a problem (Stumm-Zollinge and Fair, 1965). However, recent studies have shown that in streams that have concentrations as low as 10 ng/L can disrupt the endocrine system of fish, causing feminization of male fish in some cases (Hutchinson et al., 1999; Jobling et al., 1998; Lai et al., 2002; Tyler et al., 1998; Yu et al., 2007). The natural estrogens consist of estrone (E1), 17β-estradiol (E2), and estriol (E3), where the synthetic estrogen compounds include ethinylestradiol (EE2) and mestranol (MeEE2).

Wastewater effluents from Wastewater Treatment Plants (WWTPs) and Confined Animal Feeding Operations (CAFOs) are major estrogen contributing sources in the terrestrial environment. Municipal WWTPs discharge effluent with estrogen concentrations from 0.2 to 10 ng/L (Bartonti et al., 2000; Ternes et al., 1999). The manure produced in CAFOs can have E2 between 114 and 522 ng/g on a dry weight basis (Shemesh and Shore, 1994). Streams receiving discharged wastewater have up to 93 ng/L of E2 present (Finlay-Moore et al., 2000; Kolpin et al., 2002).

Typical WWTP processes are able to decrease the estrogen concentrations to ng/L levels (Bartonti et al., 2000; Ternes et al., 1999). Studies on dissipation of estrogens in municipal WWTP have documented that microbial degradation is the primary fate process, occurring in the activated sludge treatment (Gaulke et al., 2008; Ivanov et al., 2009; Muller et al., 2009; Pauwels et al., 2008; Shi et al., 2004; Yu et al., 2007). However, there are only few studies on the removal mechanisms of estrogens from CAFO wastewater (Chen et al., 2008; Khanal et al., 2006) and few studies have focused on the presence of estrogen compounds in water bodies near CAFOs (Arnon et al., 2008; Shemesh and Shore, 1994; Soto et al., 2004).

Texas Commission for Environmental Quality (TCEQ) which closely follows the Environmental Protection Agency (EPA) guidelines do not currently regulate surface waters as to the levels of estrogenic compounds that are discharged into streams. Current treatment, sorption and degradation, at WWTPs will lower the concentration but additional treatment is needed to get the concentration to a concentration level that does not have adverse affects.

Estrogens from CAFO waste are making their way in to the environment. In Arkansas, five springs with recharge zones that include pastures fertilized with poultry waste were sampled for fecal coliform, *E. coli*, and E2 (Peterson et al., 2000). Concentrations of E2 ranged from 6 to 66 ng/L in the sampled springs. Animal waste is one of the predominant sources of estrogenic compounds in the environment (Khanal et al., 2006; Hutchins et al., 2007; Raman et al., 2004).

US EPA regulates CAFO waste management. When CAFOs are discharging effluent they must apply for a National Pollutant Discharge Elimination (NPDES) permit (USEPA 2008). This permit does not specify limits of estrogenic compounds. CAFOs that are not discharging effluent must design an open containment system for the liquid waste that ensures discharge will not occur. Generally, CAFO waste treatment includes settling and separating the solid material from the liquid wastewater. The solid material is often land applied or composted. The supernatant goes to a series of aerobic or anaerobic lagoons lined with plastic or clay lining. Usually the lagoon liners are designed to allow for permissible infiltration. Estrogens if present in the storage wastewater can infiltrate below the liners. A study conducted in Israel documented estrogen concentrations at 32 m below a CAFO waste lagoon (Arnon et al., 2008).

After treated in the waste lagoons, the CAFO wastewater can be used to irrigate surrounding fields. Studies have been conducted on the transport of estrogens in soils and water bodies (Casey et al., 2003, 2005; Lee et al., 2003; Lim et al., 2007). Concentrations of estrogenic compounds were higher in the Fall than in the Spring for a river in Israel (Barel-Cohen et al., 2006). Lee et al. (2003) studied the sorption of E2 in soil and found a strong association between E2 and soil. Lee concluded that estrogenic compounds in soil were likely to be transported with surface runoff. Appropriate treatment of CAFO wastewater is crucial to minimize the exposure of estrogenic compounds to the aquatic environment from runoff and infiltration.

Increased residence time in CAFO lagoons is a viable option for removing estrogens. But further research should be conducted to study the factors that influence the removal of estrogens in CAFO wastewater (Zheng et al., 2008). Temperature affects microbial degradation of estrogenic compounds. However, most of the studies on the effect of temperature on estrogen degradation were conducted in soil or solid waste in CAFOs (Colucci et al., 2001; Hakk et al., 2005; Hemmings and Hartel, 2006; Jacobsen et al., 2005; Stumpeand Marschner. 2007). Optimum soil temperature for mineralization of estrogens was found to be between 30 and 37°C (Colucci et al., 2001). Accumulation of E2 can occur in agriculture soils because the mineralization rate is low (Stumpe and Marschner. 2007).

Even though there are several studies on fate, transport, and removal of nutrients in dairy CAFO wastewaters, there are only limited studies on degradation of estrogens in wastewaters resulting from dairy CAFOs (Cho et al., 2000; McNab et al., 2007; Singleton et al., 2007). Few studies conducted on degradation of estrogens in poultry or swine lagoons. Hemmings and Hartel (2006) found that mineralization of estrogens in poultry litter generally increased as temperature decreased. Jacobsen et al. (2005) found that microorganisms in swine slurry degraded 17β-estradiol when added to agricultural soil at 30°C. Aerobic composting of poultry manure decreased the water-solubility of 17β-estradiol over time (Hakk et al., 2005). Similar studies on the degradation of estrogens in dairy CAFO lagoons are needed.

In this research, the effects of temperature and pH on the aerobic degradation of 17β-estradiol in CAFO wastewater were studied. The overall objective was to determine the effect of temperature and pH on microbial degradation of 17β-estradiol by an isolated estrogen degrading bacterium and mixed cultures from CAFO wastewaters.

- Hypothesis 1: As the temperature decreases, the removal percentage of 17β-estradiol by estrogen degrading bacteria will decrease.

- Hypothesis 2: As the pH of the wastewater is more acidic, the removal percentage of 17β-estradiol by estrogen degrading bacteria will decrease.

Materials/Methodology:

Estrogen-degrading microorganism. Estrogen degrading organism isolated and sequenced by a screening study previously done by Sullivan (2010) will be used in the experiments. The isolate was confirmed as *Sphingobacterium* sp. For the batch degradation study, this isolate was grown in mineral medium (0.4 g $Na_2HPO_4 \cdot H_2O$, 0.25 g KH_2PO_4, 0.1 g $MgSO_4 \cdot 7H_2O$, 0.5 g $(NH_4)_2SO_4$, 0.25 g yeast extract, 2.5 mL trace element solution) (Haiyan et al., 2006) dissolved in 500 mL de-ionized water with 3 mg/L of 17β-estradiol eluted in ethanol. The culture was grown in 1 L conical flasks, kept on a rotary shaker at 100 rpm and incubated at 35˚C for two days.

Mixed culture from CAFO wastewater. Wastewater from two different CAFOs will be taken from the primary lagoon.

Water microcosms. Nine autoclaved 500 mL Pyrex® bottles sealed with sterilized cotton plugs were used as lab-scale bioreactors. Three bottles contained 450 mL of wastewater collected from an aerobic treatment lagoon of CAFO A. Three bottles were filled with autoclaved wastewater collected from the same lagoon treatment; and three bottles were filled with autoclaved deionized water. All bottles were spiked with 3 mg/L of 17β-estradiol. One milliliter of the mineral media enriched with *Sphingobacterium sp.* was added to the three bottles with wastewater and three bottles with autoclaved deionized water while the three bottles with autoclaved wastewater served as control for this biodegradation study. The same experimental design was repeated with wastewater collected from aerobic lagoon of CAFO B.

The effect of pH was studied by setting each bioreactor to acidic, neutral, and then alkaline pH while maintaining at a constant temperature. At each of the different pH values, the temperature was kept at 5°C, 10°C, and 25°C to observe the effect of temperature on the microbial degradation of 17β-estradiol. The study was done over a 20 day period for each temperature.

Chemicals. All chemicals used in this study including 17β-estradiol were obtained from (Fisher Scientific, Houston, TX).

17β-Estradiol Analysis. A specific immunoassay (Abraxis, Warminster, PA) was utilized in this study to determine 17β-estradiol concentrations. The analysis was conducted according to manufacturer's recommendation. Briefly, a solution of estradiol antibody and magnetic particles are added to both samples and standards in test tubes, vortex, and then reacts for 30 min at room temperature before adding estradiol enzyme conjugate. The conjugate reacts for 90 min at room temperature and then the magnetic separator holding the test tubes is inverted to separate the particles. A washing solution is added and the separator rack is inverted again. Then, a coloring reagent is added to the test tubes and reacts for 20 min at room temperature. Finally, the stopping solution is added to each tube. After 15 min, optical density (OD) of the solutions in test tubes is measured using a photometer set at 450 nm. A standard curve is generated and used to determine 17β-estradiol concentrations in samples and controls. The pH as well as the OD at 600 nm was measured at each 17β-estradiol concentration measurement. Optical density at 600 nm measures the bacterial cell growth.

Preliminary Study. Four autoclaved 500 mL Pyrex® bottles sealed with sterilized foam plugs were used as lab-scale bioreactors. All bottles contained 250 mL of autoclaved deionized water and were spiked with 3 mg/L of 17β-estradiol. The bottles were covered with aluminum foil to prevent photo-degradation of 17β-estradiol. One milliliter of the mineral media enriched with *Sphingobacterium sp.* was added to two of the bottles while the other two bottles served as control for this biodegradation study. The pH of each microcosm was measured and recorded. Two bottles (one sample and one control) were incubated at temperature 5˚C and continuously stirred at 100 rpm. The other two bottles (one sample and one control) were incubated at temperature 35˚C, continuously stirred at 100 rpm. The concentrations were measured using Abraxis immunoassay kit five times over 12 days.

Principal Findings:

There have been several technical problems encountered. Initially, a Gas Chromatography-Mass Spectrometry (GC-MS) was used to determine the concentrations of 17β-estradiol. Training on the GC-MS was obtained and a method for analyzing 17β-estradiol samples was tested. Contaminants in the column were detected and consistent standards could not be analyzed to obtain a standard curve. An ELISA kit was obtained and used to measure 17β-estradiol concentrations. The basics of the kit were learned and a specific photometer was purchased to measure the absorbance for the small sample volume. The preliminary study described in this proposal was conducted and the data was recorded. However, the absorbance values of standards did not follow a linear trend when plotted. New standards were obtained from Abraxis along with the certificate of analysis that included the standard curve that should be expected. Following the suggestion from Abraxis, the standards were allowed to reach room temperature before running the assay. Again, absorbance values of standards did not fit the certificate of analysis standard curve. This research is still ongoing.

References Cited:

Arnon, S., O. Dahan, S. Elhanany, K. Cohen, I. Pankratov, A. Gross, Z. Ronen, S. Baram, and L.S. Shore. 2008. Transport of testosterone and estrogen from dairy-farm waste lagoons to groundwater. *Environmental Science and Technology*, 42: 5521-5526.

Barel-Cohen, K., L.S. Shore, M. Shemesh, A. Wenzel, J. Mueller, and N. Kronfeld-Schor. 2006. Monitoring of natural and synthetic hormones in a polluted river. *Journal of Environmental ManageGoment*, 78: 16-23.

Bartonti, C., R. Curini, G.D'Ascenzo, A. Di Corcia, A. Gentili, and R. Sampeli. 2000. Monitoring natural and synthetic estrogens at activated treatment plants and in receiving river water. *Environmental Science and Technology,* 34: 5059-66.

Casey, F.X.M., G.L. Larsen, H. Hakk, and J. Simunek. 2003. Fate and transport of 17β-estradiol in soil-water systems. *Environmental Science and Technology*, 37: 2400-2409.
Casey, F.X.M., J. Simunek, J. Lee, G. L. Larsen, and H. Hakk. 2005. Sorption, Mobility, and Transformation of Estrogenic Hormones in Natural Soil. *Journal of Environmental Quality*, 34: 1372-1379.

Chen, M., R. QI, W. An, H. Zhang, Y. Wei, and Y. Zhou. 2008. New concept of contaminant removal from swine wastewater by a biological treatment process. *Frontiers of Biology in China*, 4(4): 402-413.

Cho, J.C., H.B. Cho, and S.J. Kim. 2000. Heavy contamination of a subsurface aquifer and a stream by livestock wastewater in a stock farming area, Wonju, Korea. *Environmental Pollution*, 109: 137-146.

Colucci, M.S., H. Bork, and E. Topp. 2001. Persistence of estrogenic hormones in agricultural soils: I. 17β-Estradiol and Estrone. *Journal of Environmental Quality*, 30: 2070-2076.

Finlay-Moore, O., P.G. Hartel, and M.L. Cabrera. 2000. 17ß-Estradiol and testosterone in soil and runoff from grasslands amended with broiler litter. *Journal of Environmental Quality*, 29: 1604–1611.

Gaulke, L, S.E. Strand, T.F. Kalhorn, and H.D. Stensel. 2008. 17a-ethinylestradiol transformation via abiotic nitration in the presence of ammonia oxidizing bacteria. *Environmental Science and Technology*, 42 (20): 7622-7627.

Haiyan, R., J. Shulan, N.U.D. Ahmad, W. Dao, and C. Chengwu. 2006. Degradation characteristics and metabolic pathway of 17-α ethynylestradiol by *Sphingobacterium* sp. *JCR5. Chemosphere*, 66: 310-316.

Hakk, H., P. Millner, G. Larsen. 2005. Decrease in water-soluble 17β -estradiol and testosterone in composted poultry manure with time. *Journal of Environmental Quality*, 34:943-950.

Hemmings, S.N.J. and P. G. Hartel. 2006. Mineralization of hormones in breeder and broiler litters at different water potentials and temperatures. *Journal of Environmental Quality*, 35:701-706.

Hutchins, S. R., M.V. White, F.M. Hudson, and D.D. Fine. 2007. Analysis of lagoon samples from different concentrated animal feeding operations for estrogens and estrogen conjugates. *Environmental Science and Technology,* 41: 738–744.

Hutchinson, T.H., N.A. Pounds, M. Hampel, and T. Williams. 1999. Impact of natural and synthetic steroids on the survival, development and reproduction of marine copepods (*Tisbe battagliai*). *Science of Total Environment,* 233: 167-179.

Ivanov, V, J. Jun-Wei Lim, O. Stabnikova, K. Yew-Hoong Gin. 2009. Biodegradation of estrogens by facultative anaerobic iron-reducing bacteria. *Process Biochemistry*, 45: 284-287.

Jacobsen, A.M., A. Lorenzen, R. Chapman, and E. Topp. 2005. Persistence of testosterone and 17β-estradiol in soils receiving swine manure or municipal biosolids. *Journal of Environmental Quality*, 34: 861-871.

Jobling, S., M. Nolan, C.R. Tyler, G. Brighty, and J. Sumpter. 1998. Widespread sexual disruption in wild fish. *Environmental Science and Technology, 32*(17): 2498–2506.

Kolpin, D.W., E. T. Furlong, M. T. Meyer, E. M. Thurman, S. D. Zaugg, L. B. Barber and H. T. Buxton. 2002. Pharmaceuticals, hormones, and other organic wastewater contaminants in U.S. streams, 1999–2000: a national reconnaissance. *Environmental Science and Technology,* 36: 1202–1211.

Khanal, S.K., B. Xie, M. Thompson, S. Sung, S.K. Ong, and J. Van Leeuwen. 2006. Fate, transport, and biodegradation of natural estrogens in the environment and engineered systems. *Environmental Science and Technology*, 40(21): 6537-6546.

Lai, K.M., M.D. Scrimshaw, J.N. Lester. 2002. Prediction of the bioaccumulation factors and body burden of natural and synthetic estrogens in aquatic organisms in the river systems. *The Science of the Total Environment*, 289: 159-168.

Lee, L.S., T.J. Strock, A.K. Sarmah, and P.S.C. Rao. 2003. Sorption and dissipation of testosterone, estrogens, and their primary transformation products in soils and sediment. *Environmental Science and Technology*, 37: 4098-4105.

Lim T.H., K.Y.H. Gin, S.S. Chow, Y.H. Chen, M. Reinhard, and J.H. Tay. 2007. Potential for 17β -estradiol and estrone degradation in a recharge aquifer system. *Journal of Environmental Engineering*, 133(8): 819-827.

McNab, W.W. JR., M.J. Singleton, J.E. Moran, and B.K. Esser. 2007. Assessing the impact of animal waste lagoon seepage on the geochemistry of an underlying shallow aquifer. *Environmental Science and Technology*, 41: 753-758.

Muller, M, D. Paturea, J.J. Godon, J.P. Delgenes, G. Hernadez-Raquet. 2009. Molecular and kinetic characterization of mixed cultures degrading natural and synthetic estrogens. *Applied Microbial and Cell Physiology*, 85: 691-701.

Pauwels, B, K. Wille, H. Noppe, H. De Brabender, T. Van de Wiele, W. Verstraete, and N. Boon. 2008. 17a-ethinylestradiol co metabolism by bacteria degrading estrone, 17B-estradiol and estriol. *Biodegradation*, 19: 683-693.

Peterson, E.W., R.K. Davis, and H.A. Orndorff. 2000. 17β-Estradiol as an indicator of animal waste contamination in mantled karst aquifers. *Journal of Environmental Quality*, 29(3): 826-834.

Raman, D. R., E.L. Williams, A.C. Layton, R.T. Burns, J.P. Easter, A.S. Daugherty, M.D. Mullen, and G.S. Sayler. 2004. Estrogen Content of Dairy and Swine Wastes. *Environmental Science and Technology*, 38: 3567-3573.

Shemesh, M. and L. S. Shore. 1994. Effect of hormone in the environment on reproduction in cattle. [In: Fields, M.J. and R.S. Sand, editors]. Boca Raton, FL: CRC Press; p. 287-297.

Shi, J, Y. Suzuki, and S. Nakai. 2004. Microbial degradation of estrogens using activated sludge and night soil-composting microorganisms. *Water Science and Technology*, 50(8): 153-159.

Singleton, M.J., B.K. Esser, J.E. Moran, G.B. Hudson, W.W. McNab, and T. Harter. 2007. Saturated zone denitrification: potential for natural attenuation of nitrate contamination in shallow groundwater under dairy operations. *Environmental Science and Technology*, 41: 759-765.

Soto, A., J. Calabro, N. Prechtl, A. Yau, E. Orlando, A. Daxenberger, A. Kolok, L. Guillette, B. Bizec, I. Lange, and C. Sonnenschein. 2004. Androgenic and estrogenic activity in water bodies receiving cattle feedlot effluent in eastern Nebraska, USA. *Environmental Health Perspectives*, 112(3): 346-352.

Stumm-Zollinger, E. and G. M. Fair (1965). Biodegradation of Steroid Hormones. *Water Pollution Control Federation*. 37 (11), 1506-1510.

Stumpe, B and B. Marschner. 2007. Long-term sewage sludge application and wastewater irrigation on the mineralization and sorption of 17-estradiol and testosterone in soils. *Science of the Total Environment*, 374: 282-291.

Sullivan, B. 2010. Characterization of tetracycline resistant bacteria from a perennial stream in a subtropical watershed.

Ternes, T.A, M. Stump, J. Mueller, K. Haberer, R.D. Wilken, M. Servos. 1999. Behavior and occurrence of estrogens in municipal sewage treatment plants—I. investigations in Germany, Canada and Brazil. *Science of the Total Environmen*t, 225: 81-90.

Tyler, C.R., S. Jobling, and J.P. Sumpter. 1998. Endocrine disruption in wildlife: a critical review of the evidence. *Critical Reviews in Toxicology*, 28(4): 319-361.

U.S. Environmental Protection Agency (USEPA). 2008. Revised national pollutant discharge elimination system permit regulation and effluent limitations guidelines for concentrated animal feeding operations in response to the waterkeeper decision. Washington, D.C., USEPA.

Yu, C.P., H. Roh, and K.H. Chu. 2007. 17β-estradiol-degrading bacteria isolated from activated sludge. *Environmental Science Technology*, 41: 486-492.

Zheng, W., S.R. Yates, and S.A. Bradford. 2008. Analysis of steroid hormones in a typical dairy waste disposal system. *Environmental Science and Technology*, 42: 530-535.

Trihalomethane Formation Potential in Rainwater Harvested from Different Roofing Materials

Basic Information

Title:	Trihalomethane Formation Potential in Rainwater Harvested from Different Roofing Materials
Project Number:	2010TX356B
Start Date:	3/1/2010
End Date:	2/28/2011
Funding Source:	104B
Congressional District:	21
Research Category:	Water Quality
Focus Category:	Treatment, Water Quality, Water Supply
Descriptors:	None
Principal Investigators:	Carolina B Mendez, Kerry A Kinney, Mary Jo Kirisits

Publications

There are no publications.

Trihalomethane Formation Potential in Rainwater Harvested from Different Roofing Materials

Project Number: 570652

Principal Investigator: Carolina Mendez, M.S., Department of Civil, Architectural and Environmental Engineering, The University of Texas at Austin, 1 University Station C1786, Austin, TX 78712. E-mail: caromend@gmail.com

Co-Principal Investigators: Mary Jo Kirisits, Assistant Professor, Department of Civil, Architectural and Environmental Engineering, The University of Texas at Austin, 1 University Station C1786, Austin, TX 78712. E-mail: kirisits@mail.utexas.edu. Phone: 512.232.7120

Kerry Kinney, Professor, Department of Civil, Architectural and Environmental Engineering, The University of Texas at Austin, 1 University Station C1786, Austin, TX 78712. E-mail: kakinney@mail.utexas.edu. Phone: 512.232.1740

Sarah Keithley, M.S. student, Department of Civil, Architectural and Environmental Engineering, The University of Texas at Austin, 1 University Station C1786, Austin, TX 78712. E-mail: sarah.keithley@gmail.com

Sarah Fakhreddine, B.S., Department of Civil, Architectural and Environmental Engineering, The University of Texas at Austin, 1 University Station C1786, Austin, TX 78712. E-mail: sarahfak@gmail.com

Abstract

Rainwater harvesting systems are one way to address the worldwide increase in water demand. If the harvested rainwater is for indoor use, residential users often disinfect it. If it is disinfected with chlorine, the presence of dissolved organic carbon (DOC) can lead to the formation of

harmful disinfection by-products such as trihalomethanes (THMs). Although the quality of harvested rainwater produced in individual residences is not regulated, it would be wise for a user to comply with United States Environmental Protection Agency drinking water standards; total THMs are regulated at 80 μg/L in tap water. In this study, we examined THM formation in chlorinated rainwater harvested from a full-scale asphalt fiberglass shingle roof. Under disinfection conditions relevant for a residence, total THMs were formed at concentrations from 28 to 78 μg/L.

Problem and Research Objectives

As the demand for safe drinking water increases, rainwater harvesting is emerging as an alternative water resource. Currently, there are no national standards or regulations for the quality of rainwater harvested at individual residences [1]. Moreover, several infectious diseases have been attributed to the consumption of untreated harvested rainwater [2]. Therefore, if harvested rainwater is intended for potable usage, it should be disinfected. In the United States, ultraviolet light and chlorine are both commonly used for the disinfection of rainwater. Chlorine has the advantage of being more cost-effective. When water is disinfected using chlorine, the dissolved organic carbon (DOC) in the water reacts with chlorine to form disinfection byproducts such as trihalomethanes (THMs). The four THMs of interest in drinking water are chloroform ($CHCl_3$), bromodichloromethane ($CHBrCl_2$), dibromochloromethane ($CHBr_2Cl$) and bromoform ($CHBr_3$). Studies have demonstrated carcinogenic effects and liver toxicity from THMs in mice [3]. The United States Environmental Protection Agency (U.S. EPA) has classified all four THMs as possible or probable human carcinogens. The U.S. EPA's maximum contaminant level (MCL) for total THMs in drinking water is 80 μg/L.

The adverse effect of THMs on human health can extend beyond drinking water to indoor air quality. For instance, chloroform is an extremely volatile compound with an outdoor air concentration below 1 $\mu g/m^3$. When chlorinated water is heated (e.g., when running a shower or using a washing machine), the chloroform readily volatilizes. Chloroform in a small shower compartment, while taking a warm shower with tap water, can reach concentrations up to 1000 $\mu g/m^3$ [4].

In a previous study, in which we analyzed harvested rainwater quality from five pilot-scale roofs (asphalt fiberglass shingle, Galvalume® metal, concrete tile, cool and green), DOC concentrations ranged from 2 to 37 mg/L [5]. Thus, DOC concentrations in harvested rainwater are greater than or equal to those found in tap water. **The presence of DOC in harvested rainwater could lead to the production of THMs after chlorination, which has consequences for human health.** Thus, the purpose of this project was to assess THM formation in harvested rainwater under typical chlorination conditions that are used in the field.

Materials/Methodology

Harvested rainwater was collected from one asphalt fiberglass shingle full-scale roof in Austin, Texas. The harvested rainwater was treated with or without filtration and with chlorination for a variety of contact times: (1) chlorination with a target residual of 2 mg/L after 10 minutes followed by quenching with sodium thiosulfate; (2) filtration and chlorination with a target residual of 2 mg/L after 10 minutes, followed by quenching with sodium thiosulfate; (3) chlorination with a target residual of 2 mg/L after 10 minutes; total contact time of 7 hours; (4) filtration and chlorination with a target residual of 2 mg/L after 10 minutes; total contact time of 7 hours.

For the experiments with filtration, a 10-micrometer (μm) filter followed by a 1-μm glass microfiber filter was used. An absolute 1-μm filter is the only way to fully protect against *Cryptosporidium* and *Giardia* cysts. Without the removal of these cysts, water is considered non-potable [6]. The harvested rainwater was disinfected using a sodium hypochlorite solution (household bleach) to achieve a target residual of 2 mg/L after a contact time of 10 minutes. Some households chlorinate their harvested rainwater as it enters the house; this method is known as point-of-entry treatment [6]. The typical chlorine contact time is simply the amount of time required for the water to travel through the house's plumbing system (approximately 5-10 minutes, depending on the house), so a contact time of 10 minutes was chosen to simulate a typical residence time in a house. If water flow is stopped, then the reaction between chlorine and DOC will continue while the water stagnates in the pipes; thus, we also chose to examine THM formation after a 7-hour contact time.

Some THM analyses were conducted at DHL Analytical (Round Rock, TX), and some were conducted at the University of Texas at Austin. Liquid-liquid extraction was used to extract THMs from the water samples using pentane as the extractant. 1,1,1-trichloroethane (TCA) was used as the internal standard. THM concentrations were measured by gas chromatography using a Hewlett Packard 6890A GC. Analyses used a splitless glass injector liner, a 60 m HP-5 capillary column, and an electron capture detector. Helium was the carrier gas, and the pressure through the column remained constant at 16.5 psi. The injection volume was 2 μL. The injector temperature was 200°C, and the detector temperature was 325°C. The oven program was: 32°C for 9 min, 10°C/min ramp to 40°C, 40°C for 3 min, and 15°C/min ramp to 150°C [7]. The run time per sample was 20 min.

Principal Findings

Harvested rainwater was collected from a full-scale residence in Austin, TX. The harvested rainwater had a DOC concentration of 3.1 mg/L and a turbidity of 1.9 nephelometric turbidity units (NTU).

As described above, the water was treated in four ways, and THMs were measured. Figure 3 shows that chloroform was the dominant THM detected. Low concentrations of bromodichloromethane and dibromochloromethane were detected, but no bromoform was detected.

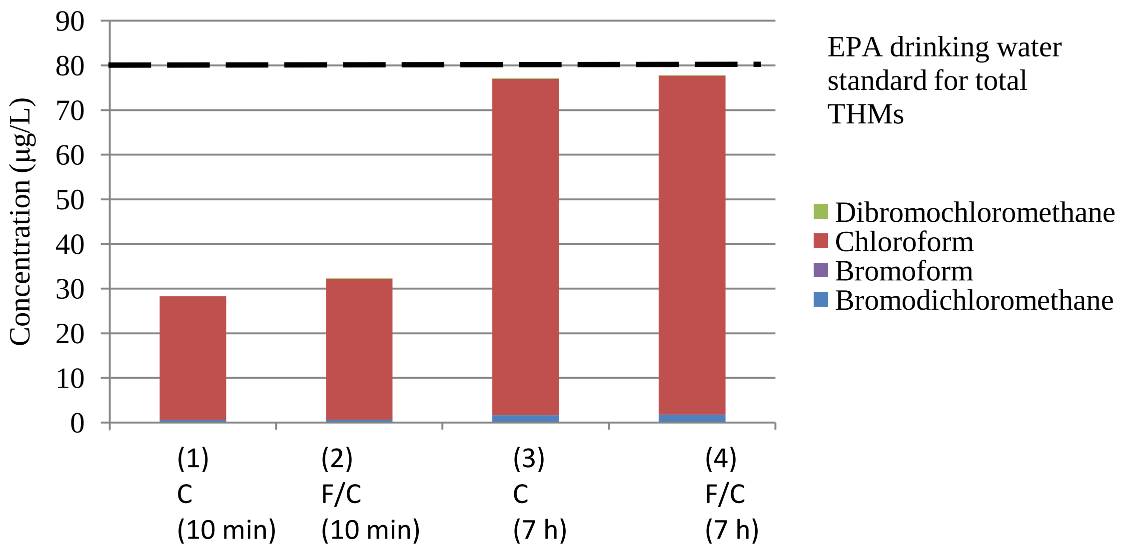


Figure 3: THM concentrations from treated rainwater harvested from a full-scale asphalt fiberglass shingle roof. F=filtration and C=chlorination (for a total contact time of 10 minutes or 7 hours)

Figure 3 indicates that total THMs were below the U.S. EPA drinking water standard of 80 μg/L when the water was chlorinated for only 10 minutes. However, total THMs approached the EPA drinking water standard when the chlorine contact time was 7 hours. It is possible that total THMs would have exceeded the drinking water standard if the contact time was longer (e.g., chlorinated water stagnated in the pipes overnight or if the user batch-chlorinated in the storage tank) or if the DOC concentration were higher. Since this particular water did not have a high turbidity, filtration of the water prior to chlorination did not have a significant impact on THM formation.

Future Work

We have just built a treatment system that more closely simulates a typical, residential treatment system. Chlorine residuals of 0.2 and 2 mg/L after 10 minutes will be targeted. An ANSI/NSF 53 certified carbon filter will be used downstream of chlorination. Rainwater harvested from a variety of roofing materials will be analyzed to determine how the roofing material affects THM formation.

Significance

Harvested rainwater is increasingly used for potable purposes. If a user treats that water by chlorination, there exists a potential for the generation of harmful THMs. Our work is significant because it demonstrated THM formation, approaching the U.S. EPA drinking water standard for total trihalomethanes, under chlorination conditions typical of a residential application.

References Cited

[1] Texas Commission on Environmental Quality. 2007. *Harvesting, Storing, and Treating Rainwater for Domestic Indoor Use.*

[2] Lye D.J. 2002. *Health risks associated with consumption of untreated water from household roof catchment systems*. Journal of the American Water Resources Association 38(5): 1301-1306.

[3] Medical College of Ohio. 2000. *Final Report: Health Risk of the Trihalomethanes Found in Drinking Water Carcinogenic Activity and Interactions.*

[4] World Health Organization. 2004. *Chloroform, Concise International Chemical Assessment Document 58.*

[5] Mendez C.B., Afshar B.R., Kinney K., Barrett M.E., and Kirisits M.J. 2010. *Effect of roof material on water quality for rainwater harvesting systems*. Texas Water Development Board: Austin, Texas.

[6] Texas Water Development Board. 2005. *The Texas Manual on Rainwater Harvesting.* Austin, Texas.

[7] Ralls, Shay M. (1999) *Enhanced Softening for Disinfection By-Product Precursor Control*. M.S. Thesis. University of Texas at Austin.

Impact of Saline Irrigation Water on Citrus Rootstocks in the Lower Rio Grande Valley

Basic Information

Title:	Impact of Saline Irrigation Water on Citrus Rootstocks in the Lower Rio Grande Valley
Project Number:	2010TX357B
Start Date:	3/1/2010
End Date:	2/28/2011
Funding Source:	104B
Congressional District:	15
Research Category:	Water Quality
Focus Category:	Agriculture, Irrigation, Water Quality
Descriptors:	None
Principal Investigators:	Catherine R Simpson, Shad D Nelson

Publications

There are no publications.

REPORT

Title Impact of Saline Irrigation Water on Citrus Rootstocks in the Lower Rio Grande Valley

Prime Agreement Number: 06HQGR0130

Research Subcontract Number: 570651

Primary PI Catherine R. Simpson

Other PIs Shad D. Nelson, PhD

Abstract

The Texas citrus industry in the Rio Grande Valley experiences periodic droughts. During such times, water restrictions from the Amistad and Falcon Reservoirs can reduce water available for agriculture. Irrigation in this region is primarily surface waters from the Rio Grande where citrus orchards are flood irrigated. Irrigation practices that use less water are being explored and evaluated. Water used to irrigate crops usually contains between 800 and 900 mg L^{-1} of salt, the equivalent of adding between 2100 and 2400 lbs salt/acre foot. Limiting irrigation in agricultural areas may lead to salt accumulation in the crop rooting depth, especially where low water use systems like drip irrigation is utilized.

Currently, Citrus trees are grafted onto hardy rootstocks in order to ensure tree survival and production. These rootstocks are used to reduce pathogen impacts and enhance their tolerance to thermal, saline and other environmental stressors. It is vital to find saline tolerant citrus rootstocks for soil and environmental conditions in the Lower Rio Grande Valley (LRGV).

This study's objectives are to assess the salinity tolerance of citrus rootstocks using typical soils found in the Rio Grande Valley. We will evaluate irrigation water salinity tolerance levels for these rootstocks during greenhouse trials.

Problem and Research Objectives

Drought and water restrictions are an ongoing problem for farmers in the Rio Grande Valley. Finding citrus rootstocks that are able to tolerate increasing salinity while using less water is vital for the agricultural community and water conservation in South Texas.

Citrus (*Citrus spp.*) is an important economic crop in the LRGV, bringing in more than $50 million for growers annually (Sauls 2008). Citrus trees are traditionally grafted onto sour orange rootstock because of its ability to tolerate the calcareous, high pH soils and heavy soil conditions in south Texas (Sauls 2008; Louzada et al. 2008). However, the sour orange rootstock is susceptible to a variety of diseases and pathogens that were previously not a problem. Increasing concerns over Citrus tristeza virus transmitted by the new arrival, the Brown Citrus Aphid, and other diseases have initialized more research into finding alternative rootstocks. These pest and pathogen resistant rootstocks must be evaluated for the varying soil and water conditions found in the Rio Grande Valley.

The decreasing availability of irrigation waters from surface waters due to drought and restrictions have put limitations on irrigation practices in the LRGV. On average, typical irrigation practices consist of flooding fields with 0.5 acre-foot /acre between 4 and 6 times during the growing season. This could increase up to 9 times during the growing season in times of drought or water shortage. Given an average EC of 1.33 dS m^{-1} (850 mg L^{-1}), this means that in a growing season as much as 4624 to 10,404 lbs of salt/ acre are added annually to citrus orchards. While most salts will be leached away by excess water, some salts will continue to accumulate. This problem will be compounded if water restrictions limit the amount of water farmers will be able to apply to their land.

The intrusion of salt water from the Gulf of Mexico causes high salinity levels in groundwater throughout the LRGV. Groundwater in this region has not typically been used for irrigation due to high spatial variability in water quality and quantity (Chowdhury and Mace). Surface water limitations may force farmers to resort to saline or brackish groundwater in order to meet crop water demands. This has led to the need for further development and evaluation of saline tolerant rootstocks.

The objectives of this study were to evaluate and assess the salinity tolerance for several citrus rootstocks. There is also a need to evaluate irrigation water deficits to determine an optimal salinity tolerance level that will also meet the crop's water needs.

To determine these factors we will set up greenhouse trials using various citrus rootstocks. We used rootstock varieties adapted to soil conditions in the Rio Grande Valley and water with varying electrical conductivities and apply them at different increments in order to evaluate the optimal salinity tolerance in a water deficit situation.

This study's purpose is to obtain preliminary data in order to further research that may be conducted during field trials of the same rootstocks. This can potentially be valuable information for growers in times of drought or water restriction when they may have few options. Water quality and availability is a problem that is escalating as increased population growth in the LRGV as well as drought and water restrictions occur.

Materials/Methodology

Initially, rootstock seeds were evaluated for the potential to be used in this study by germinating seeds in a nutrient agar supplemented with salt solutions at different concentrations. This initial evaluation evaluated germination by observing seeds collected from rootstock parent varieties grown on Texas A&M University-Citrus Center property in Weslaco, TX. Four rootstock cultivars were evaluated based on their disease resistance, tolerance to calcareous clays, fruit quality and potential yield. These rootstock cultivars were Sour Orange, C-146, C-57 and C-22. One scion variety was also tested to evaluate salinity on the scion cultivar. This *in vitro* study was conducted to minimize contamination and reduce any additive effects of repeated saline water additions.

This part of the study evaluated the *in vitro* germination and growth of citrus seeds in a nutrient agar supplemented with sea salt solution (Instant Ocean©, Spectrum Brands, Inc., Madison, WI) to have salt concentrations that correspond to approximately 0, 1, 3, 5, and 10 dS/m (+/- 1 dS/m) electrical conductivities. Each cultivar had 10 seeds per box and 2 boxes per treatment for a total of 100 seeds per cultivar and 20 seeds per treatment. The seeds were sanitized in a solution containing 10% bleach and 0.1% Tween 20 and stirring continuously for 2 hours, then rinsed with deionized water four times. In sterile conditions, the seed testa and cotyledons were cut (without damage to the micropylar end) in order to promote optimal germination and rule out seed coat factors in germination hindrance. Seeds were placed in a Magenta-7 vessel (Sigma-Aldrich) and containing Murashige and Skoog basal medium (Murashige and Skoog, 1962) supplemented with Gambourg's vitamins (Sigma-Aldrich, St. Louis, MO), and 0.4% Phytagel (Sigma-Aldrich, St. Louis, MO) along with the sea salt solution (Instant Ocean©). The seeds were kept in the dark at approximately 27°C for 2 weeks and then gradually introduced into natural light conditions. The germination was recorded daily until the 14 day point. The germinated seeds were measured for the following after 70 days total germination and growth.

- Germination rate and percentage
- Number of seedlings germinated per seed (polyembryony)
- Root length and width
- Shoot length and width
- Fresh weight and dry weight (average moisture content)

After the initial seed evaluation study, three rootstock varieties were chosen to determine the salinity tolerance of grafted and non grafted citrus trees. In this study the Sour Orange, C-22 and C-146 cultivars were evaluated. Grafted rootstocks had the scion variety 'Olinda' a Valencia sweet orange variety grafted onto the previously mentioned rootstocks, while the non-grafted varieties had no such treatment.

The trees were watered bi-weekly with a sea salt solution 0, 1, 3, 5 and 10 dS/m (+/- 1 dS/m). Each treatment contained three rootstock cultivars and 5 replications. The experimental setup as shown below was set up in a random complete block design.

Grafted Rootstocks

Grafted	**0 dS/m**	**1 dS/m**	**3 dS/m**	**5 dS/m**	**10 dS/m**
	C22-R1G- 0dS	SO -R1G- 1dS	C22-R1G- 3dS	C146- R1G- 5dS	SO -R1G- 10dS
	C146- R 1 G- 0dS	C22-R1G- 1dS	SO -R1G- 3dS	C22-R1G- 5dS	C146- R1G- 10dS
Rep 1	SO -R1G- 0dS	C146-R 1G- 1dS	C146- R1G- 3dS	SO -R1G- 5dS	C22-R1G- 10dS
	C146- R 2G -0dS	SO -R2G- 1dS	SO -R2G- 3dS	C146- R2G- 5dS	C22-R2G- 10dS
	SO -R2G- 0dS	C22-R2G- 1dS	C146- R2G- 3dS	C22-R2G- 5dS	SO -R2G- 10dS
Rep 2	C22-R2G- 0dS	C146- R2G- 1dS	C22-R2G- 3dS	SO -R2G- 5dS	C146- R2G- 10dS
	C22-R3G- 0dS	C146- R3G- 1dS	C146-R 3G- 3dS	C22-R3G- 5dS	SO -R3G- 10dS
	SO -R3G- 0dS	SO -R3G- 1dS	C22-R3G- 3dS	SO -R3G- 5dS	C146- R3G- 10dS
Rep 3	C146- R3G-0dS	C22-R3G- 1dS	SO -R3G- 3dS	C146- R3G- 5dS	C22-R3G- 10dS
	SO -R4G- 0dS	SO -R4G- 1dS	C146- R4G- 3dS	C22-R4G- 5dS	C22-R4G- 10dS
	C22-R4G- 0dS	C146- R4G- 1dS	C22-R4G- 3dS	SO -R4G- 5dS	C146- R4G- 10dS
Rep4	C146-R 4G-0dS	C22-R4G- 1dS	SO -R4G- 3dS	C146- R4G- 5dS	SO -R4G- 10dS
	C22-R5G- 0dS	C146-R5G-1dS	C22-R5G-3dS	SO-R5G-5dS	SO- R5G- 10dS
	C146- R5G- 0dS	C22-R5G-1dS	SO-R5G-3dS	C22-R5G- 5dS	C146 -R 5G- 10dS
Rep 5	SO-R 5G- 0dS	SO-R 5G- 1dS	C146-R5G-3dS	C146- R5G- 5dS	C22-R5G- 10dS

SO=Sour Orange, R=Replication, G= Grafted

Non-Grafted Rootstocks

Non Grafted	**0 dS/m**	**1 dS/m**	**3 dS/m**	**5 dS/m**	**10 dS/m**
	C146- R1NG- 0dS	SO -R1NG- 1dS	SO -R1NG- 3dS	C146- R1NG- 5dS	C22-R 1NG- 10dS
	SO -R1NG- 0dS	C22-R1NG- 1dS	C146- R1NG- 3dS	C22-R1NG- 5dS	SO -R1NG- 10dS
Rep 1	C22-R1NG- 0dS	C146-R 1NG- 1dS	C22-R1NG- 3dS	SO -R1NG- 5dS	C146-R 1NG- 10dS
	SO -R2NG- 0dS	SO -R2NG- 1dS	C146- R2NG- 3dS	C22-R2NG- 5dS	C22-R 2NG- 10dS
	C22-R2NG- 0dS	C146-R 2NG- 1dS	C22-R2NG- 3dS	SO -R2NG- 5dS	C146-R 2NG- 10dS
Rep 2	C146- R2NG- 0dS	C22-R2NG- 1dS	SO -R2NG- 3dS	C146- R2NG- 5dS	SO -R2NG- 10dS
	C22-R3NG- 0dS	SO -R3NG- 1dS	C22-R3NG- 3dS	C146- R3NG- 5dS	SO -R3NG- 10dS
	C146-R 3NG- 0dS	C22-R3NG- 1dS	SO -R3NG- 3dS	C22-R3NG- 5dS	C146- R 3NG- 10dS
Rep 3	SO -R3NG- 0dS	C146-R 3NG- 1dS	C146- R3NG- 3dS	SO -R3NG- 5dS	C22-R 3NG- 10dS
	C22-R4NG- 0dS	C146- R4NG- 1dS	C146- R4NG- 3dS	C22-R4NG- 5dS	SO -R4NG- 10dS
	SO -R4NG- 0dS	SO -R4NG- 1dS	C22-R4NG- 3dS	SO -R4NG- 5dS	C146- R 4NG- 10dS
Rep 4	C146- R4NG- 0dS	C22-R4NG- 1dS	SO -R4NG- 3dS	C146- R4NG- 5dS	C22-R 4NG- 10dS
	C22-R5NG-0dS	C146-R5NG-1dS	SO- R5NG-3dS	C22-R5NG- 5dS	SO -R5NG- 10dS
	C146-R5NG-0dS	C22-R5NG-1dS	C22-R5NG-3dS	C146- R5NG- 5dS	C146- R 5NG- 10dS
Rep 5	SO-R5NG-0dS	SO-R5NG-1dS	C146-R5NG-3dS	SO -R5NG- 5dS	C22-R 5NG- 10dS

SO=Sour Orange, R= Replication, NG=Non-grafted

The trees are part of a continuing 6 month study, and the preliminary data will be presented in this report. Salt water solutions are applied bi-weekly at a volume determined by transpiration rate and soil moisture. The soil electrical conductivity (EC) is measured monthly and the soil will be periodically flushed with reverse osmosis water when soil EC is above the treatment levels.

Physiological effects are assessed on an incremental basis. The data presented in this report is incomplete, but salinity effects have been noted and will be discussed later. The evaluations presented in this report are for the following measurements.

- Height (monthly)
- Trunk diameter (pot level on non-grafted and 1.25 in above and below graft and at graft on grafted trees) (monthly)
- Stomatal conductance (monthly)
- Chlorophyll content (SPAD) (monthly)
- Bud growth (as needed)
- Track microclimate conditions in the greenhouse (temperature, humidity, air vapor pressure deficit) (continuously through datalogger)
- Visual observation of tree health and ranking (at 3 stages)
- Chlorophyll fluorescence (monthly)
- Electrolyte leakage (every 2-3 months)

- Leaf relative water content (monthly)

At the end of the project the trees will be harvested and follow up data on root area, length and plant dry weight will be assessed.

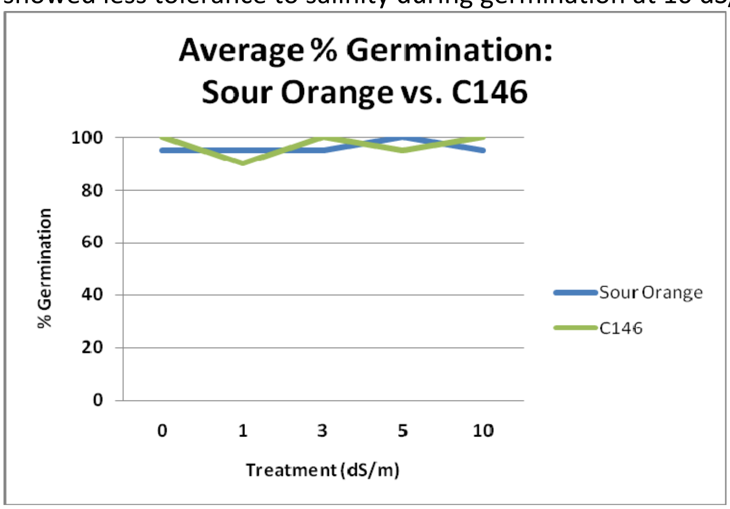
Grafted and non-grafted trees are compared on their visual, physiological and chemical parameters when subjected to salinity treatments. Rootstock varieties were also evaluated on their performance during the course of the treatment to assess which rootstock had better tolerance and overall tree health.

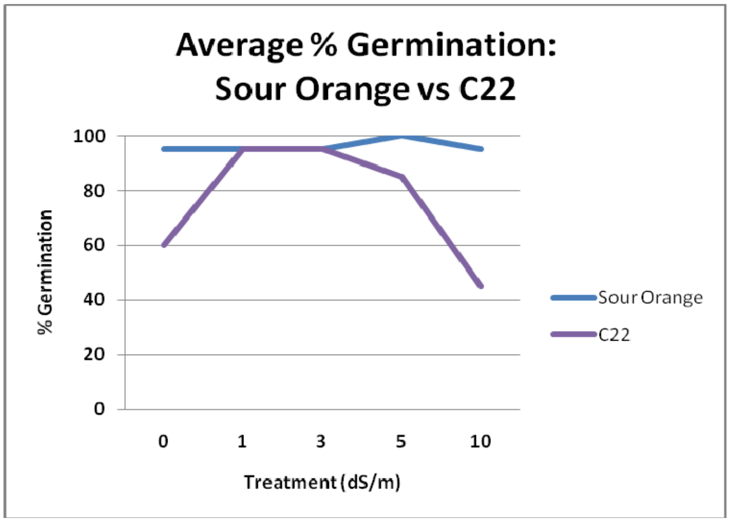
Principal Findings

As this study is still ongoing, findings at this time cannot be implied on a definite basis. However, preliminary findings will be discussed.

Germination

A preliminary study on the salinity tolerance of certain rootstock seeds was used to evaluate which rootstocks should be used for this study. According to this data, Sour Orange and C146 rootstocks tolerated salinity levels up to 10 dS/m without negative impacts on germination. C22 rootstock seeds showed less tolerance to salinity during germination at 10 dS/m levels as shown below.



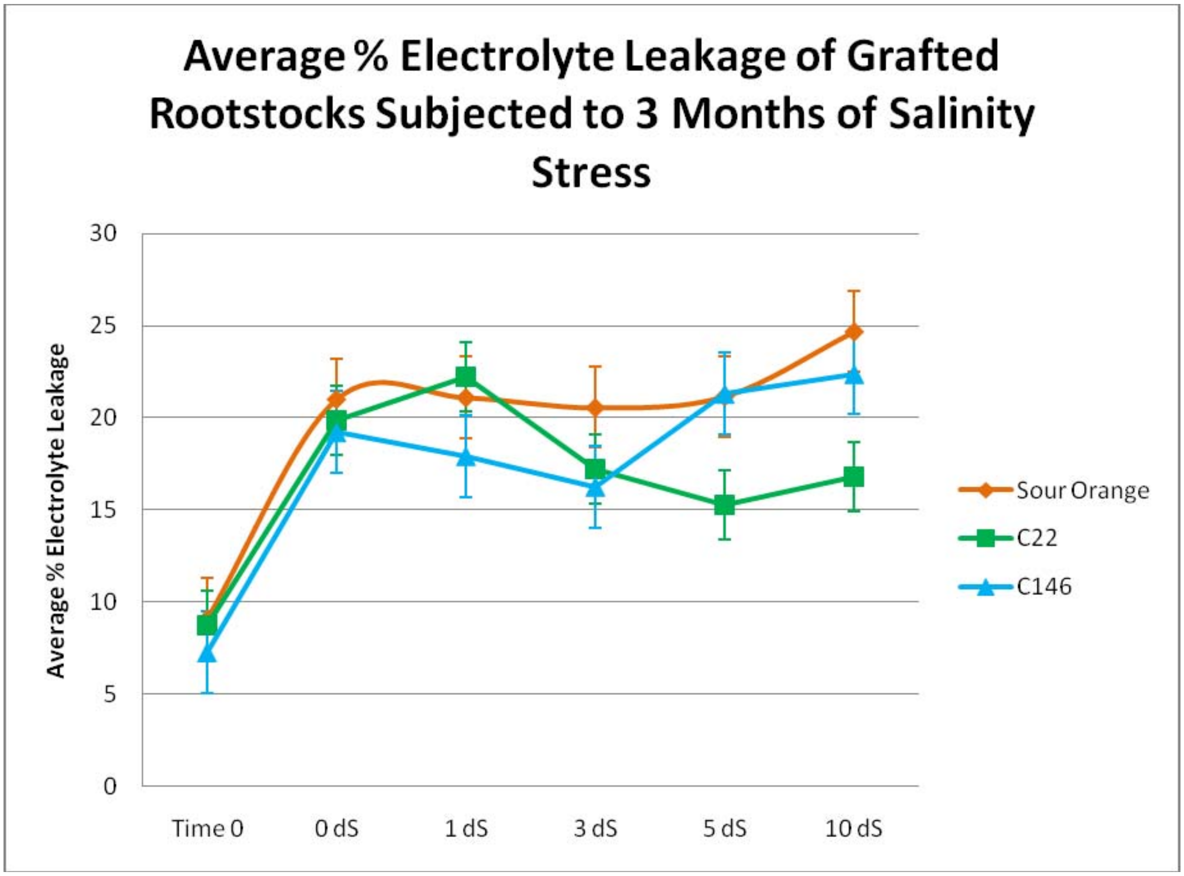


This data implies that germination of C22 seeds will be inhibited when exposed to saline conditions during initiation. From this, we decided to see how grafted and non-grafted plants of these varieties would behave when subjected to salinity in a greenhouse level study once the plants were established.

Electrolyte leakage in established plants

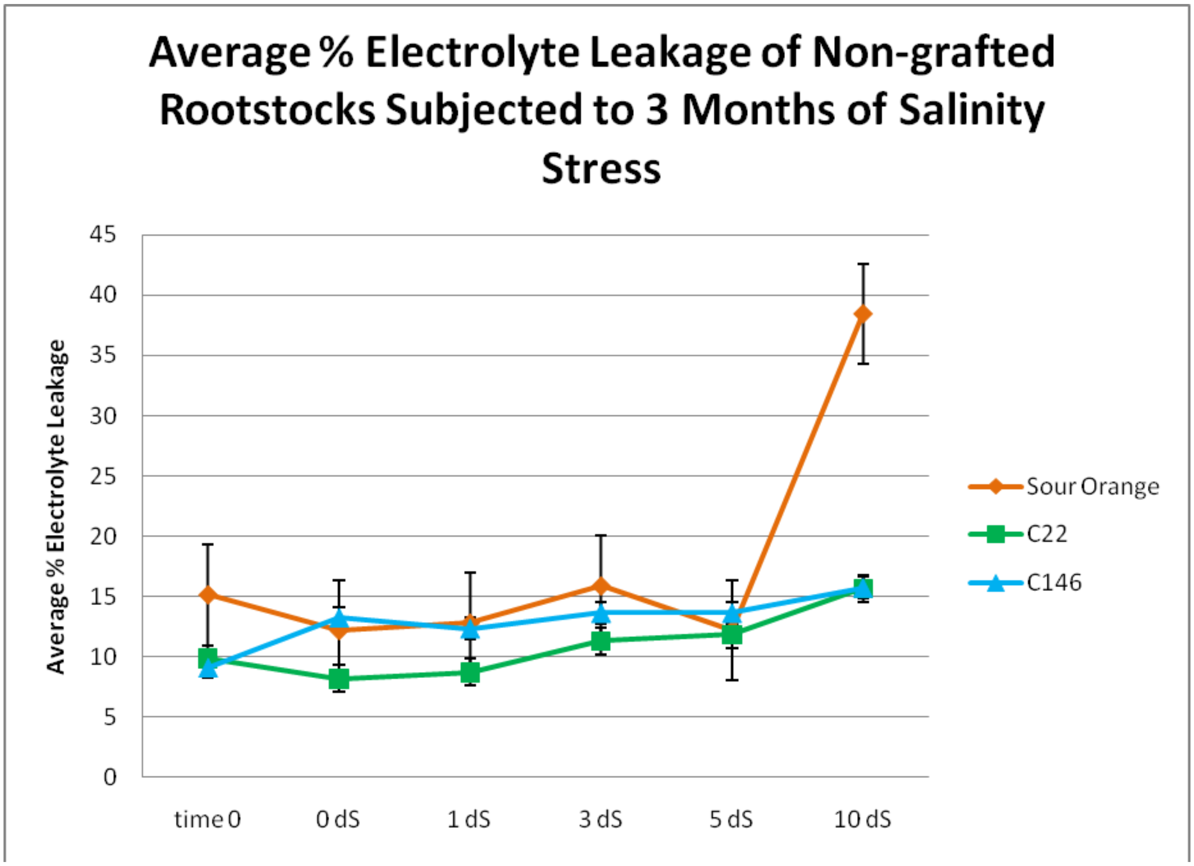
Electrolyte leakage gives a measure of the stability of cell membranes within plant tissues. Stressors cause electrolytes to leak into adjacent tissues of the plant.

Grafted plants show some differences between treatments and rootstocks with Sour Orange having more electrolyte leakage from cells, followed by C146 and C22.



Plants at Time 0 were not subjected to any stressors such as heat or salinity, the measurements were taken at the time the experiment started. These results also indicate that temperatures within the greenhouse may cause stress within the plants as well.

Non-grafted plant data showed some similarities among plants and treatments with the only real negative impact occuring to Sour Orange rootstock at 10 dS/m.



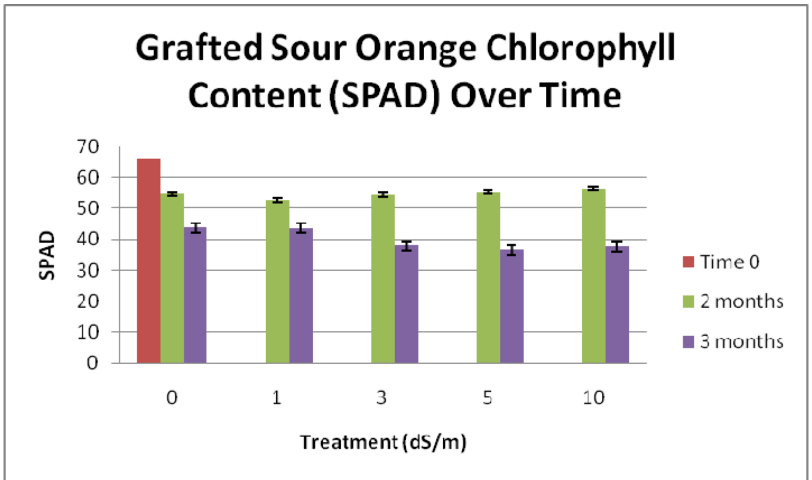
This would indicate that non grafted C22 and C146 rootstocks may be less affected by higher salinity levels while Sour Orange is negatively impacted only at the 10 dS/m level.

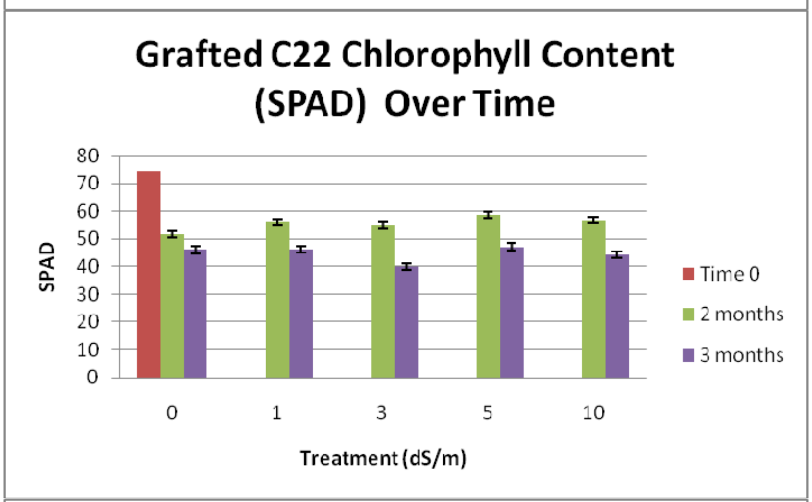
Further research must be conducted to see if new and continued growth is impacted similarly by salinity stress.

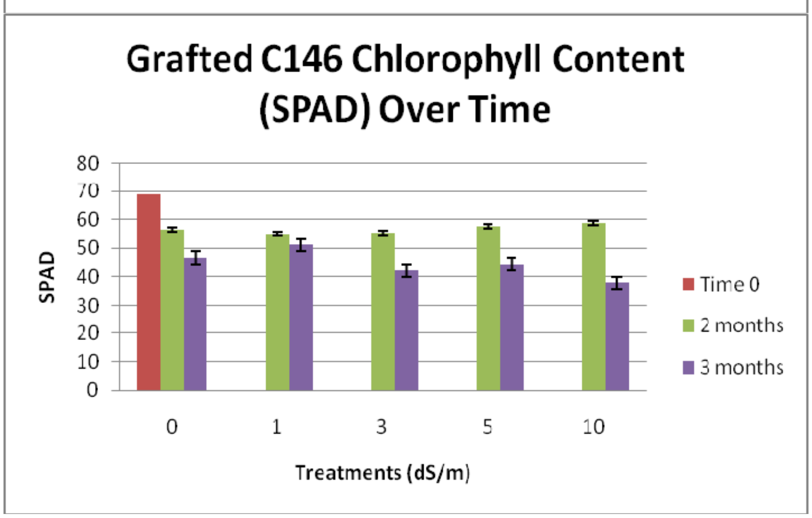
Chlorophyll content in established trees over time

Chlorophyll content measurement by SPAD is an indicator of plant health. As plant health declines, chlorophyll content decreases, usually causing yellowing and necrosis.

Chlorophyll content in grafted trees was measured over 3 months to show the health status of the plant as the study progressed. The following graphs illustrate the chlorophyll decline over time.

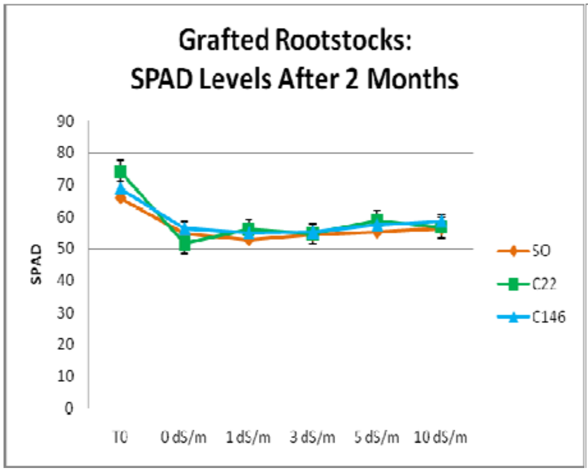


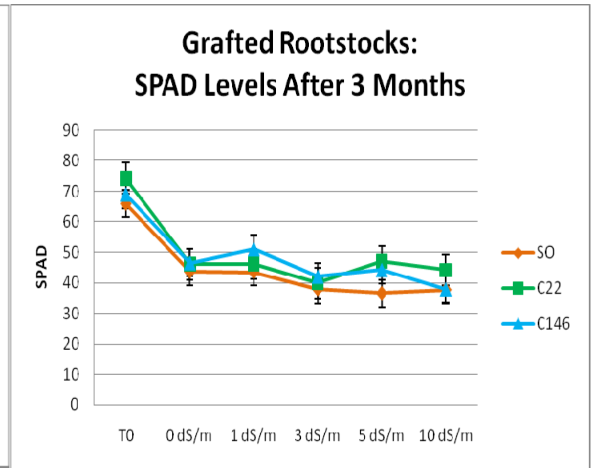




These graphs show that that there seems to be a decline in chlorophyll content in each rootstock variety over time with increased salinity treatments. It also shows that there is a slight decrease in chlorophyll content for all rootstocks over time with no salt treatment.

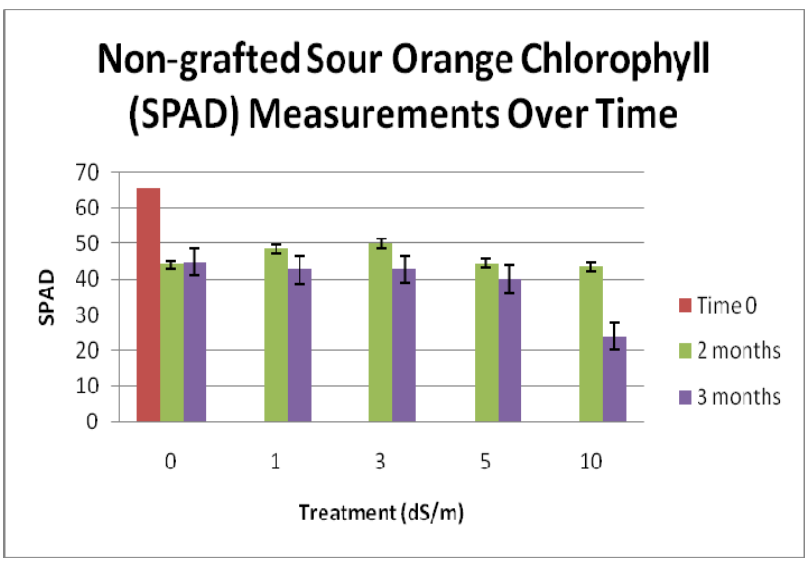
However, when the rootstock varieties are compared to one another, they show a similar trend.

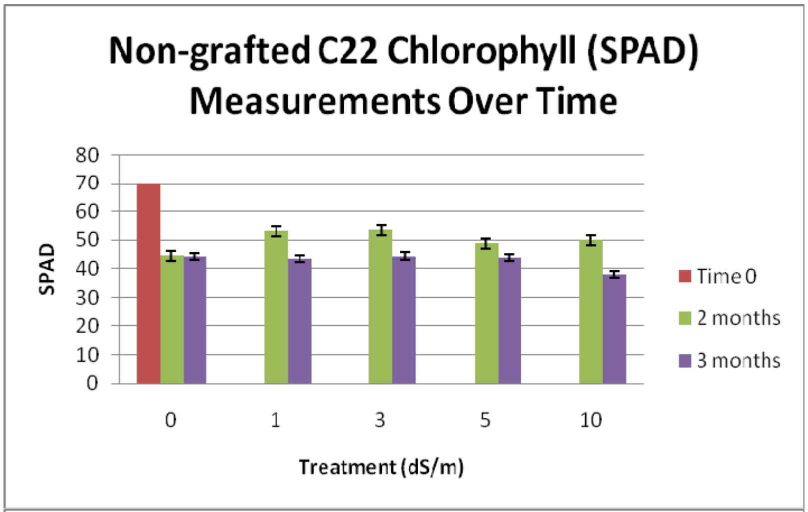


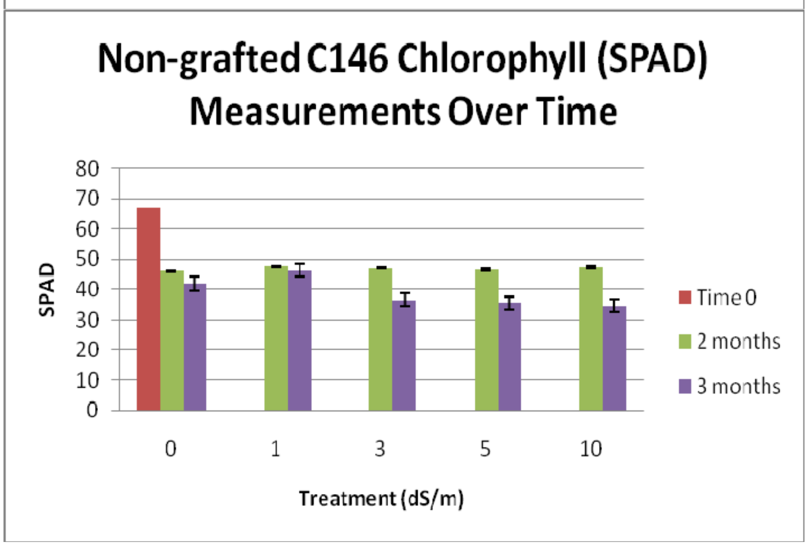


After three months, the chlorophyll content of each grafted roostock variety and each treatment look very similar. However, the total chlorophyll content has declined in each variety over three months. This may change by the culmination of the study. This may indicate that short term salinity applications may have little effect on the chlorophyll content of all of the rootstock varieties shown here.

Chlorophyll content in non-grafted trees was measured over 3 months to show the health status of the plant as the study progressed. The following graphs illustrate the chlorophyll decline over time.

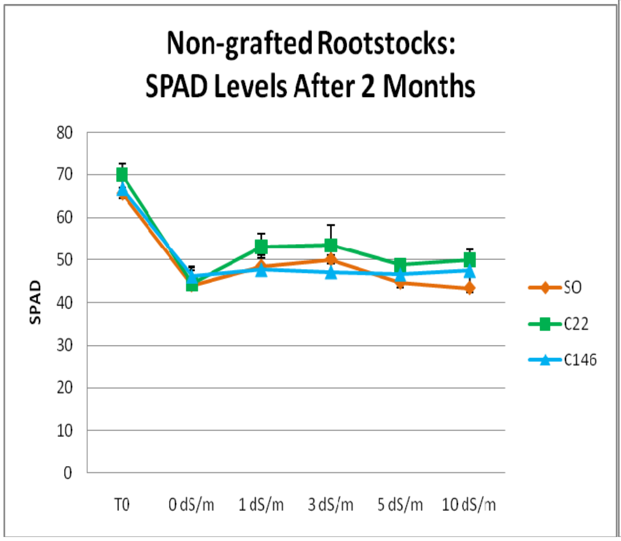


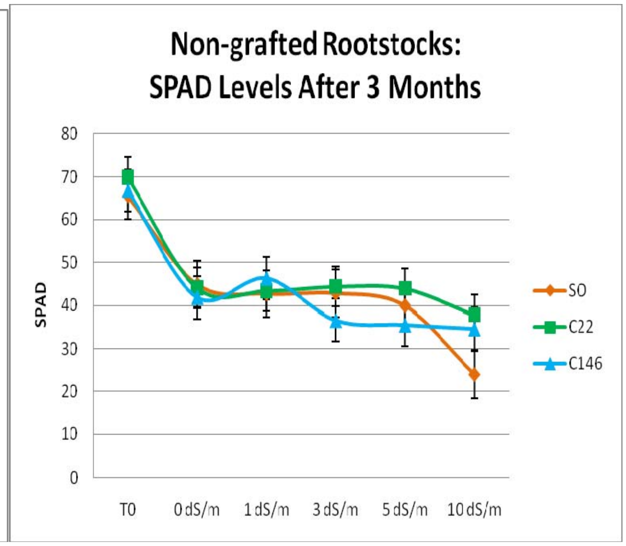




These graphs show that non-grafted Sour Orange rootstocks had the most dramatic decrease in chlorophyll content over time for the 10 dS/m treatment. C22 and C146 rootstocks showed some decline over time and per treatment.

When comparing each rootstock variety, the difference is more clearly illustrated.





After two months of treatment each roostock has a similar chlorophyll content, regardless of treatment. After three months of treatment chlorophyll content decrease is most dramatic in the Sour Orange variety at the 10 dS/m treatment. This indicates that the Sour Orange rootstock may be less suited to highly saline conditions when compared to the C22 and C146 varieties. It also shows that at salinity levels of 3 and 5 dS/m the C22 and Sour Orange varieties may be less affected by salinity stress than the C146 variety. This also may imply that short term salinity application may have little effect on chlorophyll content of each variety of rootstock.

This research will continue to study the impact of salinity on chlorophyll content for rootstocks for a total of 6 months.

These data are not complete and more information will be added by the culmination of the study. Cell membrane stability shows more consistency in non-grafted plants than grafted plants. Grafted plants showed less cell membrane stability (more electrolyte leakage) over the treatment time regardless of salinity application. However this could be due to a variety of reasons, more research must be done to clarify the data. The only non-grafted rootstock that showed less tolerance to high levels of salinity was the Sour Orange variety. From these data we find that by the 3 month stage of the experiment chlorophyll content on non-grafted and grafted rootstocks has been reduced by close to 50% in some treatments. The chlorophyll content did not vary much by treatment with the exception of the Sour Orange rootstock treated with 10 dS/m saline solution. More data must be collected to see if there is a significant difference in chlorophyll content between treatment and rootstock.

Significance

The citrus industry in Texas and throughout the US is changing. The influx of new diseases and insect pests along with increased water demands in a rapidly rising population lead to many new pressures on citrus producers. The future of citrus lies in developing virus free rootstocks, disease resistant varieties, and abiotic stress tolerance.

This research will give data on salinity tolerance of disease resistant rootstock varieties. Preliminary results show that germination of C22 seeds may be inhibited by higher salinity levels in a germination medium, while C146 and Sour Orange are less affected. However, once established, C22 rootstock varieties seem to be more tolerant of highly saline conditions when compared to the widely used Sour Orange rootstock variety. The C22 rootstock variety has been shown to produce superior yield and disease tolerance in a study done by Louzada et al. 2008. If it is found to have a high salinity tolerance it may be a better option when faced with low quality irrigation water or in areas with saline soil. This would expand the areas and conditions in which citrus can be grown in Texas and possibly globally.

References Cited (if needed)

Chowdhury, AH and RE Mace. Geochemical evolution of the groundwater in the gulf coast aquifer of south texas. Texas Water Development Board Report. http://www.igeograf.unam.mx/aih/pdf/T2/T2-19.pdf Last retrieved: December 17, 2009.

Louzada, ES; HS del Rio; M Setamou; JW Watson and DM Swietlik (2008) Evaluation of citrus rootstocks for the high pH, calcareous soils of South Texas. Euphytica 164, 13-18.

Sauls JW (2008) The Texas Citrus Industry. *Agri*Life Extension Publication. http://aggie-horticulture.tamu.edu/citrus/l2286.htm Last retrieved: December 17, 2009.

Sauls JW (2008) Rootstock and Scion Varieties. *Agri*Life Extension Publication. http://aggie-horticulture.tamu.edu/Citrus/cultivars/L2304.htm Last retrieved: December 17, 2009.

PUBLICATION

List all reports, dissertations, publications, etc., published during the reporting period as a result of the project supported by the USGS grant and required matching funds, including base grants. Please follow the following provides guidelines on how to list and format the publications based on publication type.

Simpson, C.R.; S.D. Nelson; S. Cornell; G. Schuster; and M. Setamou. 2011. Evaluation of Salinity on Citrus and Watermelon Rootstock Seed Germination. Oral Presentation. Southern Region of American Society of Horticultural Science meetings. February 5-8, 2011

NOTABLE AWARDS AND ACHIEVEMENTS

Provide a brief description of any especially notable achievements and awards resulting from work supported by section 104 and required matching funds and by supplemental grants during the reporting period.

Simpson, C.R.; S.D. Nelson; S. Cornell; G. Schuster; and M. Setamou. Evaluation of Salinity on Citrus and Watermelon Rootstock Seed Germination. Oral Presentation. Southern Region of American Society of Horticultural Science meetings. February 5-8, 2011 *2nd place Oral PhD competition.*

Received the Gerald O. Mott Meritorious Graduate Student Award in Crop Science, 2011. Awarded May 2011.

Received the 2011Outstanding PhD Student Award for the Department of Agriculture, Agribusiness and Environmental Sciences at Texas A&M University-Kingsville. Awarded April 2011.

Anthropogenic Influence on Tetracycline Resistance in a Rapidly Urbanizing Texas Stream

Basic Information

Title:	Anthropogenic Influence on Tetracycline Resistance in a Rapidly Urbanizing Texas Stream
Project Number:	2010TX359B
Start Date:	3/1/2010
End Date:	2/28/2011
Funding Source:	104B
Congressional District:	17
Research Category:	Water Quality
Focus Category:	Non Point Pollution, Surface Water, Water Quality
Descriptors:	None
Principal Investigators:	Bailey A Sullivan, R Karhikeyan

Publications

There are no publications.

REPORT

Title
Anthropogenic Influence on Tetracycline Resistance in a Rapidly Urbanizing Texas Stream

Project Number
2010TX359B

Primary PI
Bailey Sullivan

Other PIs
R. Karthikeyan

Abstract
The objective of this study was to determine the effects of land use (agricultural and urban), environmental media (streambed sediment and water), and season (spring/summer and fall/winter) on the occurrence of tetracycline resistant bacteria and three commonly found tetracycline resistance genes (tet(O), tet(W), and tet(Q)) in a perennial stream in Texas. Water and streambed samples were collected from the perennial stream at five locations with varying landuses. Heterotrophic bacteria were enumerated on nutrient agar plates containing three different levels of tetracycline (0 mM, 0.03 mM, and 0.06 mM). Statistical analysis using SAS showed tetracycline resistant bacteria were capable of growing at both low and high tetracycline levels from samples collected from all locations regardless of season. Tetracycline resistant bacteria in streambed sediments had higher counts than resistant bacteria in water. Tetracycline resistance genes were detected throughout the year in both sediment and water from all five sampling locations. This indicates that antibiotic resistance is prevalent in this perennial stream and management practices should be implemented to decrease this problem.

Problem and Research Objectives
The ability of antibiotics to prevent disease and death has deteriorated due to the development of antibiotic resistant bacteria species (WHO, 2000 and Car et al., 2008). The development of antibiotic resistance in bacteria is mainly due to two factors: mutations of cellular DNA and acquisition of new resistance genes (Thomas and Nielsen, 2005 and Bennett, 2008). The major cause of antibiotic resistance in aquatic environments is via horizontal gene transfer along with selective pressure from the environment (Baquero et al., 2008 and Zhang et al., 2009). The selective pressure can be due to overuse or misuse of antibiotics in agricultural and human use.

The objective of this study was to determine the effects of land use (agricultural and urban), environmental media (streambed sediment and water), and season (spring/summer and fall/winter) on the occurrence of tetracycline resistant bacteria and three tetracycline resistance genes (tet(O), tet(W), and tet(Q)) in a perennial stream in Texas. These three genes were chosen because they have only recently been found in natural water environments and can be correlated with microbial communities of sewage treatments, hospital wastewater, and animal production wastewater (Chopra and Roberts, 2001, Zhang et al., 2009, and McKinney et al., 2010).

Materials/Methodology

Study Area

Carters Creek (Texas Commission of Environmental Quality (TCEQ) Segment ID: 1209C) watershed, a sub-watershed of Navasota River Basin (HUC #12070103), is located in Brazos County in East Central Texas. It covers about 146 square kilometers running through the Southern Post Oak Savanna ecoregion. The 27 kilometers long perennial stream passes through landuse that is heavily urbanized in the upper reach of the watershed where it originates in Bryan/College Station, and becomes more rural in the lower reach.. Average annual rainfall in the watershed is 165 mm and average winter and summer temperature is 15°C and 24°C. The average respective stream flow during summer and winter is 115 L/d.

Sampling Protocol

Water and sediment samples were collected at five sampling locations along Carters Creek. The five sampling locations are differentiated by landuse shown in Figure 1. Samples were collected five times during the spring/summer season (between March and August) and five times during the fall/winter season (between September and February). Approximately 200 mL of water was collected using sterile Whirlpak® bags. Samples from the water column were collected from below the surface of the water by manually dipping the sample bag into the creek. Approximately 100 g of the upper sediments (about 5 cm) were collected using a shovel and stored in Whirlpak® bags. The samples were stored in coolers with Blueice® (at 5°C) and transported to laboratory. Fifty grams of the sediment samples were stored at -80°C for molecular analysis. One hundred milliliters of water samples were filtered on 0.45 µm filters then stored at -80°C for molecular analysis. The remaining water and sediment samples were processed within 8 h for viable culturing.

Culture Based Methods: Enumerating Antibiotic Resistant Bacteria

Tenfold serial dilutions were prepared with 10^{-1} dilution defined as one g of sediment sample diluted in 9 mL of sterilized water or 1 mL of water sample in 9 mL sterilized water. The diluted samples were spread plated onto 100 × 10 mm culture plates containing nutrient agar (Difco©, MD) and different levels of tetracycline hydrochloride (Calbi Chem, CA) (0 mM, 0.03 mM, and 0.06 mM . Studies have shown tetracyclines are lethal to 70% of bacteria from sandy soils at a concentration of 10 mg/L (Sarmah et al., 2006). These high concentrations will ensure that the cultural bacteria evaluated are truly resistant. The plates were incubated at 35°C for 48 h to ensure the inclusion of slow-growing heterotrophic bacteria, and shielded from light to prevent photodegradation of tetracycline.

Molecular Methods: Amplifying ARGs

DNA extraction

Genomic DNA was extracted from one gram sediment from each sampling location using MoBio© Ultra clean Soil DNA extraction kit (MoBio, CA) according to the manufacturer's protocol. Genomic DNA from the water samples was extracted from the filters using the MoBio© Ultra Clean Water DNA kit according to the manufacturer's protocol.

Qualitative PCR
A qualitative PCR assay was performed in order to determine which of the three tetracycline ARGs were present at each sampling location. Forward and Reverse primers described by Aminov et al. (2001) were used. Promega© PCR Master Mix (Promega, WI) which included buffer, dNTPs, and Taq DNA polymerase were used for the PCR. The temperature program consisted of initial denaturing at 95°C followed by 30 cycles of 15s at 95°C, 30s at the annealing temperature (*tet*(O) 60°C, *tet*(W) 64°C, *tet*(Q) 63°C, and 16S RNA 50°C), and a final extension of 7 min at 72°C. The PCR product was then separated by gel electrophoresis using 1% agarose at 5 V/cm. The gel was documented using Photodine® gel documentation station. Presence of a band was considered to confirm the presence of a targeted gene. If a band was not detected, the sample was spiked with a positive control for the gene and underwent a new PCR reaction under the previous conditions to determine if PCR inhibitors were present.

Statistical Analysis
Statistical Analysis was performed using SAS 9.2(SAS Institute Inc., Cary, NC). Significance of the data was defined as p-values ≤ 0.05. One-way ANOVA (Proc GLM) was used to generate population means, standard deviation, 95% confidence intervals (CI), and significant difference. The least significant difference (LSD) test within Proc GLM was also used for comparison of population means for categorizing significant groups

Principal Findings
Tetracycline resistant bacteria were capable of growing under all conditions year around indicating the occurrence and prevalence of antibiotic resistance in this study area. This finding was further supported by the presence of tetracycline resistant genes at all sampling locations in both sediment and water regardless of season. It was also observed that samples taken from streambed sediments had significantly higher resistant bacteria counts than water samples. Streambed sediments may promote the maintenance of resistant bacteria populations better than water and could be a potential reservoir of ARGs. There was no seasonal variability on the bacteria counts. There was no spatial variability for tetracycline resistant bacteria, and inputs from wastewater treatment facilities did not influence the tetracycline resistant bacteria counts. The rapidly urbanizing watershed used in this study may have prevented significant changes in landuse creating a more uniformed watershed and explains the lack of significant differences between sights.

Significance
Results from this research indicate that tetracycline resistant bacteria are prevalent in this watershed. Further research is being conducted to characterize the resistance in this watershed to determine if the resistance is a potential health concern.

References Cited
Aminov, R.I., Garrigues-Jeanjean, N., and Mackie, R.I. 2001. Molecular ecology of tetracycline resistance: Development and validation of primers for detection of tetracycline resistance genes encoding ribosomal protection protein. Appl. Environ. Microbiol. 67 (1), 22-32.
Baquero, F., Martinez, J., and Canton, R. 2008. Antibiotics and antibiotic resistance in water environments. Curr. Opin. Biotechnol. 19(3), 260-265.

Bennet, P.M. 2008. Plasmid encoded antibiotic resistance: acquisition and transfer of antibiotic resistance genes in bacteria. Brr J. Pharmacol. 152, S347-S357.

Car, O., Högberg, L.D, Murray, M., Nordberg, O., Sivaraman, S., Lundborg, C.S., Do, A.D., and Tomson, G. 2008. Meeting the challenge of antibiotic resistance. BMJ. 337 (a1438), 726-728.

Chopra, I.and Roberts, M. 2001. Tetracycline antibiotics: Mode of action, applications, molecular biology, and epidemiology of bacterial resistance. Microbiol. Mol. Biol. Rev. 65 (2) 232-260.

McKinney, C.W., Loftin, K.A., Meyer, M.T., Davis, J.G., and Pruden, A. 2010. *Tet* and *sul* Antibiotic Resistance Genes in Livestock Lagoons of Various Operation Type, Configuration, and Antibiotic Occurrence. Environ. Sci. Technol. In Press.

Sarmah, A.K., Meyer, M.T., and Boxall, A.B.A. 2006. A global perspective on the use, sales, exposure pathways, occurrence, fate and effects of veterinary antibiotics (Vas) in the environment. Chemosphere. 65, 725-759.

Thomas, C.M. and Nielsen, K.M. 2005. Mechanisms of, and barriers to, horizontal gene transfer between bacteria. Nat. Rev. Micro. 9(3), 711-721.

World Health Organization (WHO). 2000. WHO Annual Report on Infectious Disease: Overcoming Antimicrobial Resistance; World Health Organization: Geneva, Switzerland. Available at: http://www.who.int/infectious-disease-report/2000/. Accessed 29 Nov 29 2008.

Zhang, X., Zhang, T., and Fang, H.H. 2009. Antibiotic resistance genes in water environment. Appl. Microbiol. Biotechnol. 82(3), 397-414

PUBLICATION

No reports were published during the reporting period.

NOTABLE AWARDS AND ACHIEVEMENTS

No awards were received during the reporting period.

The Effect of Photovoltaic Nanomaterial Roofing on Harvested Rainwater Quality

Basic Information

Title:	The Effect of Photovoltaic Nanomaterial Roofing on Harvested Rainwater Quality
Project Number:	2010TX360B
Start Date:	3/1/2010
End Date:	2/28/2011
Funding Source:	104B
Congressional District:	21
Research Category:	Engineering
Focus Category:	Conservation, Water Quality, Water Supply
Descriptors:	None
Principal Investigators:	Qiao Gao, Mary Jo Kirisits

Publications

There are no publications.

The Effect of Photovoltaic Nanomaterial Roofing on Harvested Rainwater Quality

Project Number: USGS 104b Research Grant

Principal Investigator: Qiao (Amy) Gao, M.S.E. Student, Department of Civil, Architectural and Environmental Engineering, The University of Texas at Austin, 1 University Station C1786, Austin, TX 78712. E-mail: qgao@mail.utexas.edu Phone: 917.216.9135

Co-Principal Investigator: Mary Jo Kirisits, Assistant Professor, Department of Civil, Architectural and Environmental Engineering, The University of Texas at Austin, 1 University Station C1786, Austin, TX 78712. E-mail: kirisits@mail.utexas.edu. Phone: 512.232.7120

Abstract

The global freshwater and energy crisis have prompted worldwide investments in rainwater harvesting and solar energy systems. As the implementation of these two systems develops concurrently, they can easily become integrated into one rooftop structure. Photovoltaic systems have the potential to leach heavy metals and other toxins from newly installed, broken or aged modules. Since the type of roofing material used for rainwater harvesting has been shown by several studies to affect the quality of the harvested rainwater, the use of solar panels on rooftops as catchment systems may pose a health risk to consumers. Hazardous materials leached from solar panels can alter the water quality of the harvested rainwater. This paper presents a laboratory-scale investigation of the effect of new and aged photovoltaic surfaces on the quality of harvested rainwater and will assess if solar panel systems can become significant sources of contamination in harvested rainwater.

Background and Problem Statement

As the human demand for drinking grows, global freshwater resources are diminishing. The World Bank estimates that the worldwide demand for water is doubling every 21 years. In fact, by 2050, the United Nations predicts that more than 2 billion people will live in water scarce areas (Glenn, 2006). In the state of Texas, extraction of groundwater has been increasing for the last 65 years, as a result of economic and population growth, and will continue to grow until the year 2050 when these groundwater resources will dry up (Loáiciga et al., 2000). The water shortage crisis has triggered many regions in the United States, including Texas, to begin investing in rooftop rainwater harvesting systems to supplement these dwindling freshwater resources. Furthermore, the global water crisis is amplified by current fossil fuel and nuclear energy systems, motivating the need to for renewable energy technologies that do not consume as much water

The depletion of non-renewable sources of energy, like coal, oil and natural gas, and climate change brought on the global energy crisis, which prompted the investment in renewable energy resources, like solar energy. Solar energy technologies offer many environmental benefits, such as reduction of greenhouse gas emissions and reclamation of degraded land that can be used for solar harvesting (Tsoutsos et al., 2005). Solar energy technologies also provide many socioeconomic benefits, including regional energy independency, creation of jobs, diversification of the energy supply, and energy in developing countries (Tsoutsos et al., 2005). However, there are also many negative environmental and health impacts of solar energy technologies.

Health hazards can be associated with the manufacturing of photovoltaic cells. Humans can be exposed to hazardous substances, such as toxic and explosive gases, corrosive liquids and carcinogenic compounds, used in the manufacturing process (Fthenakis and Moskowitz, 2000). Humans can be exposed to these toxic materials via inhalation, ingestion, or absorption through the skin (Moskowitz, 1995). These chemicals can be released from the leaching or combustion of modules (EPRI, 2003). Furthermore, indirect human exposure is also possible through contamination of the environment, such as air, drinking water sources, and biota (Fthenakis and Moskowitz, 2000).

Installed rooftop photovoltaic systems can also present human and environmental risks. Toxic chemicals, mainly heavy metals, such as cadmium and selenium, can leach from broken, weathered and/or aged modules that are still in service or after disposal (EPRI, 2003). United States Environmental Protection Agency (USEPA) Toxicity Characteristic Leaching Procedure (TCLP) is used to test the leaching from solar panels. Current-generation Cadmium telluride (CdTe), copper indium diselenide (CIS), and amorphous silicon thin-film solar panels pass the TCLP test (Cummingham, 1998). However, these leaching tests are tested only on new solar panels, but little work has been carried out on the leaching from broken, weathered and/or aged solar panels, and leaching data are not available for other types of photovoltaic modules.

Accidental rooftop fires or combustion of expended solar panels at municipal solid waste incinerators can produce toxic fumes, affecting nearby populations and environments (Moskowitz, 1995). Furthermore, spent solar modules disposed of at landfills can become a source of contamination in local soil environments, groundwaters, and surface waters (EPRI, 2003). To our knowledge, little research has been carried out on the leaching of heavy metals and other toxic compounds from spent solar panels at landfills.

Toxic chemicals from the manufacturing, usage, and disposal of solar energy technologies can also affect the biota in the local environments. The National Institute of Environmental Health Studies (NIEHS) revealed that the systemic and reproductive systems in rats were affected through direct ingestion of maximum tolerable doses of toxic compounds from solar panels; and the pulmonary system was affected through the inhalation of these compounds (EPRI, 2003). There exists a need for a balance between higher efficiency of solar panels and lower environmental impacts. Understanding the environmental impacts of these solar modules will motivate the development of more environment-friendly materials with similar or even higher energy performance.

Since rooftop rainwater harvesting can be incorporated with a solar energy capture system to alleviate both the water and energy crisis, there exists a need for the evaluation of water quality runoff from installed solar panels. Photovoltaic technologies are becoming more affordable for residential usage. The environmental and health impacts of rising installations of solar panels at the household level coupled with the installation of rooftop rainwater harvesting systems to combat regional water shortages need to be studied.

Research Objective

Chang et al. (2004) found that the type of roofing material used for rainwater harvesting affects the quality of the harvested rainwater. Toxic compounds, such as heavy metals, may leach from broken solar panels (EPRI, 2003). An integrated solar energy and rainwater harvesting system can result in changes in the water quality of the harvested rainwater (i.e., pH, concentration of metals, total suspended solids (TSS)), and their presence in the harvested rainwater can also pose a threat to human health. Exposure to heavy metals, such as cadmium, leached from solar panels has been found to disrupt the respiratory system in rats, mice, monkeys, rabbits and hamsters (Fthenakis et al., 1999). Therefore, consumption of rainwater harvested from a photovoltaic rooftop might pose a human health risk. To our knowledge, no one has studied the impact of a photovoltaic rooftop on harvested rainwater quality. Therefore, the objective of this study is to understand how the use of photovoltaic panels as the catchment surface impacts the quality of the harvested rainwater. This objective will be addressed through the use of laboratory-scale solar panel roofs.

Materials and Methodology

This research project focuses on runoff from photovoltaic cells, which have the potential to contaminate rainwater in the rooftop collection system by changing the water quality and leaching heavy metals into the captured rainwater. A lab-scale roof system is used in these studies. The lab-scale roof system (Figure 1) consists of a 4” by 4” solar panel roof coupon set up on a stand angled at 18.4 degrees, which is typical of most rooftops.

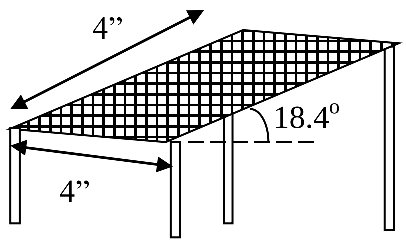


Figure 1: Lab-scale roof

Synthetic rainwater (Table 1) was synthesized for these experiments. The synthetic rainwater consisted of typical concentrations of anions and cations found in rainwater. The solution was adjusted to a typical rainwater pH of 6.5, using sodium hydroxide. The rainwater formula was adapted from Jones and Edwards (1993).

Table 1: Synthetic rainwater formula

Chemical	*Concentration (µmol/L)*	*Concentration (g/L)*
NaCl	96	5.61
K_2SO_4	10	1.74
$CaCl_2$	5	0.555
$MgCl_2$	6	0.571
NH_4NO_3	15	1.20
KH_2PO_4	0.1	0.0136

1.5L of synthetic rainwater was pumped at 13 mL/min through 23 syringes, and re-circulated for a period of 24 hours to stimulate a 10-year storm event (Figure 2).


(a) (b) (c)

Figure 2: (a) Lab-scaled rainwater runoff stimulator with peristaltic pump. (b) Roof coupon set-up. (c) 23 syringes through which synthetic rainwater dripped to stimulate rain event

After the 24-hour re-circulation of the synthetic rainwater, the runoff from the solar panels was analyzed for several water quality indicators: pH, total suspended solids, turbidity, selected metals, nitrite, and nitrate (Standard Methods, 2005). Metals concentrations were determined using Inductively Coupled Plasma/Mass Spectrometry

(ICP/MS). All of these measurements, except for the metals analysis, were performed in the Environmental and Water Resources Engineering laboratories at the University of Texas at Austin. Duplicate experiments were performed on the photovoltaic panel, and each water quality indicator was measured in triplicate.

These experiments were carried using amorphous silicon thin-film/flexible solar panels. These 3.7” by 5.9”4.8V 100mA flexible solar panels (SolMaxx-Flex-4_8V100mA) were purchased from Silicon Solar Inc., Centennial, CO (Figure 3). These flexible solar panels were chosen for the experiments because they are becoming increasingly popular among residential households due to lower manufacturing costs and ease of installation. These solar cells are produced by depositing a thin film of silicon on a durable, paper-thin flexible polymer substrate. For extended outdoor use, the solar panels have aluminum frames to protect the edges.

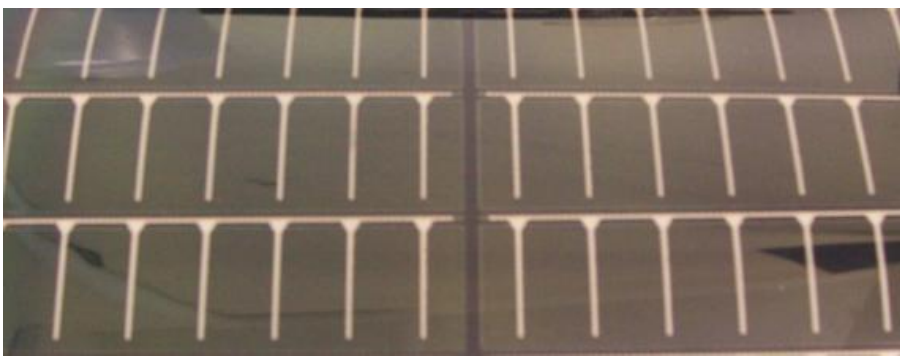


Figure 3: Amorphous silicon thin-film/flexible solar panel purchased from Silicon Solar Inc., Centennial, CO

Water quality was first measured from new thin film solar panels, and then measured after undergoing an accelerated aging/weathering process. To investigate how weathering and damaging of silicon solar cells impact the runoff water quality, accelerated aging of the thin film cells was carried out through two processes: ultraviolet (UV) treatment and heat treatment. Dry heat at 85^{o}C 1000 hours is equivalent to 20 years of weathering (Otth and Ross, 1983).

Equivalent outdoor UV exposure can be calculated as

$$Eq\,Yrs\;of UV Exp = \frac{Irradiance\;\; \frac{W}{m^2}\;\; \times Exposure\,Time\;\; s}{Annual\,UV\,Dosage\;\; \frac{J}{m^2}}$$

where average annual UV dosage is about 330MJ/m^2/year; average daily irradiance for hot and dry climates is 0.9131MJ/m^2/day, hot and humid climates is 0.7666MJ/m^2/day, and cool and mild climates is 0.9117MJ/m^2/day (Kennedy and Terwilliger, 2005). Furthermore, according to American Society of Testing Materials (ASTM) Standard G15, used for accelerated weathering of materials, a maximum of 2000MJ/m^2 for wavelengths under 400 nm is equal to 6 years of outdoor exposure.

After accelerating aging/weathering, these solar panels will be tested again to see how aging affects the water quality of harvested rainwater. These results have not been finalized and will not be presented in this report. Future experiments planned for this research also include actual outdoor exposure or weathering of the solar panels over a period of a period of months or years.

Principal Findings

Water quality of the harvested synthetic rainwater from new amorphous silicon thin-film/flexible solar panels and USEPA drinking water standards are summarized in Table 2.

Table 2: Water quality of harvested synthetic rainwater from new Si thin film cell compared to USEPA drinking water standards

	Synthetic Rainwater	***New Si Thin-Film/Flexible Cell***	***USEPA Drinking Water Standards***
pH	6.53	5.16	6.5 - 8.5
Turbidity (NTU)	0	1.5	<1
TSS (mg/L)	0	1.07	5*
Nitrate (mg-N/L)	Above Detection Limit of 30mg/L	25.15	10
Nitrite (mg-N/L)	5.75×10^{-2}	1.307×10^{-2}	1

*USEPA non-potable urban water reuse guideline

These results indicate water quality measurements for the harvested rainwater did not exceed USEPA drinking water standards except for turbidity and nitrate. However, nitrate and nitrite concentrations found from the harvested rainwater are most likely from the synthetic rainwater. Furthermore, these results do not account for a first-flush system, which diverts an initial surface runoff that is not collected for usage. Mendez et al. (2011) found that after the first-flush, the harvested rainwater met the USEPA MCL for nitrate. Therefore, in a real system, high concentrations of nitrate may be avoided by using a first-flush system.

The pH is lowered from 6.53 to 5.16, indicating that compounds, such as metals, which generally lower the pH, may have leached from the solar panel into the harvested rainwater. Nonetheless, it is important to note there that the USEPA drinking water standards are only used here as a basis of comparison, however, rainwater consumers do not have to meet these regulations depending on the end use of the rainwater.

Turbidity exceeded the USEPA drinking water standard for filtration systems; however the samples did not exceed USEPA non-potable urban water reuse guidelines, which states that the average turbidity over a 24 hour period should be less than or equal to 2 NTU and turbidity should not exceed 5 NTU at any time. These results indicate that proper treatment, such as filtration, is needed for this harvested rainwater from a newly installed thin film solar panel to be used as a potable water resource.

Table 3 presents the metals leached from the new amorphous silicon thin-film/flexible solar panel after this 24 hour re-circulation of rainwater. The metal concentrations found in the rainwater harvested from flexible solar panels were obtained by subtracting the measured concentrations in these samples with the baseline concentrations from the synthetic rainwater. These results are compared to available USEPA drinking water maximum contaminant levels (MCL) of certain metals.

Table 3: Metals leached into synthetic rainwater from new Si thin film cell compared to USEPA drinking water MCL

Metal	Concentration in Synthetic Rainwater (mg/L)	Concentration found in Rainwater Harvested from Thin-Film/Flexible Solar Panel (mg/L)	USEPA Drinking Water MCL (mg/L)
Chromium (Cr)	0	0.001	0.1
Aluminum (Al)	0.00033	0.014	0.05 to 0.2*
Manganese (Mn)	0.00042	0.0029	0.05*
Iron (Fe)	0.00013	0.03	0.3*
Copper (Cu)	0.00017	0.15	1.3
Zinc (Zn)	0.0016	0.056	5.0
Arsenic (As)	0.0000028	0.00013	0.01
Selenium (Se)	0.0000029	0.00025	0.05
Silver (Ag)	0.000046	0.0056	0.10*
Cadmium (Cd)	0.0000013	0.0003	0.0005
Antimony (Sb)	0.000014	0.00037	0.006

Barium (Ba)	0.000025	0.0042	2.0
Thallium (Tl)	0	0.000052	0.002
Lead (Pb)	0.00010	0.029	0.015
Uranium (U)	$2.3x10^{-8}$	0.0000036	0.03

*USEPA secondary drinking water standards

These results indicate that the majority of the metals that leached from the newly installed thin film solar panel did not exceed USEPA drinking water MCLs. However, lead did exceed the USEPA MCL. Potential health risks of lead in drinking water are delays in physical or mental development in infants and children, and kidney problems and high blood pressure in adults. Moreover, unlike the other metals, which are orders of magnitude less than their corresponding MCL, cadmium is present at 0.0003mg/L, which is close to the MCL of 0.0005mg/L. Therefore, cadmium, a heavy metal that causes kidney damage, should be closely monitored in subsequent experiments.

The re-circulation system of rainwater used for these experiments does not necessarily represent a real rainstorm. This lab-scale set-up only allows us to understand what water quality parameters might be affected by solar panels, but does not necessarily provide accurate concentrations of leached contaminants into rainwater. The impacts on these water quality indicators will need to be studied in more detail under more realistic conditions. It is also important to note that these results are from a newly installed solar panel. Higher concentrations of leached metals may occur as the solar panel is weathered and ages with time. The solar panels currently are in the aging process using heat treatment, and results are pending.

Table 4 presents the metals leached from the new amorphous silicon thin-film/flexible solar panel after this 24 hour re-circulation of rainwater. These results are compared to available recommended metal limits found in USEPA water reuse guidelines for non-potable uses.

Table 4: Metals leached into synthetic rainwater from new Si thin film cell compared to USEPA water reuse guidelines for non-potable uses

		USEPA Water Reuse Limits	
Metal	***Thin Film (mg/L)***	***Long-Term Use (mg/L)***	***Short-Term Use (mg/L)***
Aluminum (Al)	0.014	5.0	20
Arsenic (As)	0.00013	0.10	2.0
Boron (B)	0.14	0.75	2.0
Cadmium (Cd)	0.00030	0.01	0.05
Cobalt (Co)	0.0018	0.05	5.0
Chromium (Cr)	0.0010	0.10	1.0
Copper (Cu)	0.15	0.20	5.0
Iron (Fe)	0.030	5.0	20
Manganese (Mn)	0.0029	0.20	10
Molybdenum (Mo)	0.0019	0.01	0.05
Nickel (Ni)	0.016	0.20	2.0
Lead (Pb)	0.029	5.0	10
Selenium (Se)	0.00025	0.02	0.02
Vanadium (V)	0.00018	0.10	1.00
Zinc (Zn)	0.056	2.00	10.00

These results show that none of the metals that leached from the newly installed thin film solar panel exceeded USEPA recommended limits for non-potable water reuse, in either cases of long-term or short-term usage. Therefore, rainwater can be harvested from solar panels for non-potable uses, such as irrigation. However, once again, it is important to note here that these results are obtained from a newly installed solar panel. Higher concentrations of leached metals may occur as the solar panel is weathered and ages with time. Figure 4 shows a flexible solar panel that underwent about 3 weeks of accelerated heat treatment, which is equivalent to approximately 10 years of weathering in dry climate. The polymer packaging appears to be deteriorated.

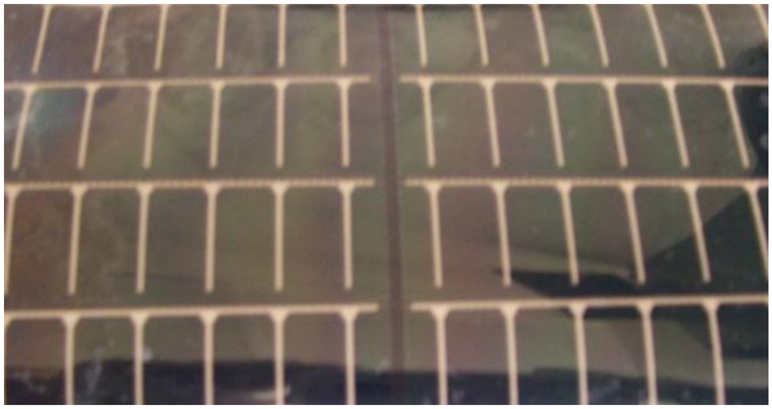


Figure 4: Accelerated weathered/aged amorphous silicon thin-film/flexible solar panel after 3 weeks of heat treatment

Results from these aged solar panel studies have not been finalized and will not be presented in this report. Our hypothesis is these metal concentrations will increase as more metals can be potential leached off the solar panels, as the protective covering of the thin-film begins to deteriorate with age.

Significance

The significance of this project is solar panels installed on rooftops can become a source of metal contaminants for rainwater harvesting systems installed in the same residential household. Results indicate that harvested rainwater from a newly installed amorphous silicon thin film solar panel suggest that the concentrations of cadmium and lead might be elevated for potable uses. Nonetheless, these water quality indicators of harvested rainwater from a solar panel may change as the solar panel undergoes weathering and aging. Further work is needed to fully understand how solar panels can impact the water quality of harvested rainwater from rooftops.

Acknowledgements

I would like to thank Olivia Beck, Tara Gloyna, and Sarah Keithley for their help on this project.

References Cited

Chang, M., MW McBroom, and R. Scott Beasley. 2004. *Roofing as a source of nonpoint water pollution*. Journal of Environmental Management. 73(4): 307-315.

Cunningham, D., 1998. *Leaching Tests using CdTe Modules*. Presented at the BNL/NREL Workshop "Photovoltaics and the Environment 1998", Keystone, CO, July 23-24.

EPRI and California Energy Commission. 2003. *Potential Health and Environmental Impacts Associated with the Manufacture and Use of Photovoltaic Cells*, 1000095.

Fthenakis, V.M. and P.D. Moskowitz, 2000. *Photovoltaics: Environmental Health and Safety Issues and Perspectives*. Progress in Photovoltaics: Research and Applications, 8: 27-38.

Fthenakis, V.M., S.C. Morris, P.D. Moskowitz, and D.L. Morgan, 1999. *Toxicity of Cadmium Telluride, Copper Indium Diselenide, and Copper Gallium Diselenide*. Progress in Photovoltaics: Research and Applications, 7: 489-497.

Glenn, J.C. and T.J. Gordon. 2006. *Millennium Project State of the Future Report.*

Jones, D.L. and A.C. Edwards. 1993. *Evaluation of polysulfone hollow fibers and ceramic suction samplers as devices for the in-situ extraction of soil solution*. Plant Soil, 150: 157–165.

Kennedy, C.E. and K. Terwilliger. 2005. *Optical durability of candidate solar reflectors*. Journal of Solar Energy Engineering, 127(2): 262–269.

Loáiciga, H., D.R. Maidment, and J.B. Valdes. 2000. *Climate-change impacts in a regional karst aquifer, Texas, USA.* Journal of Hydrology, 227(1-4): 173-194.

Mendez, C.B., J.B. Klenzendorf, B.R. Afshara, M.T. Simmons, M.E. Barrett, K.A. Kinney, and M.J. Kirisits. 2011. *The effect of roofing material on the quality of harvested rainwater*. Water Research, 45(5): 2049-2059.

Moskowitz, P.D., 1995. *An Overview of Environmental, Health and Safety Issues in the Photovoltaic Industry*. Chapter Eighteen in Solar Cells and Their Applications, John Wiley & Sons, Inc., New York, NY.

Otth, D. H. and R. G. Ross. *Assessing photovoltaic module degradation and lifetime from long-term environmental tests*. Proceedings of the 29th Institute of Environmental Sciences Technical Meeting, Los Angeles, California, USA, 1983, pp. 121-126.

Standard Methods for the Examination of Water and Wastewater. 2005. American Public Health Association, 21st Edition, Washington, DC.

Tsoutsos, T., N. Frantzeskaki, and V. Gekas. 2005. *Environmental impacts from solar energy technologies*. Energy Policy, 33:289-296.

USEPA, 2004. *Guidelines for Water Reuse.* Washington, D.C. EPA/625/R-04/108.

Low Impact Development (LID) Structures for Groundwater Management and Watershed Protection in the AMRC10 Watershed, El Paso Texas

Basic Information

Title:	Low Impact Development (LID) Structures for Groundwater Management and Watershed Protection in the AMRC10 Watershed, El Paso Texas
Project Number:	2010TX361B
Start Date:	3/1/2010
End Date:	2/28/2011
Funding Source:	104B
Congressional District:	16
Research Category:	Engineering
Focus Category:	Conservation, Hydrology, Models
Descriptors:	None
Principal Investigators:	Ricardo Marmolejo, John Walton

Publications

There are no publications.

FINAL REPORT

Low Impact Development (LID) Structures for Groundwater Management and Watershed Protection in the AMRC10 Watershed, El Paso Texas

Ricardo Sabino Marmolejo[1, 2] (PI) Dr. Zhuping Sheng[1] (Co-PI) and Dr. John Walton[2] (Co-PI)

1. Texas AgriLife Research Center at El Paso, Texas A&M University
2. Department of Civil Engineering, University of Texas at El Paso

February 2011

Acknowledgment

This project is funded in part by U.S. Geological Survey and Texas Water Resources Institute. This report is also based upon work supported in part by the Cooperative State Research, Education, and Extension Service, U.S. Department of Agriculture under Agreement No. 2008-34461-19061 and Texas AgriLife Research, Texas A&M University System. We are also in debt to Ms. Nicole Kyger, Dr. Yi Liu and Mr. Zhuming Ye who had provided great assistance for field data collection.

Abstract

The AMRC10 watershed was modeled in HEC-HMS and in Green Values. Theoretical storm water conveyance and capture models were tested in these programs along with several Low environmental Impact Development features to determine their applicability and performance at this site. Lots should all be designed with all roof downspouts draining into raingardens, at least half of all lawns should be natural landscaping using local vegetation, porous pavement should be used for all driveways, sidewalks and non-street pavement and drainage to the stormwater conveyance structures should make use of drainage swales instead of storm water pipes. To manage runoff three detention ponds should be constructed at the hydrologic top of the watershed placed to intercept runoff from above the watershed and manage its passage through the watershed. To convey runoff from the upper detention ponds through the watershed to the lower detention ponds there should be two unlined channels of widths 40ft and 70ft and each with side slopes of 25^{o} and depth of 5ft, spanned by a number of slotted check dams along regular lengths, 2ft tall. Beneath these channels should be a fourth detention pond that feeds into a final pond via an overflow pipe. Sub-watersheds will drain either into one of the two channels, the forth detention pond, or the final pond. Flow rates in the channels will be below 1.5 $^{ft}/_{sec}$, for up to and passing a 10 year storm, but will be exceeded by a 100 year storm. The watershed will infiltrate 65.1 AC-FT annually into the lots and swales above what can be expected of a traditional design. The expected first year savings of this design are $4,200,000. The channel and detention pond designs can be expected to infiltrate at least 87 AC-FT annually.

Table of Contents

List of Figures

List of Tables

Low Impact Development (LID) Structures for Groundwater Management and Watershed Protection in the AMRC10 Watershed, El Paso Texas

Principal Investigator

Ricardo Sabino Marmolejo; Graduate Student, Environmental Engineering, University of Texas at El Paso; and Research Assistant, Texas AgriLife Research Center at El Paso; rsmarmolejo@miners.utep.edu; 915-525-7407; 1380 A&M Circle; El Paso, TX; 79927

Co-Principal Investigators:

Dr. Zhuping Sheng, P.E., Ph.D.; Associate Professor, Texas AgriLife Research Center at El Paso, Texas A&M University; z-sheng@tamu.edu; 915-859-9111; 1380 A&M Circle; El Paso, TX 79927

Dr. John Walton P.E.; Professor; University of Texas at El Paso; walton@utep.edu; 915-747-8699; 500 West University Avenue, El Paso, TS 79968-9991

Introduction

Background

The AMRC10 watershed is located on the bench or mesa above the Rio Grande Valley in El Paso, Texas. The sandy soils make the area subject to erosion and this natural tendency is exacerbated by increases in peak runoff discharge caused by upstream development. Overall El Paso has a desert climate making water supply a constant challenge. Water conservation and groundwater mining have also become important issues in the southwest, as recent studies have shown that groundwater is a tenuous resource that is highly susceptible to overuse (Sheng Devere, 2005). The city of El Paso in particular relies heavily on its groundwater sources for municipal distribution, and has only recently sought for ways to address the problem of groundwater mining (Hutchison, 2006; Sheng and Devere 2005). Since 2006, after an unexpected major storm hit and flooded the city, El Paso has been addressing the concepts of artificial recharge through the management of storm water effluent, thus potentially solving two problems at once (Hutchison, 2008). However, the development of virgin land is gradually causing what was once open soil to be covered with impermeable surfaces that send storm water effluents along lined impermeable conduits to detention ponds. This necessitates very large detention ponds in most new developments, and poses the potential effect on the underlying aquifers, which will alter the cities' overall water budget and has caused salt water infiltration from underlying saline aquifers causing deterioration in the quality. The resulting increase in stormwater runoff needs to be managed, and it is preferred that it be directed into areas of artificial groundwater recharge, so as to preserve that water resource. The Ivey property which sits within the lower portion of the AMRC10 watershed is one such area, which is intended for future development.

Statement of problem

The upper portion of the AMRC10 water shed is mostly developed without adequate controls on the changes in runoff caused by urbanization. The result of this is that most of the storm water effluent generated by the upper portion is gathered and channeled into two areas on the lower watershed. These are the Center arroyo and AMRC10 arroyo. This then leads to very high peak flows through these channels during heavy rainstorm events. Almost the entirety of the lower watershed is composed of fine sand with very light brush cover. The ease of erosion of the fine sand means that high speed of the peak flows could cause a great deal of erosion and subsequent deposition in the existing detention pond. Fine sand will be readily eroded when being exposed to the flow exceeding 1.5 $^{ft}/_{sec}$ (Fortier, et al., 1926). At face value this implies that conventional concrete lined channels will be the only way to safely manage storm water effluent through this development. However, this comes into conflict with the desired low impact approach for the development. The problem then becomes the creation of a storm water management system that will both satisfy the needs of safe storm water effluent management while simultaneously allowing for low environmental impact, and keeping cost and land use within reasonable levels. The lower portion of the watershed is to be developed and an increase in runoff is expected as a result. The increased runoffs will need to be quantified and captured.

Objectives

The overall goal of this investigation is to determine if a Low environmental Impact Development (LID) can be implemented for the lower watershed without prohibitive expenses or limitations. The specific objectives of this study cover assessment of runoff and preliminary design of a storm water conveyance system with the new LID concept.

- Determine a reasonable storm intensity and duration for the design specifications.
  - Determining what is "reasonable" is expected to be one of the more difficult tasks, related to the expected intensities for the region and the performance expected of the resulting storm water system.
- Design a storm water conveyance system that will handle the flows resulting from the determined reasonable storm intensity and duration, while verifying that flow rate will not exceed 1.5 $^{ft}/_{sec}$. (Fortier, et al., 1926)
  - This will keep necessary maintenance of the system at or below the current standards by minimizing erosion in the unlined channels.
- Design the storm water conveyance system such that it will meet with low environmental impact standards, and quantify the benefits gained from such a system.
- Determine the expected increase in storm water runoff from developing the lower watershed in a low environmental impact manner and quantify the benefits of doing so.
  - Ensure that the design of the storm water conveyance system will be able to manage the runoff resulting from this development.

The anticipated benefits of such a design will be mostly in the realm of water conservation. Conjunctive management will manifest itself in the structures designed to retain and infiltrate storm water and in the surface ponds and channels that will slow down runoffs, mitigate peak runoffs and pond runoff for infiltration. The design of these structures will enhance the friendly environment of the area, creating park space and lots of natural landscape. The specifications for landscaping and the management of runoff will help to sustain future water supplies.

Study site

Geographical locations

The study area is approximately 442 acres of the Ivey property on the far east side of El Paso, Texas. The area is bounded by the I-10 freeway to the northeast, Texas highway 375 to the northwest, the Mesa drain to the southwest and the Socorro Grant to the southeast. The contributing drainage basin of the study is the area of suburban and commercial development to the north of the site. It extends to the Socorro sports center, and includes all the commercial and residential development directly east and west of the sports center. A total of over 1,900 acres of land feed runoff out of the drainage basin. After the proposed development, the site will be comprised mostly of residential and some commercial areas (Moreno Cardenas Inc. 2006).

Climate and weather

The climate of El Paso can easily be summed up as “dry and hot.” The annual evaporation measured in the lower El Paso Valley amounts at 80 to 100 in. However, the individual details of “dry and hot” paint an interesting picture of weather patterns not experienced in most other urban areas throughout the nation. Being part of the Chihuahuan desert, El Paso sees very little yearly precipitation, on average no more than 10 inches. Nearly half of this precipitation happens in the months of July, August, and September. This creates a kind of monsoon season for the city and is the result of warm moist air moving inland from the Gulf of Mexico. The wettest month is August with an average of 1.75 inches of precipitation. July and September are also wet months with an average of 1.49 inches and 1.61 inches of precipitation, respectively. January through May and November are very dry months, all with an average of under 0.5 inches of precipitation. December October and June are all mildly wet months with averages of around 0.8 inches of precipitation (HAMweather, 2003-2007).

The average daily high temperature is the highest in June at around 95^{o}F. The average daily low temperature is the lowest in January at around 33^{o}F. El Paso is not known as the Sun City without reason. Ten months out of the year the average available hours of sunshine are above 80%. Only in December and January the average available hours of sunshine is just below 80%, while May and June is 90% and April 89% (HAMweather, 2003-2007).

Hydrology

The majority of the area is bluepoint classified soil and almost all of the area has been previously graded, though there are some larger tracts that remain mildly rolling. Natural arroyos provide a great deal of drainage to the area, though there are existing concrete lined channels for drainage through the previously developed areas. The current hydrology of the study site is dominated by two arroyos that enter across I-10 and intersect at the AMRC10 reservoir. All flows from the upper watershed are funneled into these arroyos. They are ephemeral and remain dry throughout the year and only see flows during heavy or prolonged rain storms (Moreno, 2006). Deposition of fine sediment has decreased permeability in the reservoir enough that it sees standing water for an extended time after large or prolonged rain storms. The entire area of the study site is composed mostly of fine sand with some clays and silts, with light brush cover. The area is capable of rapid infiltration that decreases and even eliminates runoff for smaller rain events. However, in larger or longer storms runoff increases dramatically once the soil's infiltration rate is exceeded (US Army Corps of Engineers, 2007).

Methodology

Testing

A number of field and laboratory tests were performed to determine the characteristics of the study site. A dual ring constant head infiltration test was performed on seven sites across the entire drainage basin. Soil samples were taken at each site and dried. Constant head permeability tests and sieve tests were performed on each of the samples. A specific yield test was conducted on the sample from site 2. The purpose of the testing was to determine characteristics and behavior of soil all around the site during a rain storm.

Specific Yield Test

The test to determine specific yield was held using sand from a test site compacted into a sealed cylinder, saturated and allowed to drain over night. The resulting values were compared to the averages for fine, medium and coarse sand (Fetter, 2001).

Physical Scale Model

A river flow simulation machine was used to run a scale test of the channel designs intended for the development. Detention structures were constructed to scale within the machine and test flows matching the expected results for 10 year and 100 year storm were run through the system. The purpose of this test was to determine some of the real performance capabilities and issues of the system.

Computer Models

A HEC-HMS model was constructed using survey information compiled by Moreno Cardenas engineering firm (Moreno Cardenas Inc. 2006), and survey information previously compiled by the Hydrological team at the Texas AgriLife Research Center. HEC-HMS is a finite element modeling software that simulates overland flows from theoretical rainstorm data (US Army Corps of Engineers, 2010). Culverts, channels and other waterways were measured and delineated. Sub-water sheds were measured for area and impermeable cover, and their soil characteristics were specified based on test results.

Green Values program was used to simulate runoff from developed lots that utilize Low Environmental Impact design features to capture and store storm water. Calibration was based on the assumption that roofs will drain to raingardens at downspouts, half of all lawns will be covered by native landscaping, drainage swales will be used in place of storm water pipes and porous pavement will be used on driveways sidewalks and other non-street pavement.

The application of these properties to the project was done within the context of the differences between El Paso and the reference city for Green Values. In El Paso a raingarden will not be a lush green water sink covered in plants. Rather it will be a permeable area with several large deep root trees such as Desert Willow or Mesquite and covered with gravel. Similar structures will be used to capture the water expected to flow into swales. In El Paso any application of grass will require lots of irrigation which would defeat the purpose of such a structure, so green swales will be replaced with gutter swales using permeable pavers that lead to small catchment areas on street corners that infiltrate the water and have deep rooted trees to stabilize the soil and pull up water during drought. It has been seen in El Paso that such trees easily survive the dry months of the year by pulling up water that has been stored in the ground beneath it during the raining season.

The output data from Green Values was used for comparison against the output data from HEC-HMS of its runoff determination for lots in the new development area. This allowed for a greater degree of certainty with regard to the HEC-HMS output simulating the development's reaction to rainstorms if developed with LID criteria. Green Values output also contained detailed cost projections and anticipated water savings due to infiltration. It anticipated the decrease in needed storage, but overall overland flow values calculated in the HEC-HMS model were used for detention pond sizing. Green Values used the equivalent of a 5 year El Paso storm to make its calculations and provided detailed documentation of how modeling of the plots and runoff were determined and quantified (CNT, 2010).

Assessment of Rainstorms

Several design storms were used to assess performance of storm water structures in the new development. An Intensity Duration Frequency (IDF) chart that had been constructed for the El Paso area by the Army Corps of Engineers was used to determine the appropriate intensities, durations, and frequencies. This curve was an input for the function of HEC-HMS. Intensity and duration calculations in HEC-HMS were based on a Snyder Hydrograph with a standard lag of 0.21 hours. A 100 year 24 hour storm was used to determine maximum conveyance capabilities while smaller 10 year 24 hour, 5 year 1 hour, and 1 year 1 hour storms were used to quantify performance over a range of loadings (US Army Corps of Engineers, 2007).

Design of Strom Water Capture and Conveyance Systems

Design of the storm water capture and conveyance systems in the new development was based around two key features. First that the newly developed lots would implement LID features to help manage storm water before it becomes runoff. The second is that the major conveyance systems will be mostly unlined to allow for infiltration and provide green spaces for the development that will require no irrigation. This requires the limitations of slope intensity, flow velocities and adherence to the existing natural flow paths. The limiting flow velocity for no erosion on a fine sand surface is 1.5 $^{ft}/_{s}$ (Fortier, et al., 1926).

Structure for Capture of Rainwater and Runoff

Fig. 1 shows a topographical map with watershed delineations for the development that was taken from a document developed by Moreno Cardenas Inc. All drainage in the development will be directed towards the channels or the AMRC10 Pond and Final Pond, marked on the figure. The Capture Pond marked on the figure is intended to catch runoff from two sub watersheds that drain directly into that spot and not allow it to travel into the channels or other ponds. A drainage pipe connecting the AMRC10 Pond to the Final Pond will handle spill over conditions in the AMRC10 Pond during very large storms. The Final Pond can be designed to be the final fate of runoff from the development, or to drain legally allowable amounts into the lower watersheds which will eventually reach the nearby Mesa Drain.

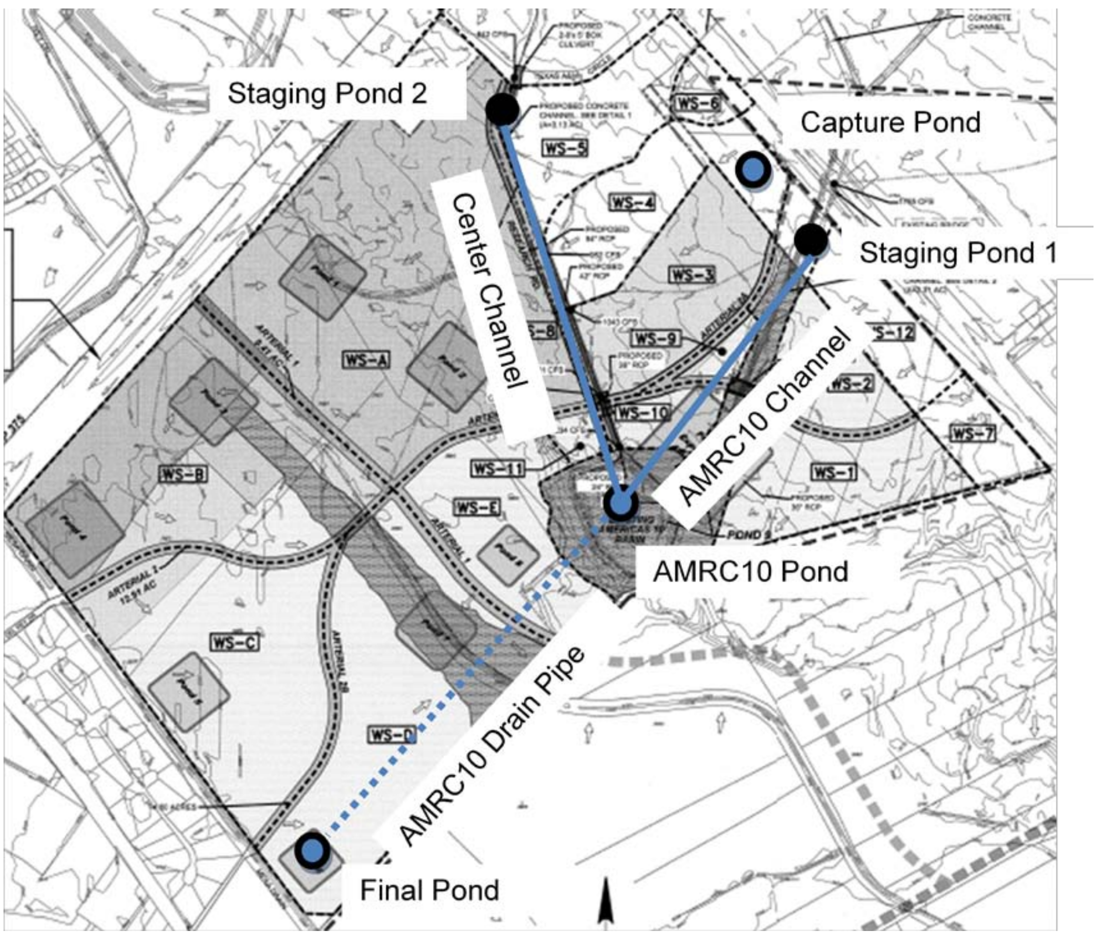


Figure 1Development Watershed Delineation by Moreno Cardenas Inc. and Storm Water Conveyance Design for this Study

An important feature of the design will be the staging ponds located at the top of the development intended to manage the flow from the upper watershed. Without these structures in place, the flows passing through the system would be large enough on a yearly basis as to make the use of unlined channels all but impossible. Fig. 4 shows the locations of the staging ponds just below I-10. The design presented includes large structures that will capture flows from upstream and provide controlled predictable releases to downstream. Shallow long slopes will allow the areas to be used for park land or sports fields, if so desired but will not have storage capacities as large as might be found in standard detention pond designs. Under the two large detention ponds that feed into the channels will be a layer of fine sand over impervious Geomembrane. The two ponds in question are marked with solid black dots on Fig. 1 and Fig. 3. The sand/membrane layers will act as an artificial perched aquifer. The artificial perched aquifer will be constructed using sand available at the site. The characteristics of this available sand are such that, at a size of 5ft deep and an expanse of 10 acres, roughly the size of the staging pond, 10 AC-FT/yr of water can be expected to be available for irrigation from the pond above the AMRC10 arroyo. At 5 ft depth, and covering 2 acres, the artificial aquifer constructed under the staging pond above the Center arroyo will have 1.8 AC-FT/yr of water available for irrigation. Taking the rain distribution of El Paso into consideration, the aquifers can be expected to be saturated at the end of September and at the middle or end of December. From January until June, it should be expected that no recharge will occur and that all irrigation uses will cause draw down. This should be matched with any intended irrigation uses, such as a sports field, or landscaping. A free flowing pipe with a screened opening inside the bottom of the perched aquifer will feed the desert climate trees used to stabilize the slopes of the channels below the ponds. A valve, accessible at the surface just above the first irrigation outlet, will allow for stopping flow when irrigation is not needed. Alternatively, a shallow well can be drilled into the perched aquifer and used to extract water for turf fields in the pond. Either application will allow avoidance of municipal services for irrigation; however the first option, the screened pipe feeding threes for slope stabilization, is much more likely to require no municipal services for irrigation in the long term as irrigating a sports field will likely quickly deplete the available water available in the saturated perched aquifer.

Fig. 2 illustrates the composition of the pond, sand layer and Geomembrane to construct the artificial perched aquifer. It also shows the general pathway for the well screened pipe to transport the stored water for gravity fed irrigation.

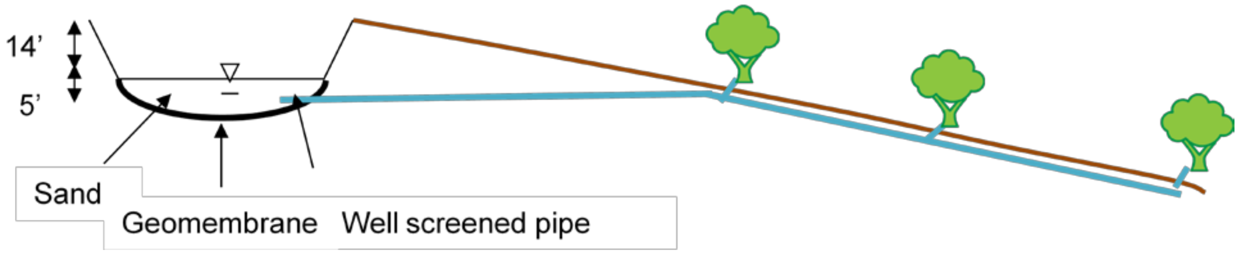


Figure 2 Pond and Artificial Perched Aquifer

Fig. 3 illustrates the spillways that will allow water from inside the staging ponds to flow into the channels. The long notch through the center of the spillway will be 0.5ft wide at the top and taper to a point. This will allow sediment to flow through the system without getting trapped in the staging ponds. The result is higher flows and the need for greater storage at the end of the system. The benefit is that there will be a much reduced need for annual maintenance due to sedimentation. It is also recommended that a wire mesh be installed over the notch to prevent serious clogging within the opening. The wire mesh can be cleared of debris as needed with much less difficulty than flushing out the whole notch.

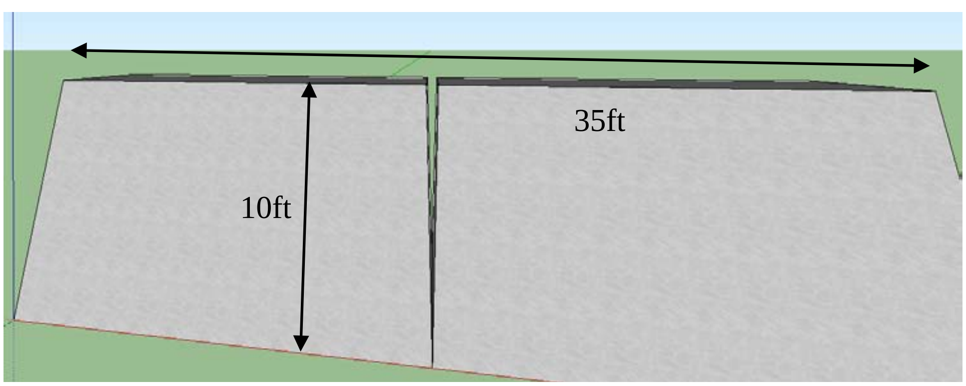


Figure 3 Staging Pond Spillway

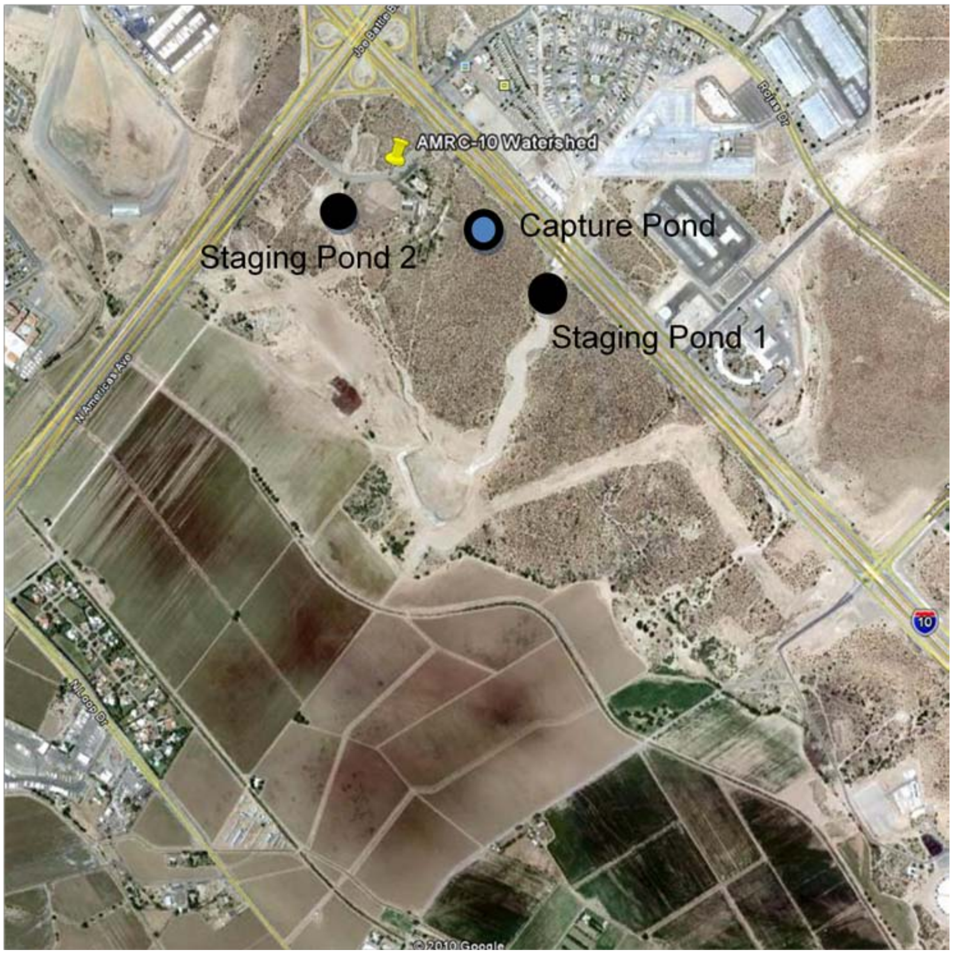


Figure 4 Staging Pond Locations

Tables 1 through 4 show the elevation, area and discharge relationships calculated for the various ponds to assess storage and release of surface flow through the ponds and, where applicable into the corresponding channels.

Table 1 Staging Pond 1 Elevation/Area/Discharge

Staging Pond 1			
Elevation (ft)	Area (AC)	Discharge (CFS)	Storage (AC-FT)
0	0.01	0	0
1	4	0.7	5.8
2	4.25	4.5	11.7
3	4.5	13.2	17.4
4	4.75	28.4	23.2
5	5	51.5	29
6	5.25	83.8	34.8
7	5.5	126.4	40.6
8	5.75	180.4	46.4
9	6	247	52.2
10	6.5	327.1	58
11	7	404.8	63.8
12	8	730.8	69.6
13	9	1195.8	75.4
14	10	1766.1	81.2

Table 2 Staging Pond 2 Elevation/Area/Discharge

Staging Pond 2			
Elevation (ft)	Area (AC)	Discharge (CFS)	Storage (AC-FT)
0	0.25	0	0
1	0.5	0.7	1.1
2	0.75	4.5	2.3
3	1	13.2	3.4
4	1.25	28.4	4.6
5	1.5	51.5	5.7
6	1.75	129.2	6.8
8	2.25	455.2	8
10	2.75	920.2	9.1

Table 3 AMRC10 Pond Elevation/Area/Discharge

AMRC10 Pond			
Elevation (ft)	Area (AC)	Discharge (CFS)	Storage (AC-FT)
0	0	0	0
2	2	0	8.7
4	3	0	17.5
6	4	0	26.2
8	5	0	34.9
10	6	77.7	43.6
12	7	403.7	52.4
14	8	868.7	61.1
15	8.5	1054.9	65.5

Table 4 Final Pond Elevation/Area

Final Pond		
Elevation (ft)	Area (AC)	Storage (AC-FT)
0	0	0
1	13	11.7
2	13.5	23.3
3	14	35
4	14.5	46.6
5	15	58.3
6	15.5	69.9
7	16	81.6
8	16.5	93.2
9	17	104.9
10	17.5	116.5
11	18	128.2
12	18.5	139.8

Design of Conveyance Channels

The arroyos conveying the runoff are designed unlined and with very shallow slopes and wide channels to keep flows shallow. Slotted check dams are included along the arroyos to increase storage, slow flows and reduce erosion. The performance of these channels and check dams were tested extensively in HEC-HMS and in scale models. Stabilization of the side slopes of these channels is achieved by the use of native desert climate trees such as Desert Willow and Mesquite, which provide significant shade and flower very nicely in the spring. Another potential for slope stabilization is the use of cellular confinement mats that drastically increase soil shear strength and allow for intricate deep root structures in the plants used for landscaping. Further testing of the local soil shear strength would be needed to determine the expected reliability of slope stability. For purposes of design, the angle of repose and typical shear strength of dense compacted sand was used. This allowed for assessment of the effects of flows for various storms in the designed unlined channels. The location of the channels is shown in Fig. 5.

Figure 5 Location of Center and AMRC10 Arroyos

Fig. 6 through Fig. 10 show a three dimensional scale model of the AMRC10 channel and its check dams. Fig.6 includes a person for perspective. Important to notice in the figure is curve of the check dam and the slots evenly spaced along its length. This design is intended to direct flows through the middle of the channel when runoff is not enough to create deeper flows. Of note is also the stone and mortar construction of the check dam. It is thought that this type of construction will be more aesthetically pleasing for the land owner.

Fig. 7 shows the check dam and channel in cross section. The channel width is 70 ft, with slopes that are 5 ft high covering 11 ft length. This creates a slope angle of roughly 25^{o}. The Center channel will be constructed identically, except that width will be 40 ft instead of 70 ft, and the slots in the check dams will be spaced accordingly.

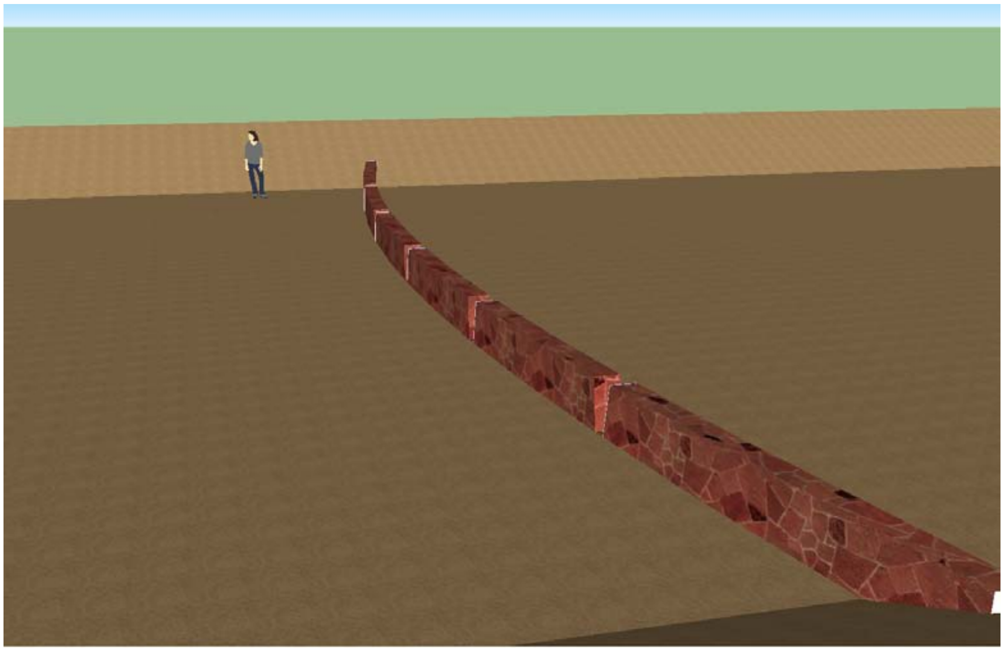


Figure 6 Scale Model, Check Dam

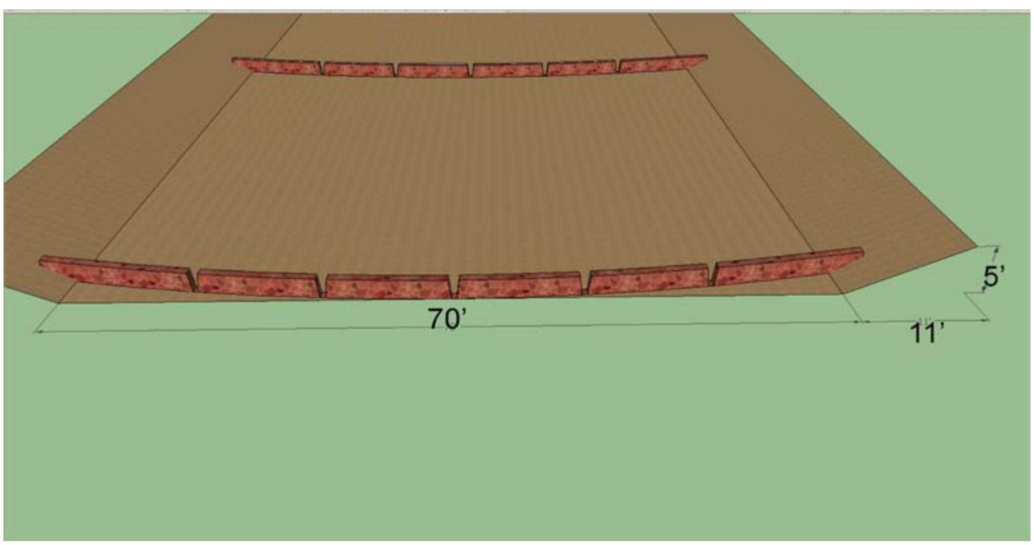


Figure 7 Scale Model, Check Dam, Channel, and Channel Dimensions

Fig. 8 through Fig. 10 show closer views of the slots in the check dams. Fig. 8 shows the spacing of the slots along the width of the channel. Fig. 9 is a close up of a single slot. The dimensions of the slot are marked on the figure. It is triangular with a 1 ft width at the top and 6 in width at the base. Fig. 10 shows the dimensions of the spacing of the slots and height of the dam. They are 11 ft 5 in apart and the dam is 2 ft tall. The dams will extend into the side slopes at least half of the 11' width to prevent flows eating around the edges. This is important to the success of the design.

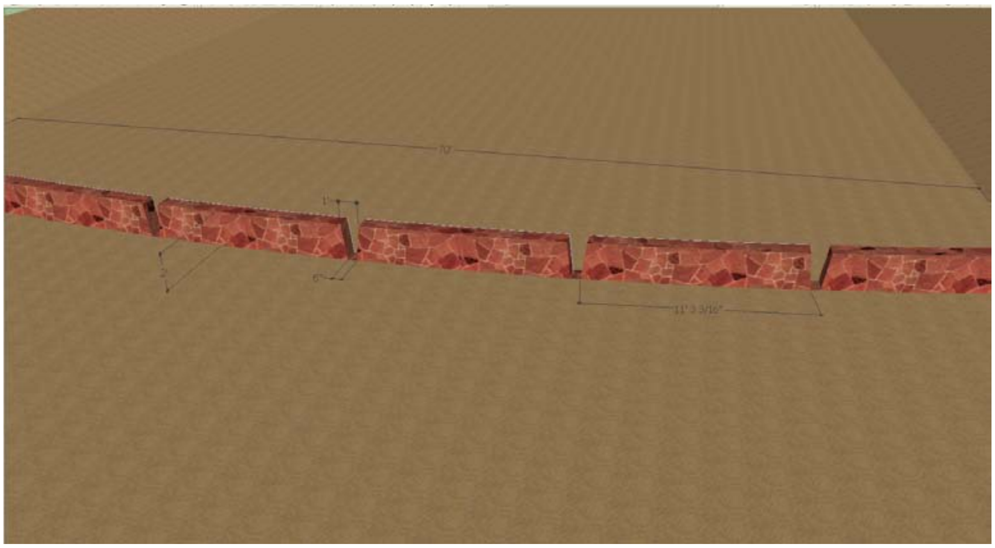


Figure 8 Check Dam and Slot Dimensions

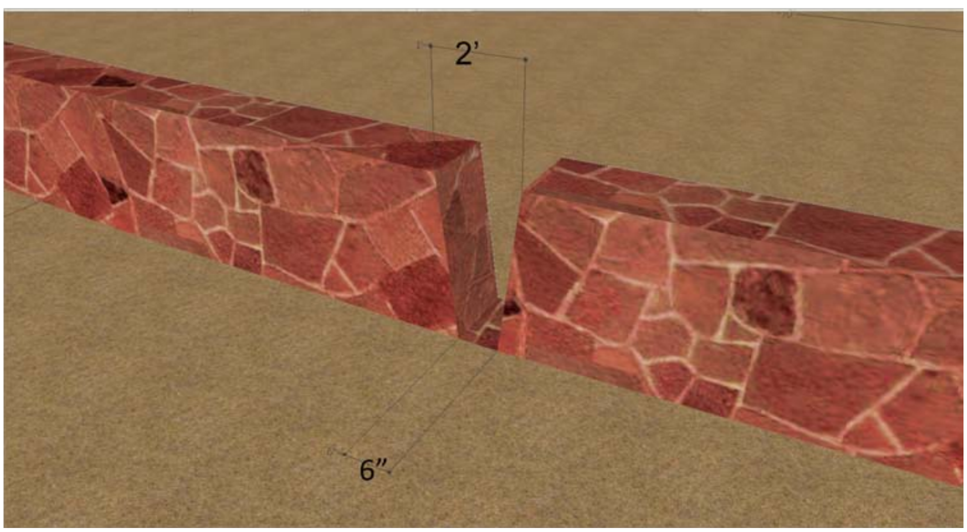


Figure 9 Slot Dimensions: Detail

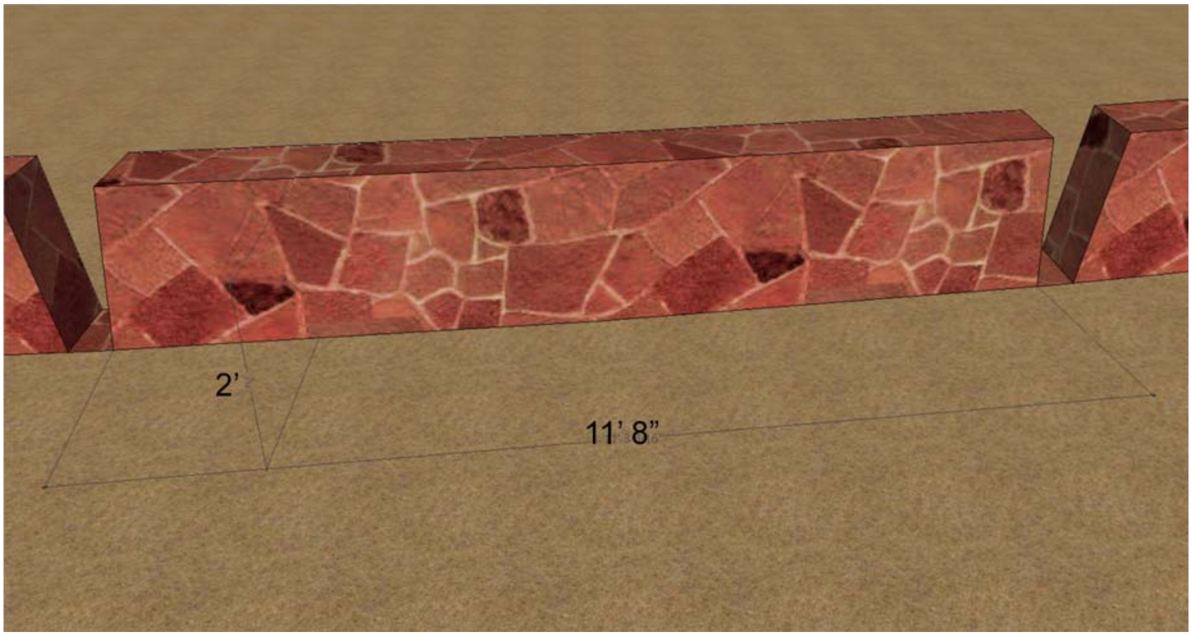


Figure 10 Check Dam Dimensions: Detail

Results and Discussion

Testing Results

Nine sites within the AMRC-10 watershed were used to run Constant Head Dual Ring Infiltration Tests and to collect soil samples for conducting Constant Head Permeability Tests in the lab and Sieve Tests. Detailed tables and figures on the results of these tests are included in the appendix section. Fig. 11 shows the locations of each of the test sites.

Figure 11 Test site map

The coordinates of each of the testing sites as determined by GPS locator are shown in Table 5.

Table 5 Site Coordinates

	Lat N	Long W
Site 2	31.6937	106.2783523
Site 3	31.707	106.278589
Site 4	31.6979	106.2835336
Site 5	31.7101	106.2737819
Site 7	31.7023	106.27858
Site 8	31.6968	106.2831023

Site 1

Site 1 has thus far been unavailable for testing. Past rain storms and heavy sedimentation have left the pond saturated and flooded, so there is no means by which an infiltration test can be conducted. Furthermore, as the “Pond” element in HEC-HMS does not allow for infiltration in compiling, such testing proved to be unnecessary.

Site 2

Site 2 is located within the upper area of the AMRC10 arroyo. The soil is very sandy, and composed entirely of sediment traveling from upstream during rainstorm events. Conducting the test on this site was difficult because the infiltration rate was so high throughout the test. This difficulty caused some rather erratic and not fully reliable results. For the final calculation and data presentation a large number of outliers were removed from the results in order to create a more reasonable estimation of the infiltration rates.

A second test was conducted on the same spot, immediately after the first test. While the first test was a constant head infiltration test, the second was a direct measurement test with dynamic head. After the data for both tests was analyzed and outliers were removed from the set, the results of both the tests were reasonably similar.

For both tests, data was plotted and a trend line was established using the power method, as this most closely resembles the behavior of infiltrating water. R^2 values were determined and outliers were altered until suitable curve fitting was established. The resulting conclusions were fairly consistent between both tests. Stable infiltration is expected to be in the area of 9 inches per hour (in/hr). Average permeability was found to be 49.1 $^{in}/_{hr}$ by the constant head permeability test in the lab. It is believed that testing errors created the huge discrepancy in the test results. Sieve testing showed the soil to have an AASHTO classification of A-3, fine sand.

Site 3

The soil appeared to be composed of sandy clay. The entire area has been graded and compacted and much of the soil is heavily consolidated. This made the test slightly difficult to set up for but fairly free of difficulties to conduct.

The recorded data for site 3 was very stable and easily plotted. There were no serious outliers. A trend line was established using the power method and the R^2 value was determined. The resulting values were found to be very reliable. Saturated infiltration rates for site 3 are expected to be in the area of 1.2 in/hr. Average permeability was found to be 0.75 $^{in}/_{hr}$ by the constant head permeability test. Sieve testing showed the soil to have an AASHTO classification of A-3, fine sand.

Site 4

Site 4 is located to the north of the AgriLife center in the undeveloped graded area adjacent to the AgriLife arroyo. The area is mostly sandy with some clay and a little silt. It has been previously graded, but has been heavily influenced by subsequent rainfall events. The soil is easily eroded and has had its slope significantly altered by surface flows during larger storms. The sandy consistency of the soil made the test easy to initiate, but the resulting high rate of infiltration made the test slightly difficult to properly conduct. The data from the test was similarly somewhat erratic and needed to be adjusted to provide usable results.

Unfortunately there were a large number of outliers which make the results fairly unreliable. After eliminating the outliers a reasonable trend line was established using the power method. The line had a suitable R^2 value. The resulting saturated infiltration rate was found to be in the area of 11 $^{in}/_{hr}$. Average permeability was found to be 0.33 $^{in}/_{hr}$ by the constant head permeability test. Sieve testing showed the soil to have an AASHTO classification of A-2, loamy sand.

Site 5

Site 5 is located a little to the east of Loop 375 and a little south of the Socorro stadium. The soil in the area was mostly sandy clay. There were scattered occurrences of caliches and some larger bits of gravel spread all throughout the site. The soil was stiffly consolidated, and that coupled with the instances of caliches made preparing the test site somewhat difficult. The test itself, however, proved simple and easy to conduct, as the slower infiltration time allowed for readings to be more easily recorded.

The data collected for site 5 was fairly consistent with only a few outliers that occurred only briefly after the test was reset and restarted. All the rest of the data for site 5 follows similar changes. The data was plotted and a trend line was established using the power method. The R^2 value was within acceptable ranges once the few outliers were removed from consideration. Infiltration rate when saturated was found to be in the area of 4 in/hr. Average permeability was found to be 2.55 $^{in}/_{hr}$ by the constant head permeability test. Sieve testing showed the soil to have an AASHTO classification of A-2, loamy sand.

Site 6

Site 6 was intended to be the commercial site north of the Socorro stadium. The site was abandoned due to time constraints and existing similarities with site 3.

Site 7

Site 7 is located on the northwest border of the residential area that is just north east of I-10. The soil at this site consisted of a sand layer spread over clayey sand. It was fully graded and compacted but not very consolidated. It is representative of the locations in the residential area that are not covered by impermeable linings nor have vegetative cover, as both types would have fairly high infiltration. Setting up the test in such soft soil was simple, but performing the test required several resets to refill the tubes.

The infiltration rate was fairly quick here, and fairly steadily so, but the resulting data was unfortunately more erratic than would be preferred. Each time the test was reset the rates changed drastically and so there were a number of wide outliers that needed to be removed before the data was really usable. As such, the results are somewhat telling, but not completely reliable. Once the outliers were removed a trend line was able to be established using the power method and the R^2 value was within the acceptable range. The infiltration rate when saturated was found to be in the area of 4.5 in/hr. Average permeability was found to be 2.31 $^{in}/_{hr}$ by the constant head permeability test. Sieve testing showed the soil to have an AASHTO classification of A-3, fine sand.

Site 8

Site 8 is located immediately adjacent to the AgriLife research center. The soil in this area was sandy with some clays and silts. It was fully graded and compacted, and fairly consolidated. There is some light brush cover on the site, but it is mostly bare. The softness of the soil made the test easy to set up. The resulting infiltration rates made the test fairly simple to conduct, and the resulting findings were fairly stable.

The resulting data from this test was very consistent. There were no obvious outliers in any of the recordings, and a trend line was able to be established using the power method without removing any data points. The R^2 value was reasonably high and the curve fit the plotted points fairly well. The resulting saturated infiltration rate was found to be in the area of 3.0 in/hr. Average permeability was found to be 0.19 $^{in}/_{hr}$ by the constant head permeability test. Sieve testing showed the soil to have an AASHTO classification of A-3, fine sand.

Site 9

Site 9 is located mostly to the east of the Socorro stadium. It is a very large area of largely undeveloped land, which is currently under the process of development. Infiltration was found to be in the area of 8 $^{in}/_{hr}$. The R^2 value was, however, fairly low at 0.24 and so the results cannot be taken and clearly indicative. Average permeability was found to be 2.43 $^{in}/_{hr}$ by the constant head permeability test. Sieve testing showed the soil to have an AASHTO classification of A-3, fine sand.

In summary, the testing was fairly successful with some variation and inconsistencies not altogether outside of expected ranges. The resulting data was enough to properly calibrate the HEC-HMS model for expected infiltration in the sub basins.

Modeling results

Primary concerns were over sizing involved the two major channels, AMRC10 arroyo and Center Channel arroyo. HEC-HMS models clearly showed that flows from the upper watershed are concentrated through these two conduits. As the main runoff control systems, designing them in an LID method was a major goal and a large challenge. Sizing the channels was a heavily iterative process that was dependant on features within the channel and the width of the channel itself. Each of the channels will be crossed by a series of staggered 2 ft tall check dams. The accumulation of sediment behind these dams was anticipated to become a problem and as such they were designed to allow outflow to wash sediment away from behind the check dams.

Center channel width is 40 ft. It holds 14 check dams evenly spaced along its length. The slope of the channel is 0.01 $^{ft}/_{ft}$. The channel is 2958 ft long. AMRC10 channel width is 70 ft. It holds 27 check dams evenly spaced along its length. The slope of the channel is 0.024 $^{ft}/_{ft}$. The channel is 2742 ft long. The existing physical conditions were maintained as much as possible in the design so as to preserve natural slope and flow direction. This will prevent erosion from flow direction changes caused by development. It is a necessary feature of unlined channel design (Temple, D.M., etc all, 2003).

One year, five year, and ten year El Paso design storms were used to determine the performance of the systems at different sizes until an effective system size was found. The limiting factor was keeping flow speeds under 1.5 $^{ft}/_{sec}$ while also keeping the system size small enough to be economical. Flow speeds were calculated from the results of the model estimations of water elevation, volumetric flow rates, and channel widths.

For a 1-year storm the highest estimated flow speed in the AMRC10 channel was in the area of 0.2 $^{ft}/_{sec}$, 6.1CFS at 0.45ft depth. Many portions of the channel did not experience any flow at all. The highest flow in the Center Channel was estimated to be around 0.4 $^{ft}/_{sec}$, 18.5CFS at 1.1ft depth. It should be noted that flow concentrations are expected where individual subwatersheds are outputting into the channel. Channel lining may be necessary at these junctions.

For a 10-year storm the highest estimated flow speed in the AMRC10 channel is 1.22 $^{ft}/_{sec}$, 230CFS, at 2.7ft depth. Highest estimated flow for the Center channel was 1.5 $^{ft}/_{sec}$, 163.4CFS at 2.75ft depth. Similarly, spiked flow speeds are expected where sub watersheds dump into the channel. The resulting higher flows below the sub watersheds are evidence of the increase.

For a 100-year storm the highest estimated flow speed in the AMRC10 channel is 3.1 $^{ft}/_{sec}$, 728CFS at 3.4ft depth. In the Center Channel the highest estimated flow speed was 2.8 $^{ft}/_{sec}$, 388CFS at 3.5ft depth. For the 100 year storm the two channels should directly infiltrate around 31 Acre-ft of runoff.

Table 6 lists the calculated maxes.

Table 6 HEC-HMS Model Results

	Center Channel			AMRC10 Channel		
Storm Size	Depth (ft)	Speed (ft/sec)	Flow (CFS)	Depth (ft)	Speed (ft/sec)	Flow (CFS)
1	1.1	0.4	18.5	0.45	0.2	6.1
10	2.75	1.5	163.4	2.7	1.22	230
100	3.5	2.8	388	3.4	3.1	728

Results of Scale Model Test

In the scale simulation test a river flow simulation machine was used to construct a scale model of a stretch of the Center Channel to assess the effects of real flowing water as would result from storm runoff on the strength, integrity and performance of the design. The model channel was constructed in sand as a 1:40 scale stretch with similarly scaled runoff detention structures. The check dams were constructed of sheet aluminum cut to exactly simulate the designed check dams at a 1:40 scale. Also tested were check dams constructed of what would be large boulders cemented into the channel bad, at scale. The concept is that such an approach with natural building materials would be much more aesthetically pleasing and preferable from a developer and buyer point of view. It was desired to see how such structures would perform under the same loading as the aluminum scale check dam models.

The machine holding the constructed scale model channel and check damns is shown in Fig. 12. Fig. 13 is a close-up of the check dam structures within the model. In Fig. 12 one can see clearly the scale height and open flow spaces of the boulder check dam and the scale height and slotted openings in the standard check dam.

Figure 12 Scale Model of Center Channel for Testing

Figure 13 Scale Model Close Up

Fig. 14 and Fig. 15 show water flowing through the model channel to a depth concurrent with computer modeled 10 year storm. You can see clearly the retention and flow velocity reduction caused by the check dams. It can also be seen in Fig. 15 that the flow is directed more toward the center of the channel by the curvature of the check dams. During the test it was seen that the slots in the check dams will create significant erosion just beneath them and that this was be guarded against. Gabions placed just beneath the slots are suggested. In the bolder check dams it was seen that flow in between the gaps will cause significant erosion as well. It will be necessary to cement them in place with adequate footing and to place gabions directly beneath the boulders to prevent erosion there. Flowing dye through the system showed localized flow speed increases through the slots, between the boulders and in flow over the check dams. This localized increased flow speed is what caused increased erosion around the check dams and cannot easily be mitigated outside of reinforcing against the potential erosion.

Figure 14 Scale Model Check Dam Performance 10 Year

Figure 15 Check Dam Flow Direction

Fig. 16 shows the system at full flow during 10 year depth simulation. Little significant erosion was observed except for within the boulder check dams and just below the standard check dams. It can be reasonably surmised that the system will hold up well to this size of a storm.

Figure 16 Scale Model 10 Year Steady Flow

Fig. 17 shows full flow at depth for a simulated 100 year storm. The green dye used to indentify localized flow speeds is also seen in the figure. The dye demonstrated areas where flow speeds were significantly decreased and the small areas directly around the checks where speeds were significantly increased. In the figure the slope erosions caused by such a high flow are seen.

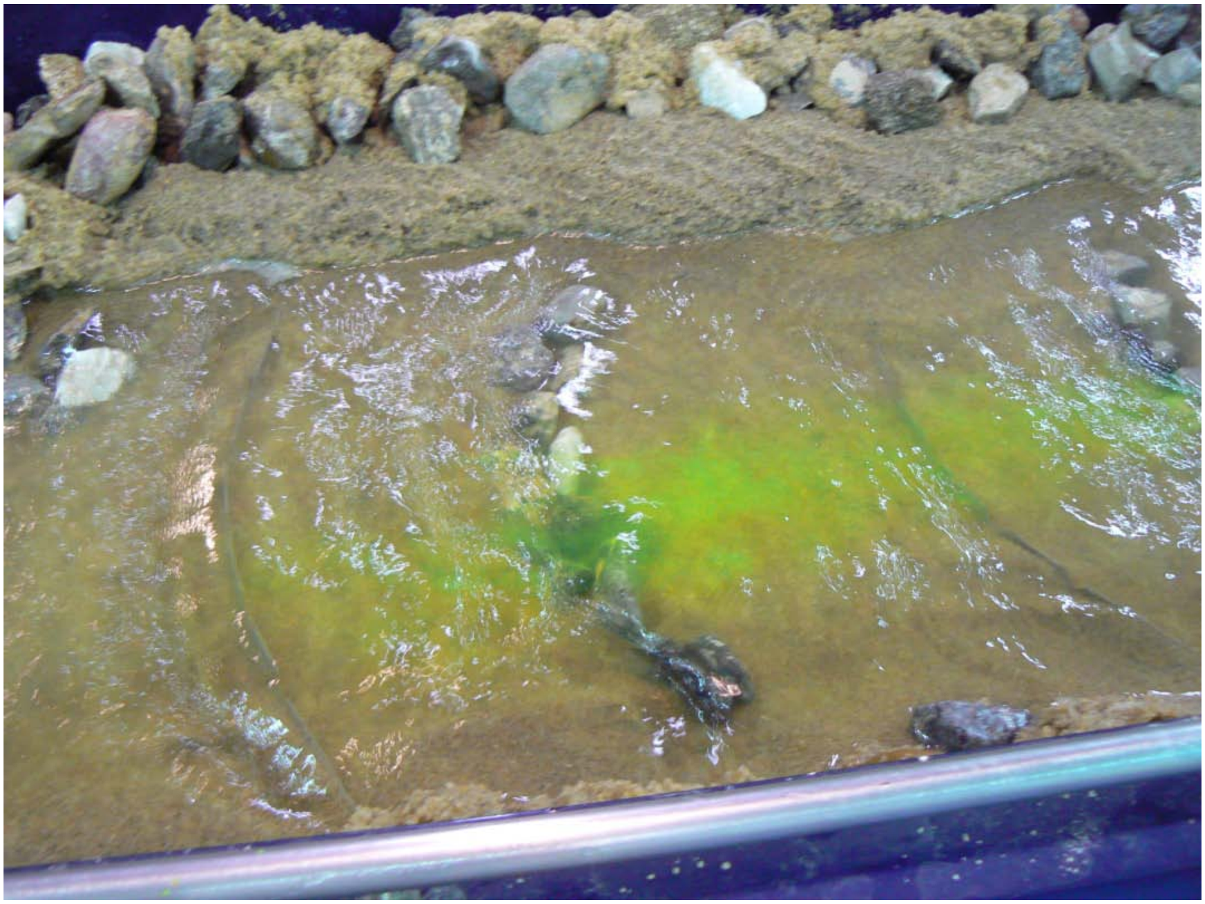


Figure 17 Scale Model 100 Year Steady Flow

Fig. 18 shows the aftermath of 100 year flow simulation. In particular, what is shown in the figure is the most damaged portion of the model. During a 100 year storm significant erosion was seen along all channel sides and below each check dam, especially the final dam. It was demonstrated that each dam significantly backed up flows behind it, decreasing flow speeds for the checks behind it and decreasing the erosion they experienced. As the final check, the last check dam experienced the highest velocity flows and the most erosion. It can be expected that where the channels expels into a detention pond, or where flows are increased by an inlet structure there will need to be some extra reinforcement against erosion.

Slope degradation was also witnessed at higher flows. As the sand used in the machine is relatively comparable to the sand that will be available on site it becomes apparent that some form of slope stabilization will be needed if it is intended that such large scale erosion and destruction in the system is to be avoided. Fortunately, the design is specified such that a different, stronger soil composition is to be used on the side slopes and other reinforcement methods are to be applied as well.

The overall results of the scale model test have to do with the expected maintenance of the channels. As one would expect needed maintenance increases with the size of the storm. Since most upkeep will revolve around managing sedimentation and looking at the damaged caused in the testing one can make the assumption that the typical annual storm will require little to no maintenance. However the larger storms will cause a small degree of damage or sediment deposition. For 100 year storms or higher it can be expected that some slope reconstruction may be necessary. As it is impossible to prevent all cases of erosion, even under very low flows, some sediment management will be needed on an annual basis, but this value can be expected to be fairly low and perhaps even negligible.

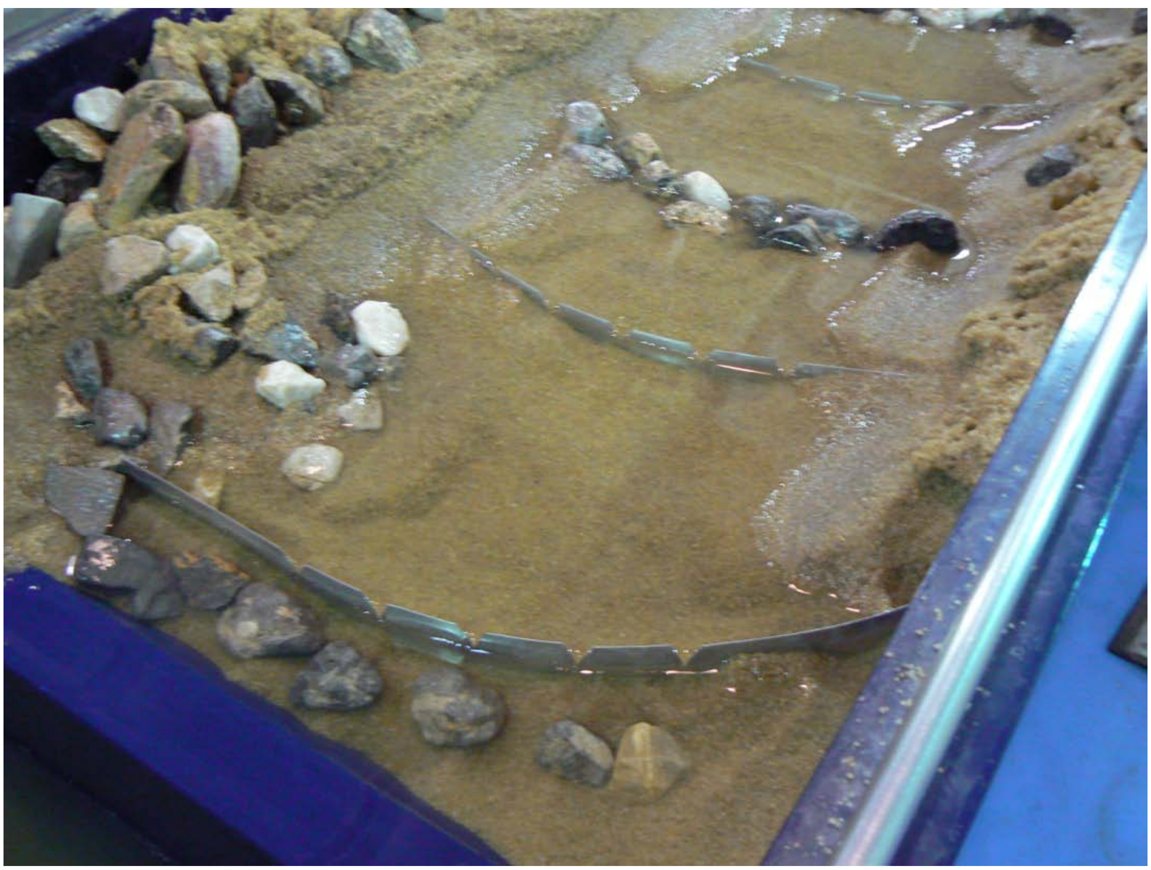


Figure 18 Scale Model After 100 Year

By the specific yield test it was determined that the specific yield for the soil at site 2 is 18%. It should be considered that the specific yield for different grain sizes in the event of soil engineering or placement in different locations will see some fluctuation and further calculations should be made in these cases. Fig. 19 shows the test during draining and weighing.

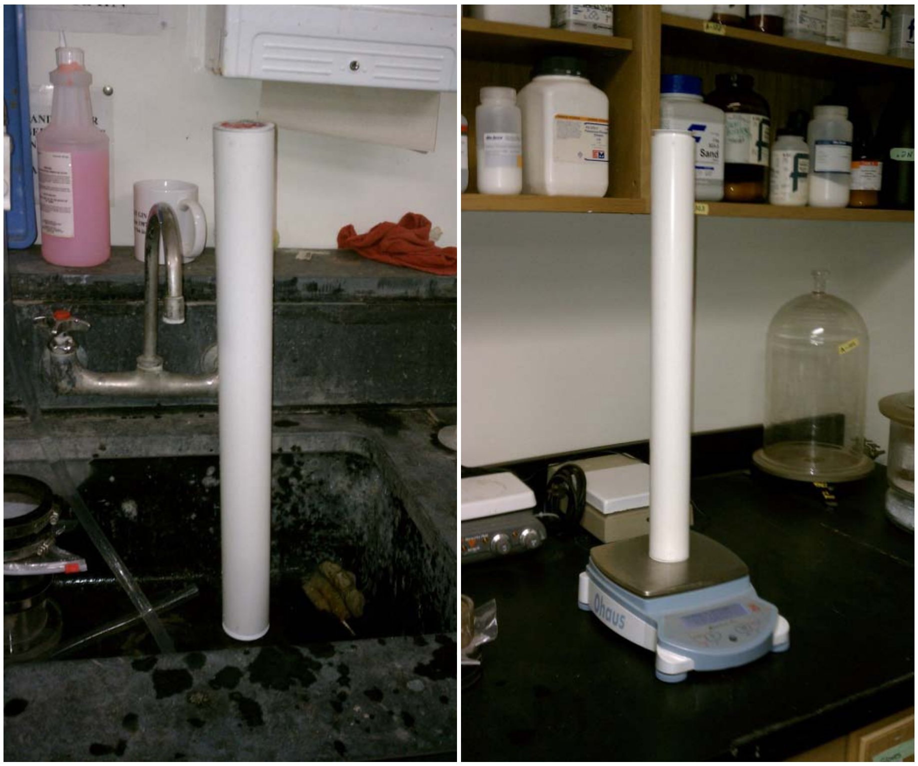


Figure 19 Specific Yield Test

Storage, Retention and Water Savings – HEC-HMS and Green Values Comparison (anticipated annual)

Outflows calculated on each lot were compared between HEC-HMS and Green Values for an El Paso 5 year storm to calibrate the choices within the models and verify similitude.

Green Values calculated a first year savings of $4,200,000 on the development if certain Low Impact development features were implemented on each lot. In this particular design roofs will drain to raingardens at all downspouts. Half of all lawns will be covered by gardens with natural native landscaping. Porous pavements will be used on driveways sidewalks and other non-street pavements. Drainage swales will be used in place of stormwater pipes. A 50 year life cycle was assumed for all cost and benefit calculations. In calculating dollar values, Green Values used Low Cost, Mid Cost and High Cost estimates for Construction, Maintenance and component Lifespan. These estimates were applied individually to concrete sidewalk and driveway, curbs and gutters, detention basins, green roofs, native plants, porous pavement, rain garden, sewer pipes, standard roof, street, trees, turn, vegetated swale averaged, vegetated swale planting, vegetated swale, and planter box. Each item was estimated as applicable for the specifics of this development and those that were not applicable were not included in the estimation. The Green Values website cited in this document provides a list of textbook citations as justification for its estimation procedures. Per lot life cycle costs Reduction can be expected to be $57,000 and total life cycle costs reductions can be expected to be $13,400,000. First year savings per lot can be expected to be in the range of $18,000. Per lot benefits over the 50 year life cycle can be expected to be increased by $650 and total life cycle benefits to be increased by $157,900. Benefits are calculated based on an assessment of reduced air pollutants, carbon dioxide sequestration, tree value, energy use and urban heat island effect reduction, groundwater recharge, reduced energy use, total suspended solids and total phosphorus removal, reduced treatment benefits, aesthetic, erosion prevention, flood prevention, habitat, mobility, property value, public health, raingardens, recreation, salt use reduction, shelter and sound absorption. As with cost estimates, a detailed list of citations and methods can be found on the Green Values website cited in this document. Table 7 summarizes the results of this analysis.

Table 7 Costs and Benefits Green Value Analysis

Costs			
Present Value Over 50 Year Life Cycle	Conventional	Green	Reduction
Per Lot Life Cycle Costs	$260,903.00	$203,825.00	$57,079.00
Total Life Cycle Costs	$61,051.00	$47,695,007.00	$13,356,377.00
First Year Site Construction and Maintenance Costs	Conventional	Green	Reduction
Per Lot Costs	$60,630.00	$42,567.00	$18,063.00
Total Costs	$14,187,514.00	$9,960,695.00	$4,226,819.00
Benefits			
Present Value Over 50 Year Life Cycle	Conventional	Green	Reduction
Per Lot Life Benefits	$ -	$675.00	$675.00
Total Life Benefits	$ -	$157,874.00	$157,874.00

Costs and benefits were further subjected to a breakout analysis. The findings of this analysis are summarized on Table 8. It presents a number of the same values as Table 7 but includes the present worth of the 50 year lifecycle savings for public costs and homeowner costs based on a per lot and total basis. Taking the total first year costs and maintenance saving and converting them to an equivalent annual worth across the 50 year life cycle, it is found that the equivalent annual savings is $164,000. This means that the first year savings experienced are the same as spending $164,000 less per year on maintenance and upkeep.

Green Values also calculated an annual increase in recharge from the developed lots of 65.1 AC-FT/yr, over what would be expected from a conventional development. The channel and detention pond designs can be expected to infiltrate at least 90.5 AC-FT annually. Of this, the 11.8 AC-FT/yr that is stored under the staging ponds can be counted against required annual irrigation requirements for parkland and counted as a public savings calculated against water costs. This is in addition to those public savings calculated by Green Values.

Table 8 Cost and Benefit Breakout Green Values Analysis

Cost Breakout		
Developer's Construction and Maintenance Costs	Conventional	Green
Per Lot Costs	$60,630.00	$42,567.00
Total Costs	$14,187,514.00	$9,960,695.00
Present Value Over 50 Year Life Cycle Public Costs	Conventional	Green
Per Lot Life Cycle Cost	$9,717.00	$7,252.00
Total Life Cycle Cost	$2,273,720.00	$1,696,858.00
Present Value Over 50 Year Life Cycle Homeowner costs	Conventional	Green
Per Lot Life Cycle Cost	$190,556.00	$154,006.00
Total Life Cycle Cost	$44,590,150.00	$3,603,745.00
Benefit Breakout		
Present Value Over 50 Year Life Cycle Public Benefits	Conventional	Green
Per Lot Life Cycle Benefits	$ -	$675.00
Total Life Cycle Benefits	$ -	$157,874.00
Present Value Over 50 Year Life Cycle Homeowner Benefits	Conventional	Green
Per Lot Life Cycle Benefits	$ -	$ -
Total Life Cycle Benefits	$ -	$ -

Alternative Designs

Steep Sided Detention/Staging Ponds

It is to be noted that significant changes in performance can be obtained by altering certain design choices. The staging damns at the top of the developments are very strong controlling factors dictating the flow rates and water depths passing through the main channels. The presented design contains ponds that have wide shallow, non-reinforced slopes that behave more like shallow pools than like detention ponds. This allows for their use as fields or park space during off seasons and flood control during rainy seasons. If altered to have steep, reinforced slopes and significantly higher storage, while covering the same area, they will no longer be able to serve such purposes but can easily be designed such that even a 100 year storm will not cause significant damage in any of the channels. Such a design would see flow rates in the channels reduced by more than 50% in some cases.

Concrete Lined Channels

If the unlined channels were to be redesigned as concrete lined channels significantly less land space would be needed. However, they would no longer be available for designation as park land and would significantly increase flow speeds during large storms. Because of this they would need to be fenced as to avoid injury or death in the channels during large storms. Storage in the detention ponds in the lower portion of the development would need to be significantly increased to account for the elimination of any infiltration in the channels during rainstorms. Even 1 year storms would see the need for some detention in the lower ponds where the unlined design sees almost no flow in the channels for a 1 year storm and no use of storage in the lower ponds.

Cemented Boulders as Check Dams

In the scale test, placing rocks that cover the same space as the check dams, in terms of height and slots for flow, were tested alongside the scale check dams. It was found that these performed easily as well as the check dams themselves as a means of slowing flow speeds while looking significantly more aesthetically pleasing. If such materials could be found at full scale, cementing them into the locations of the check dams and placing gabions beneath them would allow for flow control structures that look far more natural to the surrounding landscape and still maintain the same level of performance that is expected of the designed check dams. This also carries the potential for some decrease in cost as large stone tends to be readily available in the El Paso area and is a common building material for stone walls. For such a design, more reinforcement against erosion would be necessary. A sizable area just beneath the boulder check dams would need to be covered with gabions.

Conclusions and Recommendations

The most important conclusion reached through experimentation and modeling is that an environmentally friendly design can be implemented in this development without being prohibitively expensive. The greatest hurdle to achieving this has been identified to be the volume of flow coming into the development from the upper portion of the watershed and this exploration has demonstrated that the problem can be mitigated and the flows passing through the development can be controlled to a great degree, allowing for designs that increase infiltration and large amounts of natural landscaping.

The required flow speed is below 1.5 $^{ft}/_{sec}$ in order to prevent erosion in the unlined channels and avoid an excessive need for annual maintenance. In order to achieve this it is recommended that staging ponds be installed, hydraulically, at the top of the development in order to capture and manage the runoff that originates in the upper portion of the watershed. These ponds can be designed to allow controlled flows through the development that will be much simpler to manage and control. The viability of this approach has been shown through modeling and experimentation. Depending on the slopes used in the two main staging ponds the flows passing through the development can be controlled to varying degrees. With standard steep slopes the ponds will have enough storage to reduce runoff flows through the development to a degree that even a 100 year storm will not cause flow speeds higher than 1.5 $^{ft}/_{sec}$. However, the benefits of shallow slopes are recommended as there will be less need for unsightly fencing and the ponds will be able to be used for park land or sports fields. The result is that most storms, up to and beyond a 10 year storm, will not cause flow speeds high enough to damage any of the storm water structures. However, it is noted that for this design storms that are much larger than a 10 year storm will require maintenance of the structures to prevent serious damage.

It is recommended that unlined channels be designed to convey the runoff to its final destination using curved check dams as a means of further controlling the speed of flows. The curve of the checks will direct flow toward the middle of the channel so that typical flows will not erode the banks. This has also been verified through experimentation. The checks should either be a masonry wall with five evenly placed “V” slots that allow for immediate flow, or should be constructed of cemented large boulders or boulder-like masonry structures. The “V” slots or the gaps between boulders will allow flow to locally speed up and wash unwanted sediment from behind the checks so that they are not buried. The staging ponds above the channels will prevent an inordinate amount of sediment to wash into the channels to begin with, and in this way the conveyance system will maintain its functionality through the annual storm cycle. Slope stability in the banks of the channels will be maintained by the planting of Desert Willow and Mesquite trees all along the banks. Or by the installation of cellular confinement mats that drastically increase soil shear strength. Performance of such as system has been verified through scale simulation. It is recommended that the use of the boulder check dam design and the planting of Desert Willow and Mesquite be used as this will create the maximum aesthetic value of the system while maintaining performance.

For the development lots it is recommended that designs be implemented that have all roof downspouts draining into raingardens, at least half of all lawns should be natural landscaping using local vegetation, porous pavement should be used for all driveways, sidewalks and non-street pavement, and drainage to the stormwater conveyance structures should make use of drainage swales instead of storm water pipes. The property owner will need to confer with an appropriate design firm to properly designate slopes, sizing, and other appropriate design specifics to implement these criteria.

Before actual design and construction it is recommended that further testing be done, specifically that pilot tests be run for the intended channel and detention pond designs. This will make certain that they can be expected to perform as has been shown in computer modeling. A pilot scale of each channel, and the staging ponds including their underlying artificial perched aquifers are highly recommended.

References:

CNT. "Green Values Stormwater Management Calculator" Green Values Stormwater Toolbox 2004-2010 http://greenvalues.cnt.org/calculator/calculator

Fetter, C.W., *Applied Hydrogeology* Prentice Hall, 598, 2001, 4th ed.

FHWA (Federal Highway Administration). 1995. *Best Management Practices for Erosion and Sediment Control*. FHWA-SLP-94-005. Federal Highway Administration, Sterling, VA.

Fortier, S., and F. C. Scobey. "Permissible Canal Velocities." *Trans. ASCE*, 89, (1926), pp. 940-54.

HAMweather, "Climate for El Paso, Texas" rssWeather.com Your local weather feed http://www.rssweather.com/climate/Texas/El%20Paso/ 2003-2007.

Hutchison, William R. Conceptual Evaluation of Surface Water Storage in El Paso County, El Paso Water Utilities, November 2008

Hutchison, William R. P.G. "Hueco Bolson Groundwater Conditions and Management in the El Paso Area" El Paso Water Utilities EPWU Hydrogeology Report 04-01 March 2004 http://www.epwu.org/water/hueco_bolson/1.0Introduction.pdf

Hwang, Ned H. C., Houghtalen, Robert J., *Fundamentals of Hydraulic Engineering Systems* Prentice Hall, 416, 1996, 3rd Ed.

Michelsen, A. and Z. Sheng, 2007. Paso del Norte 2006 Floods: Water Resource Agency Assessments and Recommendations for Improved Management and Preparation, 2007 Annual Conference, American Water Resources Association, Albuquerque, NM, November 12-15, 2007.

Moreno Cardenas Inc. "Ivey Property Conceptual Master Drainage Plan (Alternative A)" "Conceptual Master Drainage Plan (Alternative B)" Verde Realty October, 2006

Moreno Cardenas Inc. "Preliminary Existing Drainage Conditions Plan (Ivey Property Alternative A)" "Preliminary Existing Drainage Conditions Plan (Ivey Property Alternative B)" Verde Realty October, 2006

Richard L. Duble "Buffalo Grass" "Bermuda Grass" Turfgrass Specialist Texas Cooperative Extension *Text and images copyright © Richard Duble.* http://aggie-horticulture.tamu.edu/plantanswers/turf/publications/buffalo.html http://aggie-horticulture.tamu.edu/plantanswers/turf/publications/bermuda.html

Sheng, Z. and J. Devere. 2005. Understanding and managing the stressed Mexico-USA transboundary Hueco bolson aquifer in the El Paso del Norte region as a complex system, Journal of Hydrogeology. 13(5-6): 813-825.

Sheng, Z. 2005. An aquifer storage and recovery system with reclaimed wastewater to preserve native groundwater resources in El Paso, Texas, Journal of Environmental Management. 75(4): 367-377.

Temple, D.M., Cook, K.R., Neilson, M.L., Yenna, S.K. "Design of Grass-Lined Channels: Procedure and Software Update" American Society of Agricultural Engineers. Paper No. 03-2099. 2003 http://www.ars.usda.gov/research/publications/Publications.htm?seq_no_115=149993

Texas Department of Transportation. "Hydraulic Design Manual" Roadside Channel Design 2009 http://onlinemanuals.txdot.gov/txdotmanuals/hyd/roadside_channel_design.htm

Texas A&M System, AgriLife Extension, Irrigation Technology Center. "El Paso County" A Project of the Irrigation Technology Center 2009 http://texaset.tamu.edu/elpaso.php

US Army Corps of Engineers Albuquerque District. Post-Flood Assessment Summer Floods of 2006 El Paso, Texas, Department of the Army, September 2007.

US Army Corps of Engineers Hydrologic Engineering Center. Hydrologic Modeling System HEC-HMS http://www.hec.usace.army.mil/software/hec-hms/documentation/HEC-HMS_Users_Manual_3.5.pdf August 2010

USEPA National Pollutant Discharge Elimination System (NPDES). "Grass Lined Channels" United States Environmental Protections Agency 2004 http://cfpub.epa.gov/npdes/stormwater/menuofbmps/index.cfm?action=browse&Rbutton=detail&bmp=38

USEPA (U.S. Environmental Protection Agency). 2004. Development Document for Final Action for Effluent Guidelines and Standards for the Construction and Development Category. EPA-821-B-04-001. Washington, DC.

Zack Guido. "Groundwater in the Arid Southwest" University of Arizona Southwest Climate Change Network September 15, 2008 http://www.southwestclimatechange.org/impacts/water/groundwater

Appendix

Table A 1 Intensity Frequency Duration

ARI* (years)	5 min	10 min	15 min	30 min	60 min	120 min	3 hr	6 hr	12 hr	24 hr	48 hr	4 day	7 day	10 day	20 day	30 day	45 day	60 day
1	0.22	0.33	0.41	0.55	0.68	0.79	0.83	0.94	1.03	1.19	1.28	1.45	1.64	1.81	2.28	2.69	3.21	3.66
2	0.28	0.43	0.53	0.71	0.88	1.02	1.07	1.20	1.31	1.52	1.64	1.86	2.10	2.33	2.93	3.45	4.10	4.68
5	0.38	0.57	0.71	0.96	1.19	1.38	1.43	1.58	1.71	2.00	2.15	2.45	2.78	3.10	3.85	4.50	5.29	6.05
10	0.45	0.69	0.86	1.15	1.43	1.67	1.72	1.87	2.01	2.37	2.56	2.91	3.32	3.71	4.56	5.29	6.17	7.03
25	0.56	0.85	1.05	1.41	1.75	2.06	2.11	2.27	2.41	2.88	3.15	3.56	4.07	4.57	5.52	6.34	7.31	8.29
50	0.64	0.97	1.20	1.62	2.01	2.36	2.42	2.58	2.72	3.29	3.62	4.07	4.67	5.25	6.25	7.13	8.15	9.21
100	0.72	1.10	1.37	1.84	2.28	2.69	2.75	2.91	3.04	3.71	4.13	4.60	5.32	5.98	7.01	7.93	9.00	10.13
200	0.81	1.24	1.53	2.07	2.56	3.03	3.10	3.25	3.36	4.16	4.68	5.17	5.99	6.76	7.79	8.74	9.83	11.03
500	0.94	1.42	1.76	2.38	2.94	3.50	3.58	3.71	3.79	4.79	5.46	5.99	6.96	7.84	8.91	9.82	10.91	12.19
1000	1.03	1.57	1.95	2.63	3.25	3.88	3.97	4.08	4.14	5.29	6.12	6.66	7.73	8.73	9.80	10.69	11.73	13.04

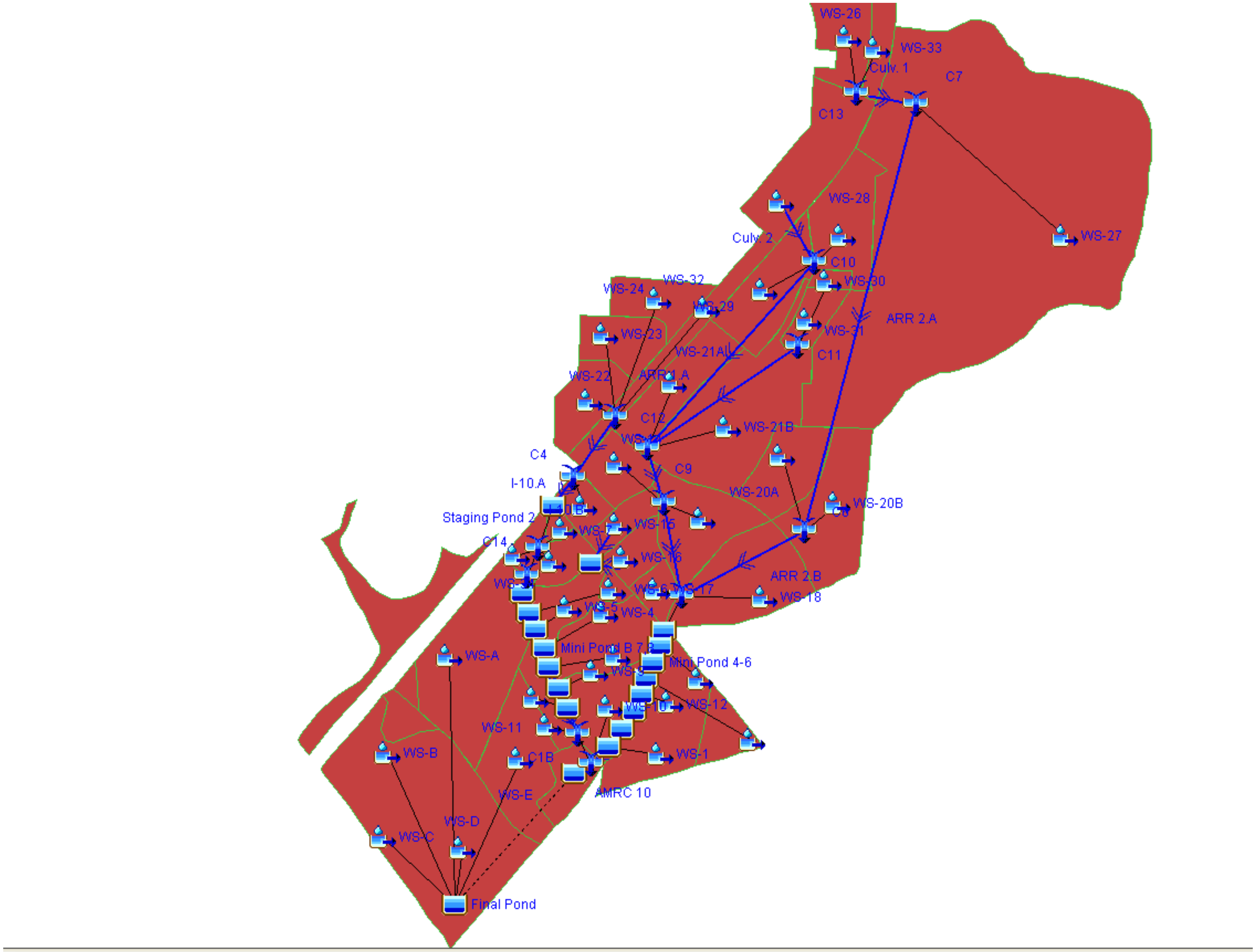


Figure A 1 HEC-HMS UI Model

Table A 2 Sub basin Parameters

WS	Area (Mi^2)	Initial Loss (in)	Constant Rate (in/hr)	Impervious (%)	Standard Lag (hr)	Peaking Coefficient
24	0.039	0.8	0.4	0	0.21	0.67
32	0.048	0.5	0.25	100	0.21	0.67
23	0.042	0.1	0.05	85	0.21	0.67
22	0.044	0.1	0.05	50	0.21	0.67
13	0.022	0.1	0.05	20	0.108	0.67
7	0.023	0.5	0.25	30	0.138	0.67
35	0.038	0.5	0.25	25	0.126	0.67
34	0.018	0.1	0.25	10	0.105	0.67
15	0.023	0.1	0.05	80	0.21	0.67
16	0.023	0.1	0.05	83	0.21	0.67
6	0.007	0.5	0.25	40	0.122	0.67
5	0.066	0.1	0.05	20	0.21	0.67
4	0.066	0.5	0.25	5	0.21	0.67
3	0.058	0.5	0.25	0	0.21	0.67
8	0.103	0.5	0.25	0	0.21	0.67
25	0.091	0.1	0.05	90	0.21	0.67
29	0.069	0.8	0.4	4	0.21	0.67
28	0.07	0.1	0.05	80	0.21	0.67
31	0.023	0.8	0.4	0	0.124	0.67
30	0.007	0.1	0.05	50	0.113	0.67
21B	0.155	0.1	0.05	90	0.4	0.67
21A	0.06	0.1	0.05	80	0.21	0.67
19	0.075	0.5	0.25	65	0.21	0.67
14	0.035	0.1	0.05	10	0.21	0.67
26	0.044	0.1	0.05	60	0.21	0.67
33	0.015	0.1	0.05	100	0.1	0.67
27	0.921	0.8	0.4	5	1.22	0.67
20B	0.094	0.1	0.05	90	0.21	0.67
20A	0.05	0.1	0.05	90	0.21	0.67
18	0.097	0.8	0.4	60	0.25	0.67
17	0.018	0.1	0.05	50	0.21	0.67
2	0.099	0.5	0.25	5	0.21	0.67

Table A 3 Arroyo Surveys

T	Station	Elevation
	0	3697.525
	16	3697.525
	17	3688.525
	87	3689.17
	120	3689
	157	3690
	158	3702.57
	179	3702.57

s	Sation	Eleveation
	0	3697.525
	16	3697.525
	17	3688.525
	50	3689
	87	3689.17
	157	3689.57
	158	3702.57
	179	3702.57

AR 3.C(O)	Station	Elevation
	0	3701.545
	3.5	3695.85
	12	3692.93
	20	3692.93
	40	3692.93
	55	3693
	75	3693.2
	78.65	3698.3

AR 3.C(Q)	Station	Elevation
	0	3603.75
	4.45	3603.49
	5	3599.72
	8	3599.7
	12	3599.69
	18.5	3599.74
	19	3603.36
	33.93	3603.635

ARR 3.B(K)	Station	Elevation
	0	3630.29
	14	3630.46
	23.48	3633.3
	31.8	3626.44
	59	3626.43
	66.1	3630.43
	94	3628.38
	105	3627.9

ARR .3B(M)	Station	Elevation
	0	3706.49
	4	3703.68
	6	3703.55
	8	3705.99
	11	3704.54
	13	3705.21
	15	3703.2
	20	3707.41

ARR 3.C(N)	Station	Elevation
	4.6	3699.915
	9.6	3695.3
	23.5	3695.41
	27.3	3695.18
	36.8	3695.95
	45.2	3695.53
	60.5	3699.21
	73.7	3699.56

ARR 3C(P)	Station	Elevation
	0	3699.25
	7.8	3698.97
	10	3690.25
	13.5	3688.74
	44	3688.95
	81	3689.04
	104.7	3697.09
	112	3697.66

ARROYO-T1	Station	Elevation
	5.8	3624.77
	7	3617.73
	13	3613.73
	95	3614.83
	221	3614.62
	225	3617.3
	228.2	3623.11
	235.5	3623.91

ARROYO-TT	Station	Elevation
	0	3623.58
	8.7	3622.67
	10	3615.58
	18	3611.07
	102	3611.74
	196.5	3612.39
	199	3621.51
	203.5	3621.46

ARROYO-U	Station	Elevation
	0	3718.34
	57	3714.2
	69.1	3706.91
	137	3707.56
	199	3707.2
	205	3708.12
	208	3720.5
	254	3721.01

ARROYO-U1	Station	Elevation
	0	3718.34
	57	3714.2
	69.1	3706.91
	137	3707.56
	199	3707.2
	205	3708.12
	208	3720.5
	254	3721.01

ARROYO-V	Station	Elevation
	0	3734.62
	4	3734.37
	24	3725.05
	55	3722.3
	64	3716.18
	116	3715.41
	147	3718.22
	162.6	3736.09

ARROYO-V1	Station	Elevation
	11.2	3657.505
	21	3632.53
	27	3627.9
	65	3626.894
	114	3626.8
	124	3632.845
	126.2	3655.02
	130.4	3655.035

Table A 4 Channel Routing

Culv. 1	
Length (ft)	390
Slope (ft/ft)	0.03
Manning's n	0.013
Shape	Rectangle
Width (ft)	4
Material	Concrete Box

ARR 2.A	
Length (ft)	6000
Slope (ft/ft)	0.022
Manning's n	0.03
Shape	Rectangle
Width (ft)	40
Material	Unlined

ARR 2.B	
Length (ft)	5000
Slope (ft/ft)	0.017
Manning's n	0.013
Shape	Rectangle
Width (ft)	50
Material	Concrete Lined

Culv. 2	
Length (ft)	390
Slope (ft/ft)	0.05
Manning's n	0.013
Shape	Rectangle
Width (ft)	18
Material	Concrete Box

ARR 1.A	
Length (ft)	2600
Slope (ft/ft)	0.019
Manning's n	0.03
Shape	Rectangle
Width (ft)	50
Material	Unlined

ARR 1.B	
Length (ft)	2500
Slope (ft/ft)	0.025
Manning's n	0.03
Shape	Rectangle
Width (ft)	60
Material	Concrete Lined

ARR 1.C	
Length (ft)	2400
Slope (ft/ft)	0.014
Manning's n	0.012
Shape	Rectangle
Width (ft)	60
Material	Concrete Lined

ARROYO-V	
Length (ft)	350
Slope (ft/ft)	0.006
Manning's n	0.03
Shape	Eight Point
Left Manning's n	0.03
Right Manning's n	0.03
Cross Section	ARROYO-V
Material	Unlined

AYYOU-V1	
Length (ft)	140
Slope (ft/ft)	0.014
Manning's n	0.03
Shape	Eight Point
Left Manning's n	0.03
Right Manning's n	0.03
Cross Section	ARROYO-V1
Material	Unlined

ARROYO-U	
Length (ft)	535
Slope (ft/ft)	0.021
Manning's n	0.03
Shape	Eight Point
Left Manning's n	0.03
Right Manning's n	0.03
Cross Section	ARROYO-U
Material	Unlined

ARROYO-U1	
Length (ft)	235
Slope (ft/ft)	0.017
Manning's n	0.03
Shape	Eight Point
Left Manning's n	0.03
Right Manning's n	0.03
Cross Section	ARROYO-U1
Material	Unlined

ARROYO-T1	
Length (ft)	300
Slope (ft/ft)	0.023
Manning's n	0.03
Shape	Eight Point
Left Manning's n	0.03
Right Manning's n	0.03
Cross Section	ARROYO-T1
Material	Unlined

ARROYO-TT	
Length (ft)	140
Slope (ft/ft)	0.029
Manning's n	0.03
Shape	Eight Point
Left Manning's n	0.03
Right Manning's n	0.03
Cross Section	ARROYO-TT
Material	Unlined

ARROYO-T	
Length (ft)	380
Slope (ft/ft)	0.026
Manning's n	0.03
Shape	Eight Point
Left Manning's n	0.03
Right Manning's n	0.03
Cross Section	ARROYO-T
Material	Unlined

ARROYO-S	
Length (ft)	330
Slope (ft/ft)	0.024
Manning's n	0.03
Shape	Eigth Point
Left Manning's n	0.03
Right Manning's n	0.03
Cross Section	ARROYO-S
Material	Unlined

Culv. 3	
Length (ft)	1680
Slope (ft/ft)	0.03
Manning's n	0.013
Shape	Rectangle
Width (ft)	16
Material	Concrete Lined

I-10.A	
Length (ft)	400
Slope (ft/ft)	0.03
Manning's n	0.013
Shape	Rectangle
Width (ft)	20
Material	Concrete Box

I-10.B	
Length (ft)	400
Slope (ft/ft)	0.03
Manning's n	0.013
Shape	Circle
Diameter (ft)	4
Material	Concrete Cylinder

I-10.C	
Length (ft)	400
Slope (ft/ft)	0.03
Manning's n	0.013
Shape	Circle
Diameter (ft)	4
Material	Concrete Cylinder

ARR 3.B (K)	
Length (ft)	250
Slope (ft/ft)	0.012
Manning's n	0.03
Shape	Eight Point
Left Manning's n	0.03
Rigth Manning's n	0.03
Cross Section	ARR 3.B(K)
Material	Unlined

ARR 3.B(L)	
Length (ft)	380
Slope (ft/ft)	0.003
Manning's n	0.03
Shape	Eight Point
Left Manning's n	0.03
Right Manning's n	0.03
Cross Section	ARR 3.B(L)
Material	Unlined

ARR 3.B(M)	
Length (ft)	650
Slope (ft/ft)	0.014
Manning's n	0.03
Shape	Eight Point
Left Manning's n	0.03
Right Manning's n	0.03
Cross Section	ARR 3.B(M)
Material	Unlined

ARR 3.C(N)	
Length (ft)	775
Slope (ft/ft)	0.006
Manning's n	0.03
Shape	Eight Point
Left Manning's n	0.03
Right Manning's n	0.03
Cross Section	ARR 3.C(N)
Material	Unlined

ARR 3.C(O)	
Length (ft)	220
Slope (ft/ft)	0.014
Manning's n	0.03
Shape	Eight Point
Left Manning's n	0.03
Right Manning's n	0.03
Cross Section	ARR 3. C(O)
Material	Unlined

ARR 3.C(P)	
Length (ft)	300
Slope (ft/ft)	0.007
Manning's n	0.03
Shape	Eight Point
Left Manning's n	0.03
Right Manning's n	0.03
Cross Section	ARR 3.C(P)
Material	Unlined

ARR 3.C(Q)	
Length (ft)	380
Slope (ft/ft)	0.026
Manning's n	0.03
Shape	Eight Point
Left Manning's n	0.03
Right Manning's n	0.03
Cross Section	ARR 3.C(Q)
Material	Unlined

Table A 5 Site 2 Infiltration Tests

Time (min)	Tube Depth (in)	Change in Tube Depth (in)	Change in Tube Volume (in^3)	Change in Inner Ring Depth (in)	Rate of Infiltration (in/min)	Rate of Infiltration (in/hr)	Infiltration (CFS/Acre)
0	18.4						
1	17.9	0.4	4.2	0	0	2.2	2.3
2	16.8	1.1	10.8	0.1	0.1	5.7	5.8
3	15.4	1.4	13.2	0.1	0.1	7	7.1
4	13.9	1.6	15	0.1	0.1	8	8
5	12.3	1.6	15	0.1	0.1	8	8
6	10.6	1.8	16.8	0.1	0.1	8.9	9
7	8.8	1.8	17.4	0.2	0.2	9.3	9.3
8	6.9	1.9	18	0.2	0.2	9.6	9.7
9	4.9	2	19.2	0.2	0.2	10.2	10.3
10	2.8	2.1	19.8	0.2	0.2	10.5	10.6
14.5	21.3						
15	20.8	0.5	4.8	0	0.1	5.1	5.1
16	19.7	1.1	10.2	0.1	0.1	5.4	5.5
17	18.4	1.3	12	0.1	0.1	6.4	6.4
18	16.8	1.6	15.6	0.1	0.1	8.3	8.4
19	15.1	1.7	16.2	0.1	0.1	8.6	8.7
20	13.4	1.8	16.8	0.1	0.1	8.9	9
21	11.5	1.9	18	0.2	0.2	9.6	9.7
22	9.6	1.9	18	0.2	0.2	9.6	9.7
23	7.8	1.9	18	0.2	0.2	9.6	9.7
24	5.7	2.1	19.8	0.2	0.2	10.5	10.6
25	3.8	1.9	18.6	0.2	0.2	9.9	10
26	1.6	2.1	20.4	0.2	0.2	10.8	10.9
30.2	21.5						
32	19.9	1.6	15.6	0.1	0.1	4.5	4.6
34	17	2.9	27.6	0.2	0.1	7.3	7.4
36	13.5	3.5	33.7	0.3	0.1	8.9	9
38	9.9	3.6	34.3	0.3	0.2	9.1	9.2
40	6.1	3.8	36.7	0.3	0.2	9.7	9.8
42	2.4	3.8	36.1	0.3	0.2	9.6	9.7

Table A 6 Table A5 Cont.: Infiltration Tests

Time (min)	Tube Depth (in)	Change in Tube Depth (in)	Change in Tube Volume (in^3)	Change in Inner Ring Depth (in)	Rate of Infiltration (in/min)	Rate of Infiltration (in/hr)	Infiltration (CFS/Acre)
0	2.5	8.9					
5	3.4	8			0.2		10.5
10	4.5	6.9			0.2		
15	5.3	6.2			0.2		
20	6.1	5.3			0.2		10.5
25	7.1	4.3			0.2		
30	7.9	3.5			0.2		9
35	8.6	2.8			0.2		9
40	9.4	2			0.2		9

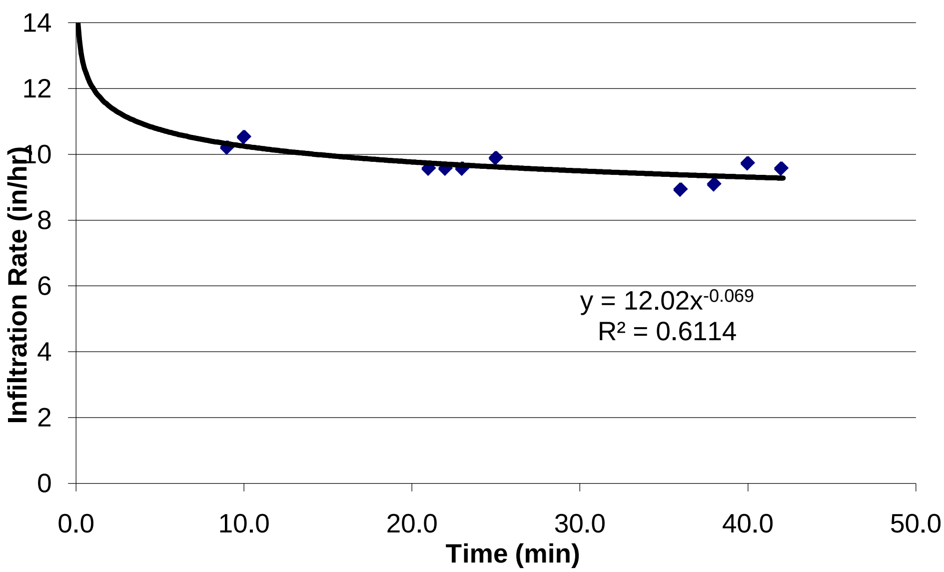


Figure A 2 Site 2 Static Head Infiltration Test

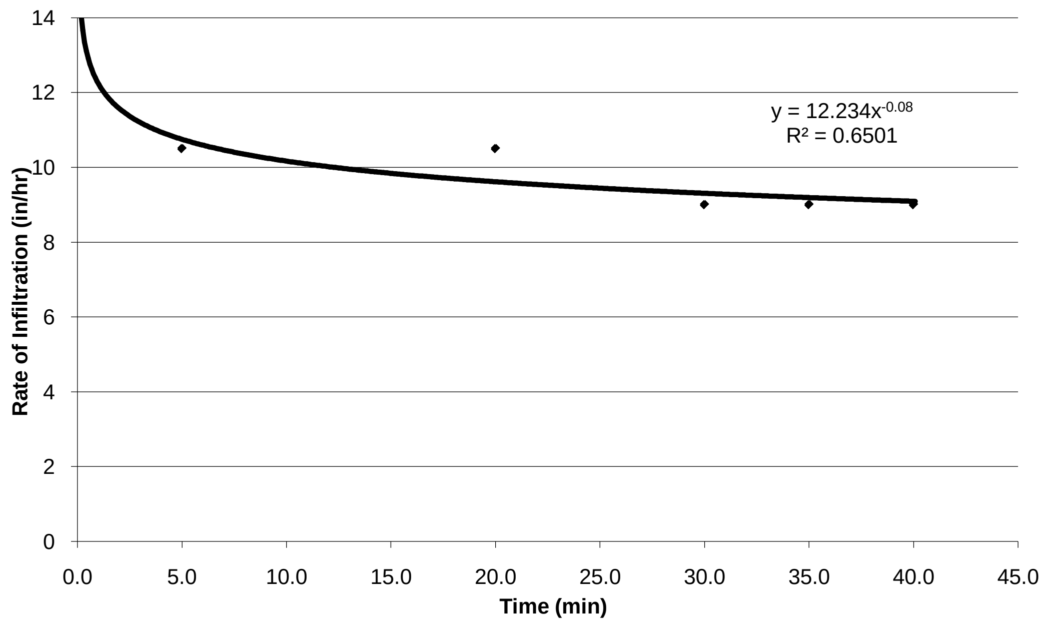


Figure A 3 Site 2 Falling Head Infiltration Test

Table A 7 Site 2 Permeability Test

Time (sec)		Time	Height (cm)		Water Level	Permeability	Permeability
Start	End	Interval	Start	End	Change (cm)	(cm/s)	(in/hr)
0	120	120	53.1	49.2	3.9	0.033	46
120	240	120	49.2	45.2	4	0.033	47.2
240	470	230	45.2	37.2	8	0.035	49.2
470	821	351	37.2	24.9	12.3	0.035	49.6
821	1148	327	24.9	13.4	11.5	0.035	49.8
1148	1292	144	13.4	8.4	5	0.035	49.2
1292	1365	73	8.4	5.7	2.7	0.037	52.4
					Average	0.035	49.1

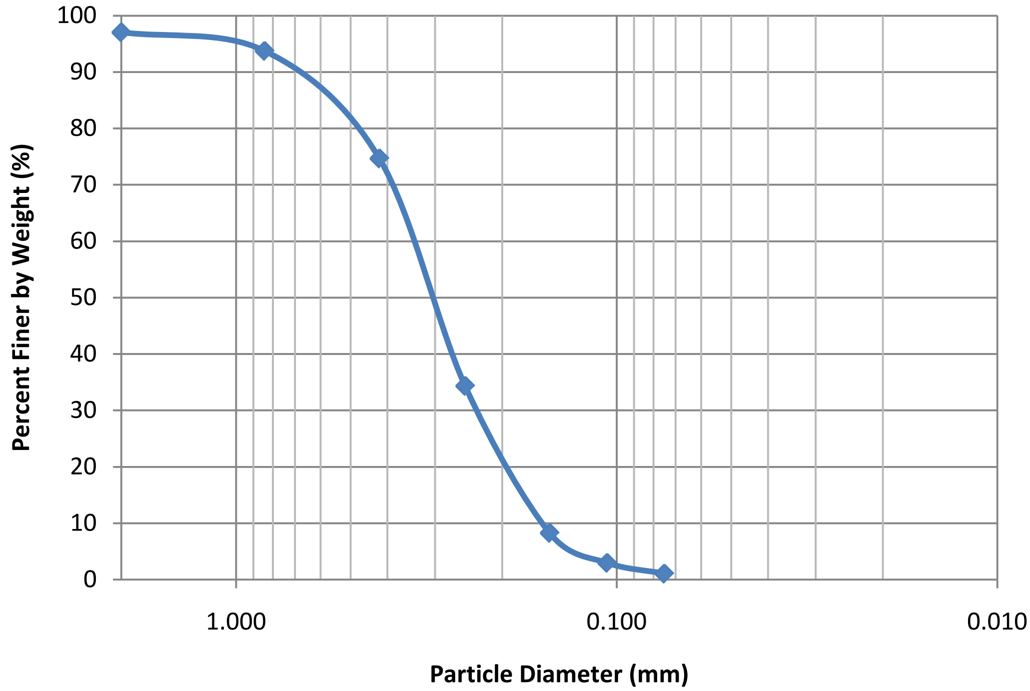


Figure A 4 Site 2 Sieve Test

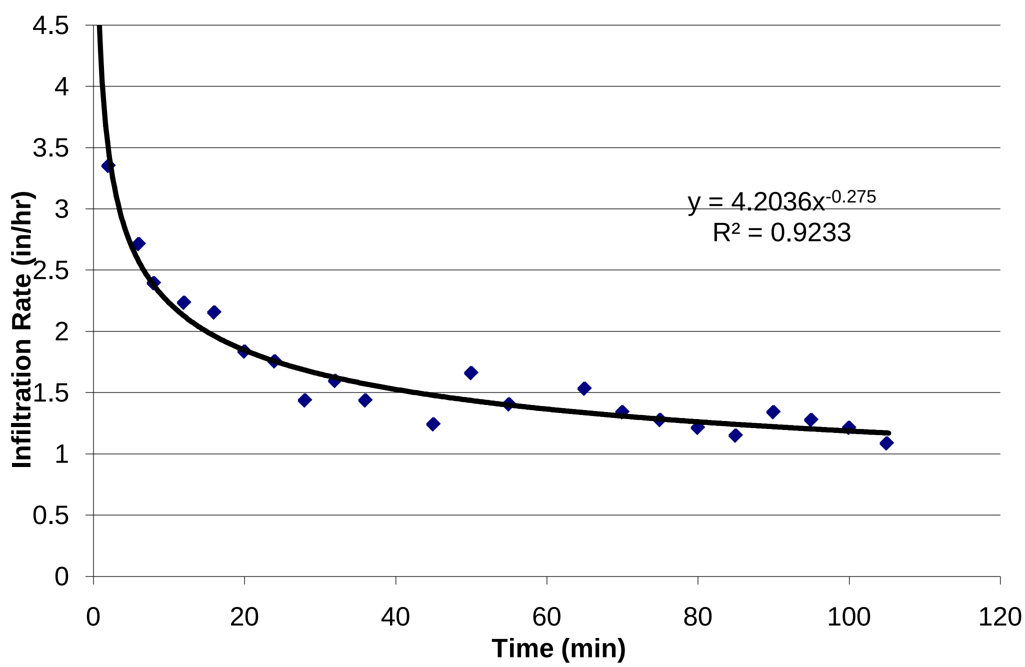


Figure A 5 Site 3 Static Head Infiltration Test

Table A 8 Site 3 Infiltration Test

Time (min)	Tube Depth (in)	Change in Tube Depth (in)	Change in Tube Volume (in^3)	Change in Inner Ring Depth (in)	Rate of Infiltration (in/min)	Rate of Infiltration (in/hr)	Infiltration (CFS/Acre)
0	20.8						
2	19.5	1.3	12.6	0.1	0.1	3.3	3.4
6	17.4	2.1	20.4	0.2	0	2.7	2.7
8	16.4	0.9	9	0.1	0	2.4	2.4
12	14.7	1.8	16.8	0.1	0	2.2	2.3
16	13	1.7	16.2	0.1	0	2.2	2.2
20	11.6	1.4	13.8	0.1	0	1.8	1.8
24	10.2	1.4	13.2	0.1	0	1.8	1.8
28	9.1	1.1	10.8	0.1	0	1.4	1.4
32	7.8	1.3	12	0.1	0	1.6	1.6
36	6.7	1.1	10.8	0.1	0	1.4	1.4
45	4.5	2.2	21	0.2	0	1.2	1.3
50	2.9	1.6	15.6	0.1	0	1.7	1.7
55	1.5	1.4	13.2	0.1	0	1.4	1.4
62.5	19.8						
65	19.1	0.8	7.2	0.1	0	1.5	1.5
70	17.8	1.3	12.6	0.1	0	1.3	1.4
75	16.5	1.3	12	0.1	0	1.3	1.3
80	15.3	1.2	11.4	0.1	0	1.2	1.2
85	14.2	1.1	10.8	0.1	0	1.1	1.2
90	12.9	1.3	12.6	0.1	0	1.3	1.4
95	11.6	1.3	12	0.1	0	1.3	1.3
100	10.4	1.2	11.4	0.1	0	1.2	1.2
105	9.4	1.1	10.2	0.1	0	1.1	1.1

Table A 9 Site 3 Permeability Test

Time (min)		Time	Height (cm)		Water	Permeability	Permeability
Start	End	Interval	Start	End	Level Change	(cm/s)	(in/hr)
0	33	33	54.9	54.5	0.4	0.0002	0.28
33	210	177	54.5	51.4	3.1	0.00029	0.41
210	241	31	51.4	51	0.4	0.00022	0.3
0	68820	68820	51	35.5	15.5	0	0.01
					Average	0.00018	0.25

Time (min)		Time	Height (cm)		Water	Permeability	Permeability
Start	End	Interval	Start	End	Level Change	(cm/s)	(in/hr)
0	33	33	55.5	52.4	3.1	0.00157	2.21
33	241	208	52.4	52.1	0.3	0.00002	0.03
0	68820	68820	52.1	41.8	10.3	0	0.003
					Average	0.00053	0.75

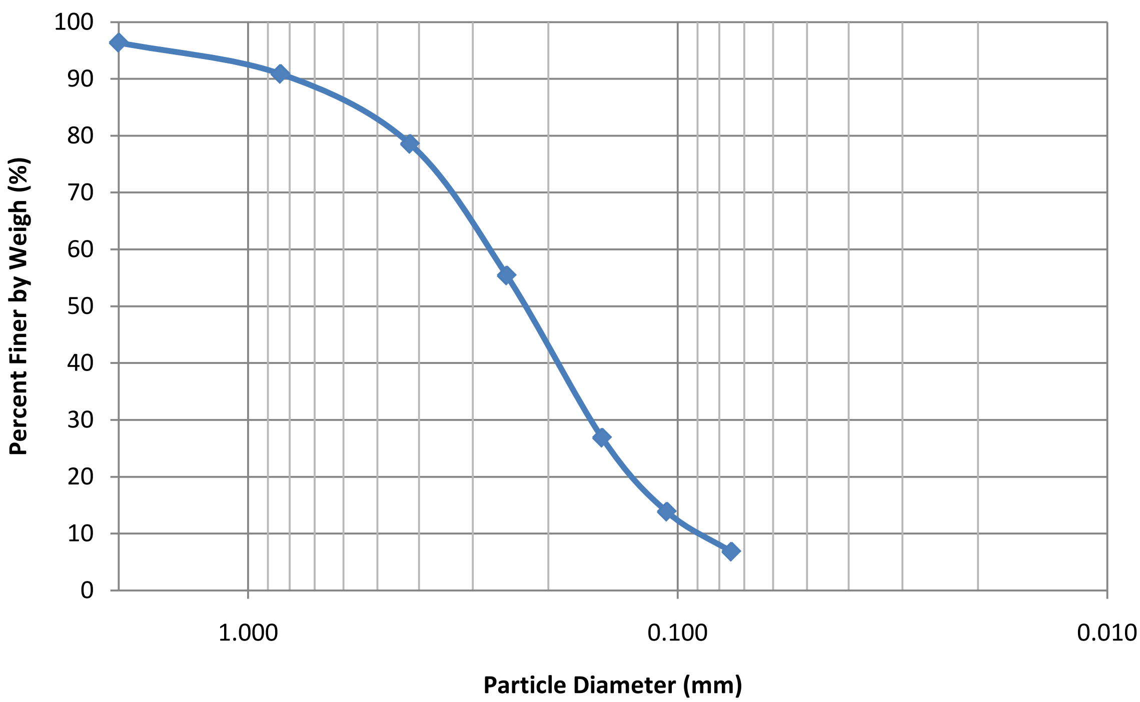


Figure A 6 Site 3 Sieve Test

Table A 10 Site 4 Infiltration Test

Time (min)	Tube Depth (in)	Change in Tube Depth (in)	Change in Tube Volume (in^3)	Change in Inner Ring Depth (in)	Rate of Infiltration (in/min)	Rate of Infiltration (in/hr)	Infiltration (CFS/Acre)
0	21.5						
2.5	13	8.5	81.7	0.7	0.3	17.4	17.5
3	11.4	1.6	15	0.1	0.3	16	16.1
4	8.1	3.3	31.9	0.3	0.3	16.9	17
5	4.8	3.4	32.5	0.3	0.3	17.2	17.4
6	1.5	3.3	31.3	0.3	0.3	16.6	16.7
0	17.5						
2	14.9	2.6	24.6	0.2	0.1	6.5	6.6
4	11.3	3.7	35.5	0.3	0.2	9.4	9.5
6	6.8	4.4	42.7	0.4	0.2	11.3	11.4
8	2.3	4.6	43.9	0.4	0.2	11.6	11.7
							0
0	22						0
2	19.3	2.8	26.4	0.2	0.1	7	7.1
4	15.6	3.6	34.9	0.3	0.2	9.3	9.3
6	11.4	4.2	40.3	0.4	0.2	10.7	10.8
8	6.8	4.7	45.1	0.4	0.2	12	12.1
10	2	4.8	45.7	0.4	0.2	12.1	12.2
0	21.4						
3	17	4.4	42.7	0.4	0.1	7.5	7.6
4	15.1	1.9	18.6	0.2	0.2	9.9	10
6	11	4.1	39.1	0.3	0.2	10.4	10.5
8	6.5	4.5	43.3	0.4	0.2	11.5	11.6
10	1.8	4.8	45.7	0.4	0.2	12.1	12.2
0	21.8						
2	19.5	2.3	21.6	0.2	0.1	5.7	5.8
4	16	3.5	33.7	0.3	0.1	8.9	9
6	11.9	4.1	39.7	0.4	0.2	10.5	10.6
8	7.4	4.4	42.7	0.4	0.2	11.3	11.4
10	2.8	4.7	45.1	0.4	0.2	12	12.1

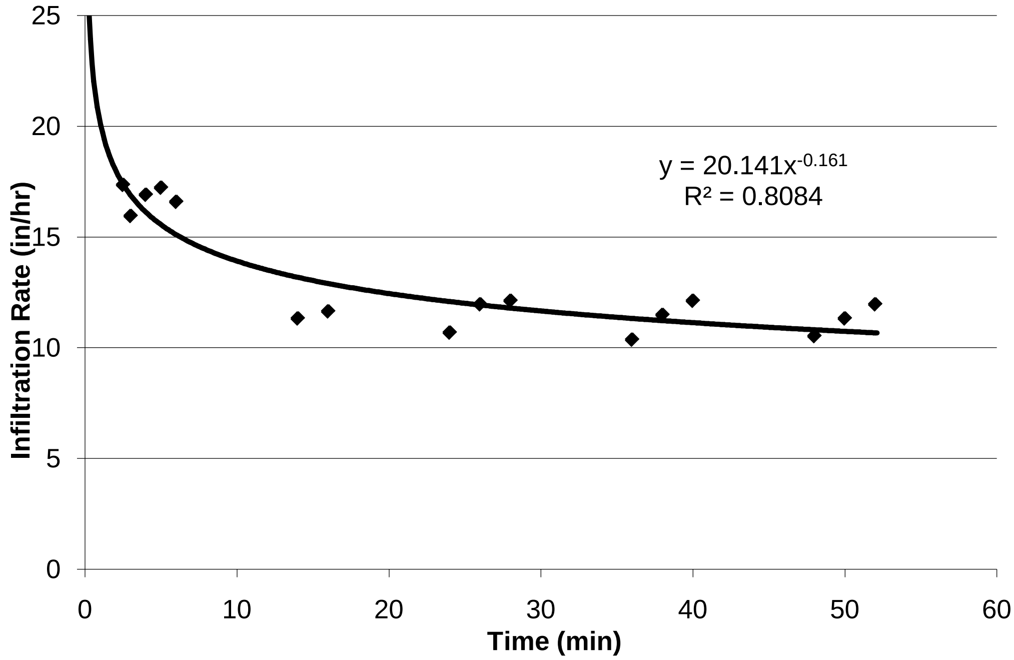


Figure A 7 Site 4 Static Head Infiltration Test

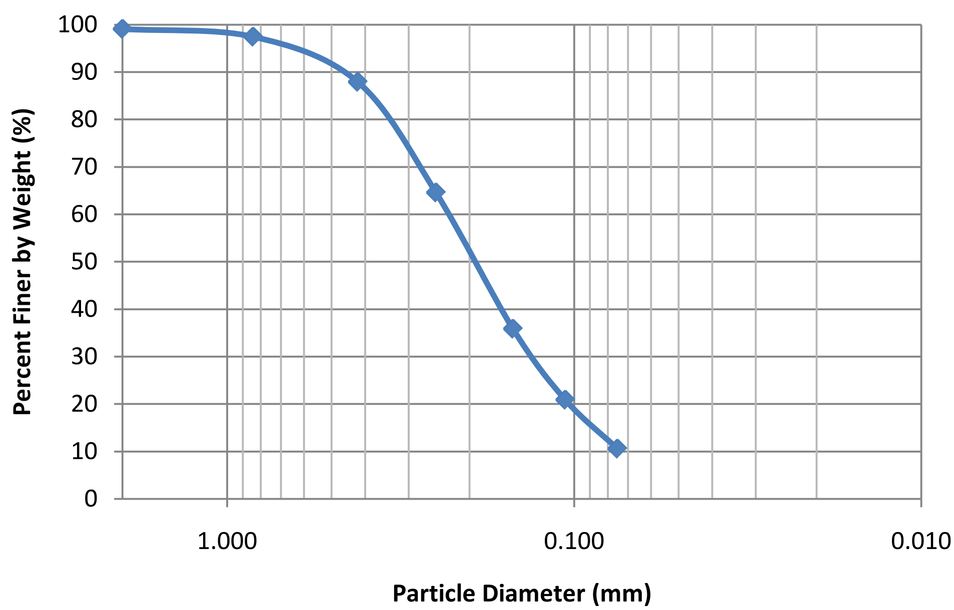


Figure A 8 Site 4 Sieve Test

Table A 11 Site 4 Permeability Test

Time Start	Time End	Time Interval	Height (cm) Start	Height (cm) End	Water Level Change	Permeability (cm/s)	Permeability (in/hr)
0	10260	10260	54.7	53	1.7	0.00016	0.23
10260	15000	4740	53	52.2	0.8	0.00017	0.24
0	240660	240660	54.9	13.2	41.7	0.00017	0.25
					Average	0.00017	0.24

Time Start	Time End	Time Interval	Height (cm) Start	Height (cm) End	Water Level Change	Permeability (cm/s)	Permeability (in/hr)
0	3420	3420	54.6	53.9	0.7	0.0002	0.29
3420	10440	7020	53.9	51.8	2.1	0.00029	0.42
10440	14040	3600	51.8	50.8	1	0.00027	0.39
14040	17760	3720	50.8	49.8	1	0.00026	0.38
0	68340	68340	49.8	35	14.8	0.00021	0.31
0	10260	10260	35	33	2	0.00019	0.28
10260	15000	4740	33	32.1	0.9	0.00019	0.27
0	240660	240660	54.5	9.2	45.3	0.00019	0.27
					Average	0.00023	0.33

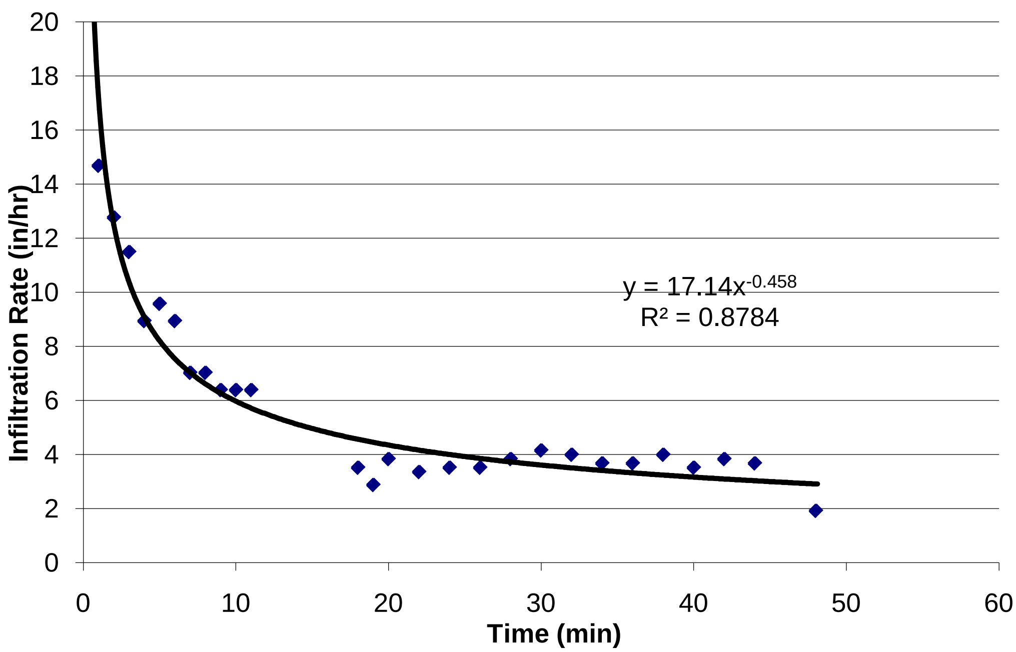


Figure A 9 Site 5 Static Head Infiltration Test

Table A 12 Site 5 Infiltration Test

Time (min)	Tube Depth (in)	Change in Tube Depth (in)	Change in Tube Volume (in^3)	Change in Inner Ring Depth (in)	Rate of Infiltration (in/min)	Rate of Infiltration (in/hr)	Infiltration (CFS/Acre)
0	21.5						
1	18.6	2.9	27.6	0.2	0.2	14.7	14.8
2	16.1	2.5	24	0.2	0.2	12.8	12.9
3	13.9	2.3	21.6	0.2	0.2	11.5	11.6
4	12.1	1.8	16.8	0.1	0.1	8.9	9
5	10.3	1.9	18	0.2	0.2	9.6	9.7
6	8.5	1.8	16.8	0.1	0.1	8.9	9
7	7.1	1.4	13.2	0.1	0.1	7	7.1
8	5.8	1.4	13.2	0.1	0.1	7	7.1
9	4.5	1.3	12	0.1	0.1	6.4	6.4
10	3.3	1.3	12	0.1	0.1	6.4	6.4
11	2	1.3	12	0.1	0.1	6.4	6.4
14	22.2						
15	22.1	0.1	1.2	0	0	0.6	0.6
16	21.8	0.3	2.4	0	0	1.3	1.3
17	21.5	0.3	3	0	0	1.6	1.6
18	20.8	0.7	6.6	0.1	0.1	3.5	3.5
19	20.3	0.6	5.4	0	0	2.9	2.9
20	19.5	0.8	7.2	0.1	0.1	3.8	3.9
22	18.2	1.3	12.6	0.1	0.1	3.3	3.4
24	16.8	1.4	13.2	0.1	0.1	3.5	3.5
26	15.4	1.4	13.2	0.1	0.1	3.5	3.5
28	13.9	1.5	14.4	0.1	0.1	3.8	3.9
30	12.3	1.6	15.6	0.1	0.1	4.1	4.2
32	10.8	1.6	15	0.1	0.1	4	4
34	9.3	1.4	13.8	0.1	0.1	3.7	3.7
36	7.9	1.4	13.8	0.1	0.1	3.7	3.7
38	6.3	1.6	15	0.1	0.1	4	4
40	4.9	1.4	13.2	0.1	0.1	3.5	3.5
42	3.4	1.5	14.4	0.1	0.1	3.8	3.9
44	2	1.4	13.8	0.1	0.1	3.7	3.7
48	0.5	1.5	14.4	0.1	0	1.9	1.9

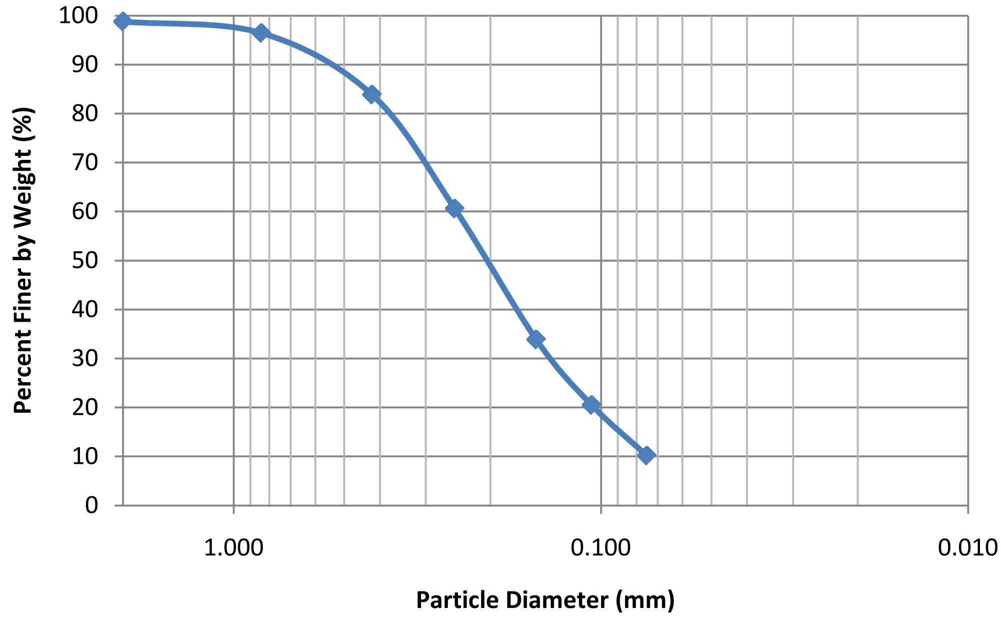


Figure A 10 Site 5 Sieve Test

Table A 13 Site 5 Permeability Test

Time			Height (cm)		Water		
Start	End	Time Interval	Start	End	Level Change	Permeability (cm/s)	Permeability (in/hr)
0	8160	8160	55	52.1	2.9	0.00036	0.5
8160	11700	3540	52.1	51.5	0.6	0.00017	0.24
11700	14400	2700	51.5	50.6	0.9	0.00033	0.47
					Average	0.00028	0.41

Time			Height (cm)		Water		
Start	End	Time Interval	Start	End	Level Change	Permeability (cm/s)	Permeability (in/hr)
0	8160	8160	54.5	45.4	9.1	0.0011	1.58
8160	11700	3540	52.1	41.1	11	0.0031	4.4
11700	14400	2700	41.1	37.9	3.2	0.0012	1.68
					Average	0.0018	2.55

Table A 14 Site 7 Infiltration Test

Time (min)	Tube Depth (in)	Change in Tube Depth (in)	Change in Tube Volume (in^3)	Change in Inner Ring Depth (in)	Rate of Infiltration (in/min)	Rate of Infiltratio n (in/hr)	Infiltration (CFS/Acre)
0	21.5						
2	20.3	1.2	11.4	0.1	0.1	3	3.1
4	18.3	2	19.2	0.2	0.1	5.1	5.1
6	16.2	2.1	20.4	0.2	0.1	5.4	5.5
8	13.9	2.3	21.6	0.2	0.1	5.7	5.8
10	11.8	2.2	21	0.2	0.1	5.6	5.6
12	9.6	2.1	20.4	0.2	0.1	5.4	5.5
14	7.6	2.1	19.8	0.2	0.1	5.3	5.3
16	5.6	1.9	18.6	0.2	0.1	4.9	5
18	3.4	2.3	21.6	0.2	0.1	5.7	5.8
20	1.3	2.1	19.8	0.2	0.1	5.3	5.3
26	21.3						
28	20.6	0.7	6.6	0.1	0	1.8	1.8
30	19.2	1.4	13.8	0.1	0.1	3.7	3.7
32	17.7	1.5	14.4	0.1	0.1	3.8	3.9
34	16	1.7	16.2	0.1	0.1	4.3	4.3
36	14.2	1.8	17.4	0.2	0.1	4.6	4.7
38	12.3	1.9	18	0.2	0.1	4.8	4.8
40	10.4	1.9	18	0.2	0.1	4.8	4.8
42	8.7	1.8	16.8	0.1	0.1	4.5	4.5
44	6.8	1.9	18	0.2	0.1	4.8	4.8
46	4.9	1.9	18.6	0.2	0.1	4.9	5
48	2.9	1.9	18.6	0.2	0.1	4.9	5
51.1	21.4						
52	20.9	0.5	4.8	0	0	2.7	2.8
54	19.4	1.5	14.4	0.1	0.1	3.8	3.9
56	17.8	1.6	15.6	0.1	0.1	4.1	4.2
58	16	1.8	17.4	0.2	0.1	4.6	4.7
60	14.3	1.8	16.8	0.1	0.1	4.5	4.5
62	12.5	1.8	16.8	0.1	0.1	4.5	4.5
64	10.7	1.8	17.4	0.2	0.1	4.6	4.7
66	8.7	2	19.2	0.2	0.1	5.1	5.1
68	6.9	1.8	16.8	0.1	0.1	4.5	4.5
70	4.6	2.3	22.2	0.2	0.1	5.9	6
72	2.7	1.9	18.6	0.2	0.1	4.9	5

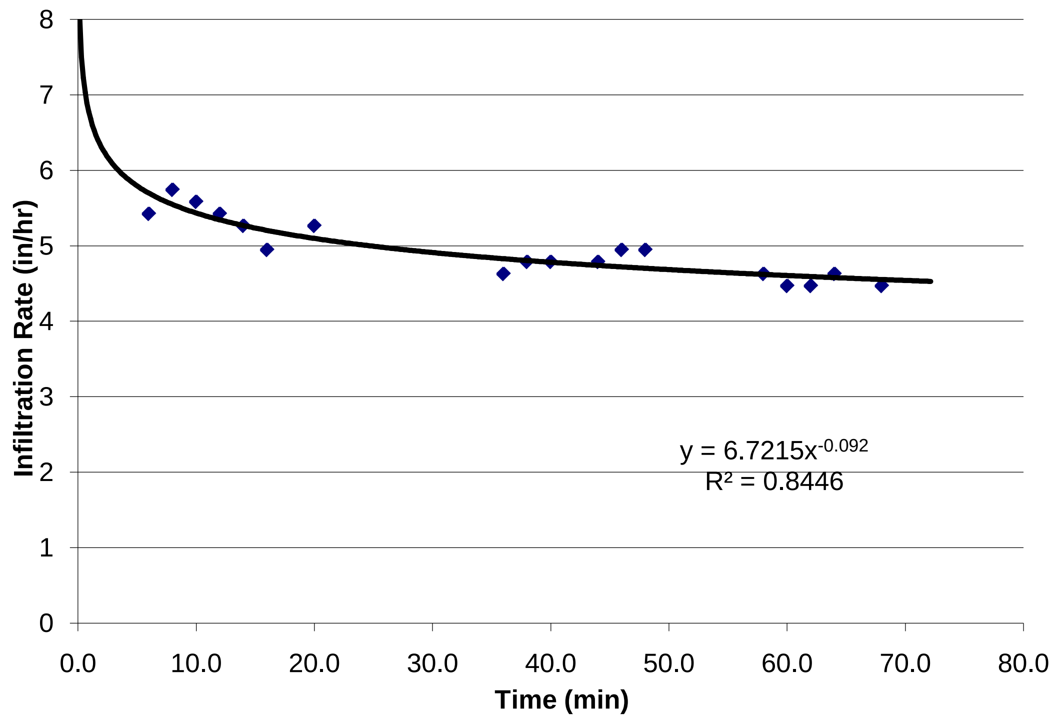


Figure A 11 Site 7 Static Head Infiltration Test

Table A 15 Site 7 Permeability Test

Time		Time Interval	Height (cm)		Water Level Change	Permeability (cm/s)	Permeability (in/hr)
Start	End		Start	End			
0	1260	1260	54.1	53.6	0.5	0.0004	0.56
1260	1800	540	53.6	53.2	0.4	0.00074	1.05
1800	2460	660	53.2	52.7	0.5	0.00076	1.07
2460	3120	660	52.7	52.1	0.6	0.00091	1.29
					Average	0.0007	0.99

Time		Time Interval	Height (cm)		Water Level Change	Permeability (cm/s)	Permeability (in/hr)
Start	End		Start	End			
0	1260	1260	54.8	52.9	1.9	0.0015	2.14
1260	1800	540	52.9	52	0.9	0.0017	2.36
1800	2460	660	52	50.9	1.1	0.0017	2.36
2460	3120	660	50.9	49.8	1.1	0.0017	2.36
					Average	0.0016	2.31

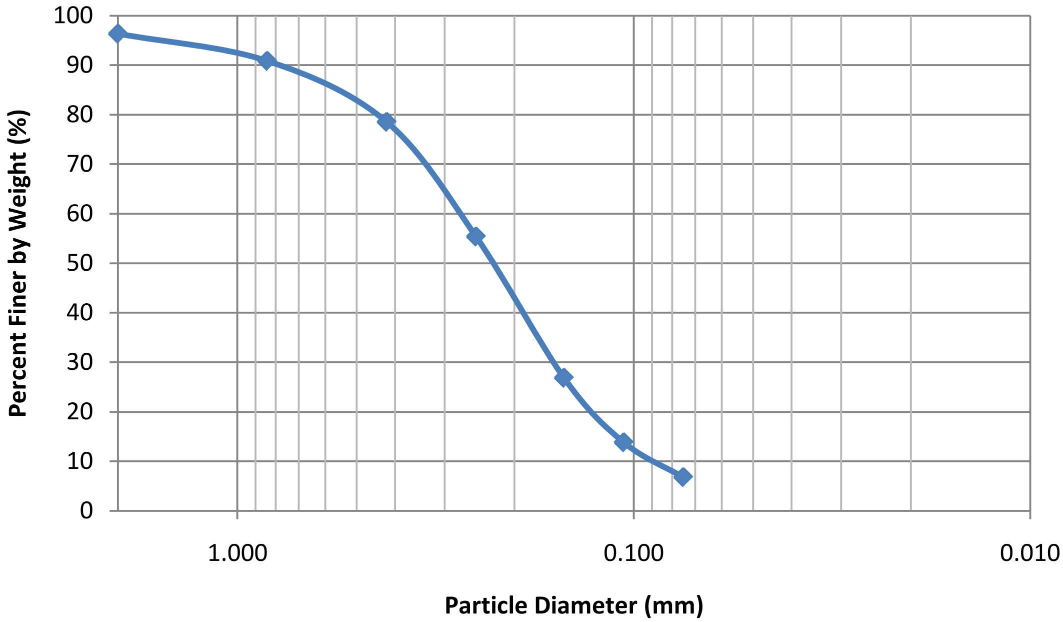


Figure A 12 Site 7 Sieve Test

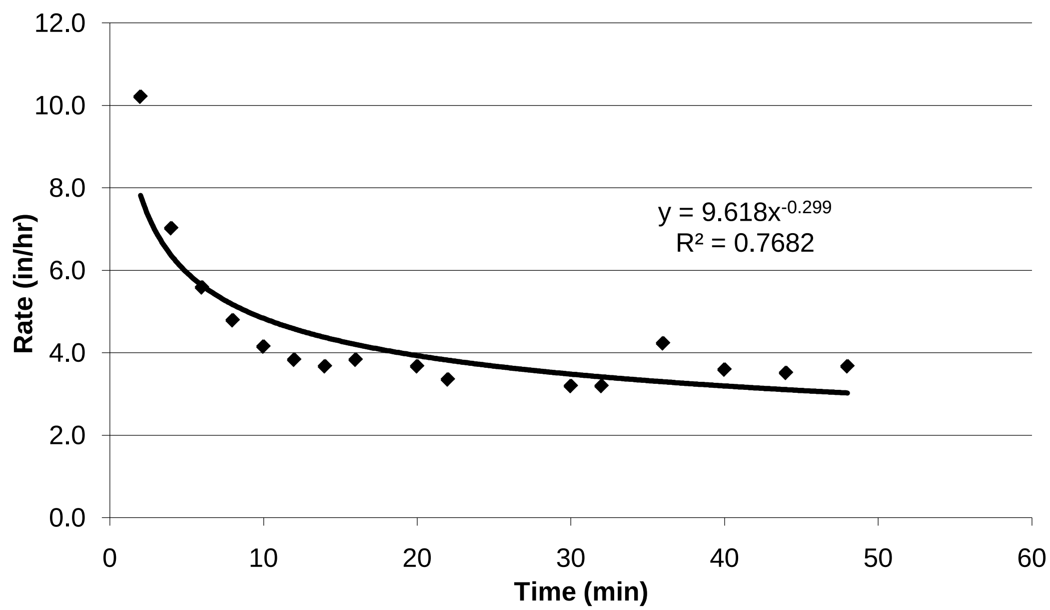


Figure A 13 Site 8 Static Head Infiltration Test

Table A 16 Site 8 Infiltration Test

Time (min)	Tube Depth (in)	Tube Depth (in)	Change in Tube Depth (in)	Change in Tube Volume (in^3)	Change in Inner Ring Depth (in)	Rate of Infiltration (in/min)	Rate of Infiltration (in/hr)	Infiltration (CFS/Acre)
0	21.5							
4	16.4		5.1	49.3	0.4	0.1	6.5	6.6
8	11.5		4.9	46.9	0.4	0.1	6.2	6.3
12	6.8	21.4	4.8	45.7	0.4	0.1	6.1	6.1
22		12.8	8.7	83.5	0.7	0.1	4.4	4.5
26		6.8	5.9	57.1	0.5	0.1	7.6	7.6
30		1.9	4.9	46.9	0.4	0.1	6.2	6.3
0	22							
2	18		4	38.5	0.3	0.2	10.2	10.3
4	15.3		2.8	26.4	0.2	0.1	7	7.1
6	13.1		2.2	21	0.2	0.1	5.6	5.6
8	11.2		1.9	18	0.2	0.1	4.8	4.8
10	9.6		1.6	15.6	0.1	0.1	4.1	4.2
12	8.1		1.5	14.4	0.1	0.1	3.8	3.9
14	6.6		1.4	13.8	0.1	0.1	3.7	3.7
16	5.1		1.5	14.4	0.1	0.1	3.8	3.9
18	3.9		1.3	12	0.1	0.1	3.2	3.2
20	2.4		1.4	13.8	0.1	0.1	3.7	3.7
22	1.1	21.8	1.3	12.6	0.1	0.1	3.3	3.4
26		19.4	2.4	22.8	0.2	0.1	3	3.1
28		17.4	2.1	19.8	0.2	0.1	5.3	5.3
30		16.1	1.3	12	0.1	0.1	3.2	3.2
32		14.9	1.3	12	0.1	0.1	3.2	3.2
36		11.6	3.3	31.9	0.3	0.1	4.2	4.3
40		8.8	2.8	27	0.2	0.1	3.6	3.6
44		6	2.8	26.4	0.2	0.1	3.5	3.5
48		3.1	2.9	27.6	0.2	0.1	3.7	3.7

Table A 17 Site 8 Permeability Test

Time		Time Interval	Height (cm)		Water Level Change	Permeability (cm/s)	Permeability (in/hr)
Start	End		Start	End			
0	1500	1500	54.7	54.6	0.1	6.70E-05	0.09
1500	3600	2100	54.6	54.5	0.1	4.80E-05	0.07
0	66060	66060	54.5	50	4.5	6.80E-05	0.1
0	1740	1740	50	49.9	0.1	5.70E-05	0.08
0	1380	1380	49.9	49.8	0.1	7.20E-05	0.1
0	1440	1440	49.8	49.7	0.1	6.90E-05	0.1
0	12120	12120	49.7	49	0.7	5.80E-05	0.08
0	900	900	49	48.7	0.3	0.00033	0.47
0	5400	5400	48.7	48.6	0.1	1.90E-05	0.03
0	238140	238140	48.6	36.6	12	5.00E-05	0.07
					Average	8.40E-05	0.12

Time		Time Interval	Height (cm)		Water Level Change	Permeability (cm/s)	Permeability (in/hr)
Start	End		Start	End			
0	3120	3120	54.7	54.4	0.3	9.60E-05	0.14
3120	5460	2340	54.4	54	0.4	0.00017	0.24
0	238140	238140	54	23.5	30.5	0.000136	0.18
					Average	0.00013	0.19

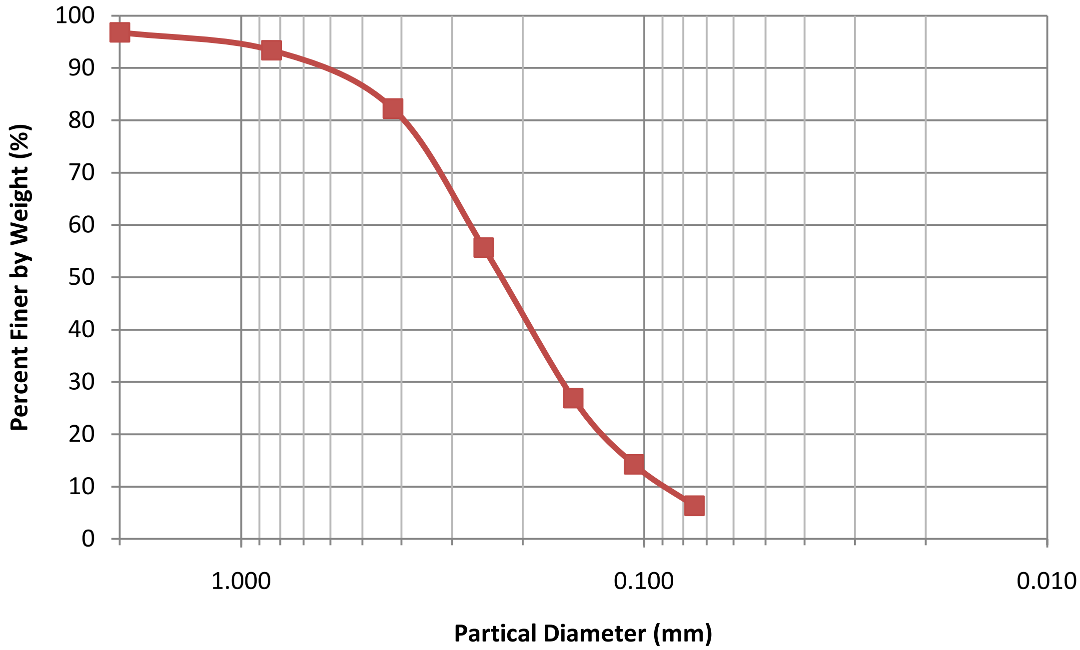


Figure A 14 Site 8 Sieve Test

Table A 18 Site 9 Infiltration Test

Time (min)	Tube Depth (in)	Delta Tube Depth (in)	Delta Tube Volume (in^3)	Delta Inner Ring Depth (in)	Infiltartion (in/min)	Infiltration (in/hr)	Infiltration (CFS/Acre)
1	21.5						
2	20.1	1.4	13.5	0.1	0.1	7.1	7.2
3	18.9	1.2	11.5	0.1	0.1	6.1	6.2
4	17.9	1	9.6	0.1	0.1	5.1	5.1
5	16.3	1.6	15.4	0.1	0.1	8.2	8.2
6	14.5	1.8	17.3	0.2	0.2	9.2	9.3
7	13.3	1.2	11.5	0.1	0.1	6.1	6.2
8	11.7	1.6	15.4	0.1	0.1	8.2	8.2
9	9.9	1.8	17.3	0.2	0.2	9.2	9.3
10	8.6	1.3	12.5	0.1	0.1	6.6	6.7
11	6.9	1.7	16.3	0.1	0.1	8.7	8.7
13	5.4	1.5	14.4	0.1	0.1	3.8	3.9
14	3.8	1.6	15.4	0.1	0.1	8.2	8.2
17.17	2.2	1.6	15.4	0.1	0	2.6	2.6

Table A 19 Table A 18 Cont.: Site 9 Infiltration Test

Time (min)	Tube Depth (in)	Delta Tube Depth (in)	Delta Tube Volume (in^3)	Delta Inner Ring Depth (in)	Infiltartion (in/min)	Infiltration (in/hr)	Infiltration (CFS/Acre)
18	21.4						
19	20.6	0.8	7.7	0.1	0.1	4.1	4.1
20	19.6	1	9.6	0.1	0.1	5.1	5.1
21	18.4	1.2	11.5	0.1	0.1	6.1	6.2
23	17.1	1.3	12.5	0.1	0.1	3.3	3.3
24	14.5	2.6	25	0.2	0.2	13.3	13.4
25	12.8	1.7	16.3	0.1	0.1	8.7	8.7
27	11.3	1.5	14.4	0.1	0.1	3.8	3.9
28	8.2	3.1	29.8	0.3	0.3	15.8	16
29	6.3	1.9	18.3	0.2	0.2	9.7	9.8
30	4.9	1.4	13.5	0.1	0.1	7.1	7.2
31	3.3	1.6	15.4	0.1	0.1	8.2	8.2
34.25	1.6	1.7	16.3	0.1	0	2.7	2.7
35	21.4						
36	20.2	1.2	11.5	0.1	0.1	6.1	6.2
37	19.1	1.1	10.6	0.1	0.1	5.6	5.7
38	17.8	1.3	12.5	0.1	0.1	6.6	6.7
39	16.6	1.2	11.5	0.1	0.1	6.1	6.2
40	15.2	1.4	13.5	0.1	0.1	7.1	7.2
41	13.7	1.5	14.4	0.1	0.1	7.7	7.7
42	12.3	1.4	13.5	0.1	0.1	7.1	7.2
43	10.8	1.5	14.4	0.1	0.1	7.7	7.7
44	9.2	1.6	15.4	0.1	0.1	8.2	8.2
45	7.6	1.6	15.4	0.1	0.1	8.2	8.2
46	6	1.6	15.4	0.1	0.1	8.2	8.2
47	4.4	1.6	15.4	0.1	0.1	8.2	8.2
48	2.8	1.6	15.4	0.1	0.1	8.2	8.2
49	1.1	1.7	16.3	0.1	0.1	8.7	8.7

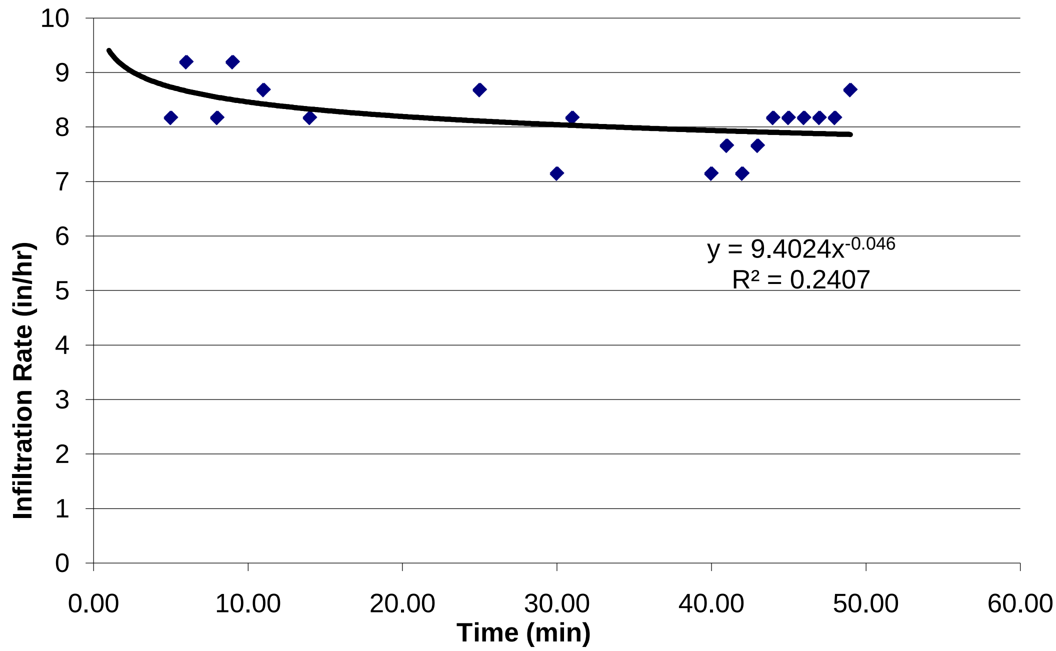


Figure A 15 Site 9 Static Head Infiltration Test

Table A 20 Site 9 Permeability Test

Time		Time	Height (cm)		Water	Permeability	Permeability
Start	End	Interval	Start	End	Level Change	(cm/s)	(in/hr)
0	840	840	54.8	53.8	1	0.001	1.7
840	13380	12540	53.8	38.3	15.5	0.001	1.8
13380	14700	1320	38.3	36.5	1.8	0.001	1.9
14700	15300	600	36.5	35.7	0.8	0.001	1.9
					Average	0.001	1.8

Time		Time	Height (cm)		Water	Permeability	Permeability
Start	End	Interval	Start	End	Level Change	(cm/s)	(in/hr)
0	840	840	54.4	53.1	1.3	0.002	2.2
840	13380	12540	53.1	31.2	21.9	0.002	2.5
13380	14700	1320	31.2	28.9	2.3	0.002	2.5
14700	15300	600	28.9	27.8	1.1	0.002	2.6
					Average	0.002	2.4

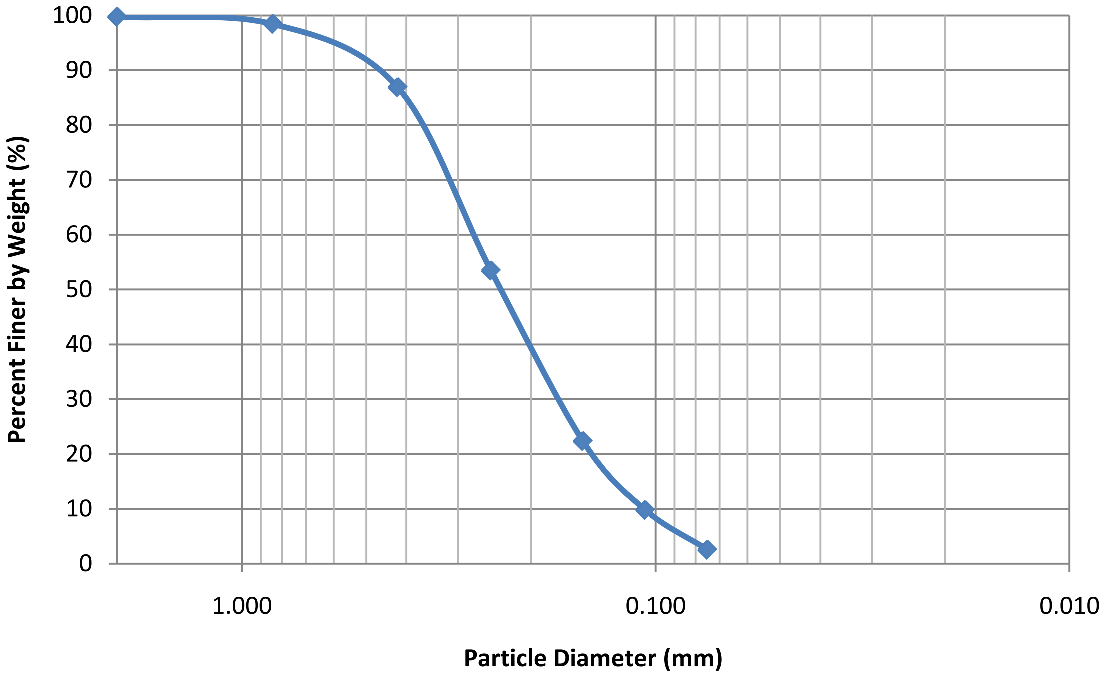


Figure A 16 Site 9 Sieve Test

Watershed Protection Plan Development for the Geronimo Creek Watershed

Basic Information

Title:	Watershed Protection Plan Development for the Geronimo Creek Watershed
Project Number:	2010TX363B
Start Date:	3/1/2010
End Date:	2/28/2011
Funding Source:	104B
Congressional District:	21, 28
Research Category:	Ground-water Flow and Transport
Focus Category:	Water Quality, Hydrology, Models
Descriptors:	None
Principal Investigators:	Kyna McKee, Kyna McKee

Publications

1. McKee. K, 2011, Estimation of E. coli concentrations from nonpoint sources using GIS, "MS Dissertation," Biological and Agricultural Engineering, College of Agriculture and Life Sciences, Texas A&M University, College Station, Texas, 88.
2. McKee, K., R, Karthikeyan, and P.Smith. 2011. Estimation of E. coli concentrations from point and non point sources in a watershed using spatial tools (Poster Presentation). 2011 Land Grand and Sea Grant National Water Conference, National Water Program, Washington, D.C., USA.

REPORT

Title Watershed Protection Plan Development for the Geronimo Creek Watershed

Project Number 2010TX363B

Principal Investigator

Kyna McKee
Master of Science Student
Department of Biological and Agricultural Engineering
Texas A&M University
kmckee@tamu.edu
Cell: (210) 289-0068
325 Scoates Hall
2117 TAMU
College Station, TX 77843

Co-Principal Investigators (faculty advisors)

Patricia Smith
Associate Professor
Department of Biological and Agricultural Engineering
Texas A&M University
Patti-smith@tamu.edu
Office: (979) 845-3630
302 B Scoates Hall
2117 TAMU
College Station, TX 77843

R. Karthikeyan
Assistant Professor
Department of Biological and Agricultural Engineering
Texas A&M University
karthi@tamu.edu
Office: (979) 845-7951
306 A Scoates Hall
2117 TAMU
College Station, TX 77843

Abstract
When developing a Watershed Protection Plan (WPP) or a Total Maximum Daily Load (TMDL), it is often difficult to accurately assess the pollutant load for a watershed as a result of inadequate water quality monitoring data. According to the Texas Commission on Environmental Quality (TCEQ), there are 274 bacteria impairments in Texas water bodies out of 386 impaired water bodies. Data on bacteria in water bodies is often more sparse than other types of water quality data, which hinders the development of WPPs or TMDLs. To address this problem, a spatial watershed model was developed to simulate bacteria concentrations in streams resulting from nonpoint sources using the Spatially Explicit Load Enrichment Calculation Tool (SELECT) combined with a simple rainfall-runoff model. SELECT is an automated Geographical Information System (GIS) tool that can estimate potential *E. coli* loads from point and non point sources in watersheds using spatial characteristics such as land use, population density, and soil type. The watershed model applies a rainfall-driven loading function to the potential *E. coli* loads calculated by the output of SELECT. The SELECT methodology combined with this watershed model was applied to estimate *E. coli* loads in the Geronimo Creek watershed, located in central Texas. The simulated *E. coli* concentrations from the model were compared to actual monthly routine grab sample *E. coli* data collected at two sampling site near the outlet of the subwatershed. The runoff volumes were predicted with good to very good agreement for both sampling sites. Nash – Sutcliffe efficiencies range from 0.74 to 0.84 and root mean square error – observations standard deviation ratio (RSR) range from 0.51 to 0.40. The predicted *E. coli* concentrations performed unsatisfactorily for both sites and four calibration methods. The results show that the model does not include significant factors contributing to the transport of *E. coli* bacteria but can be modified to include these factors.

Problem and Research Objectives

When developing a Watershed Protection Plan (WPP) or a Total Maximum Daily Load (TMDL), it is often difficult to accurately assess the pollutant load for a watershed because not enough water quality monitoring data is available. Bacteria are the most common reason for impairment of Texas water bodies. According to the Texas Commission on Environmental Quality (TCEQ), there are 274 bacteria impairments in Texas water bodies out of 386 impaired water bodies (TCEQ 2008). Bacteria water quality data is often more sparse than other types of water quality data, which hinders the development of WPPs or TMDLs.

In order to develop WPPs or TMDLs, additional bacteria water quality data must be collected which is costly and time consuming. The bacteria load analysis for a watershed cannot begin until the water quality monitoring data collection is completed. Generally, water quality data can take anywhere from a year to multiple years to collect for a substantial dataset. The U.S. EPA estimates water quality monitoring of all TMDLs nationally, “The cost of water quality monitoring to support the development of TMDLs is expected to be approximately $17 million per year” (USEPA 2001). A considerable portion of developing a TMDL is to allocate pollutant load and to identify potential sources. This can be done with modeling which can be costly and require a significant amount of input data.

Models such as Soil and Water Assessment Tool (SWAT) and Hydrological Simulation Program- FORTRAN (HSPF) have been used for bacterial modeling (Benham, et al., 2006; Sadeghi & Arnold, 2002). Other simplistic microbial models such as, the potential non-point pollution index (PNPI) and a Spatially Explicit Delivery MODel (SEDMOD), have been developed to rank the potential pollution impacts of areas from nonpoint sources primarily utilizing land use and geomorphology (Fraser, et al. 1998; Munafo, et al. 2005).

SELECT is an automated Geographic Information System (GIS) tool that can assess potential *E. coli* loads in a watershed based on spatial factors such as land use, population density, and soil type (Teague, et al., 2009). SELECT is able to calculate a potential *E. coli* load and highlight areas of concern for best management practices (BMPs) to be implemented. The potential *E. coli* load in SELECT is calculated by distributing the contributing sources spatially over the entire watershed. The population densities of potential contributors are determined with stakeholder input to accuracy represent the watershed, however, SELECT is a worst case scenario model and assumes that the largest amount of contribution possible from individual sources.

Current bacteria models either require extensive monitoring data within the watershed for calibration or are not able to predict actual *E. coli* concentrations in the water body. A simple model that is able to predict actual bacteria concentrations in a water body is needed in order to develop TMDLs or WWPs within the state of Texas. The objective of this study was to develop a model that would estimate the runoff volume and the *E. coli* concentration contributing from surface runoff at a sampling site drainage area outlet.

The overall objective of this research project was to develop a conceptual model in ArcGIS 9.X utilizing the potential *E. coli* load estimated by SELECT to simulate *E. coli* concentrations occurring in Geronimo Creek. It was presumed that precipitation is the main driving factor for the transport of *E. coli* bacteria from sources to the stream. Also the affects of temperature were negligible, since in Texas watersheds the monthly normal daily mean temperatures do not vary from month to month by more than 10 °F.

(1) To apply SELECT to Geronimo Creek watershed using stakeholder inputs concerning the *E. coli* sources and the population densities.
(2) Another sub objective was to develop an automated rainfall-runoff model in ArcGIS 9.X utilizing rain gauges located in and around the Geronimo Creek watershed and to estimate the *E. coli* concentrations in the creek.

Methodology

E. coli concentrations were calculated using a modified delivery factor originally developed by McElroy et al. (1976) for pollutant loading from livestock facilities:

$$C = (Y * D)/(a * R * A) \quad (1)$$

where

C = concentration of *E. coli* at sampling site (CFU/mL)

Y = daily loading rate of *E. coli* at sampling site (CFU)

a = unit conversion factor (2.54×10^4) – to convert from in•m^2 to mL

R = daily runoff at sampling site (in)

A = grid cell area (m^2) – 900 m^2

D = delivery factor (dimensionless)

The equation was intended for livestock facilities but was applied to multiple non-point sources calculated using SELECT and ArcGIS 9.X. The variable concentration of pollutant in runoff (C) was calculated using the equation above to determine the concentration of *E. coli* in Geronimo Creek. The loading rate (Y) was calculated in SELECT for livestock, wildlife, and domestic sources. McElroy et al. (1976) acknowledged that the quantity of pollutants discharged depends mostly on runoff volume.

Runoff (R)

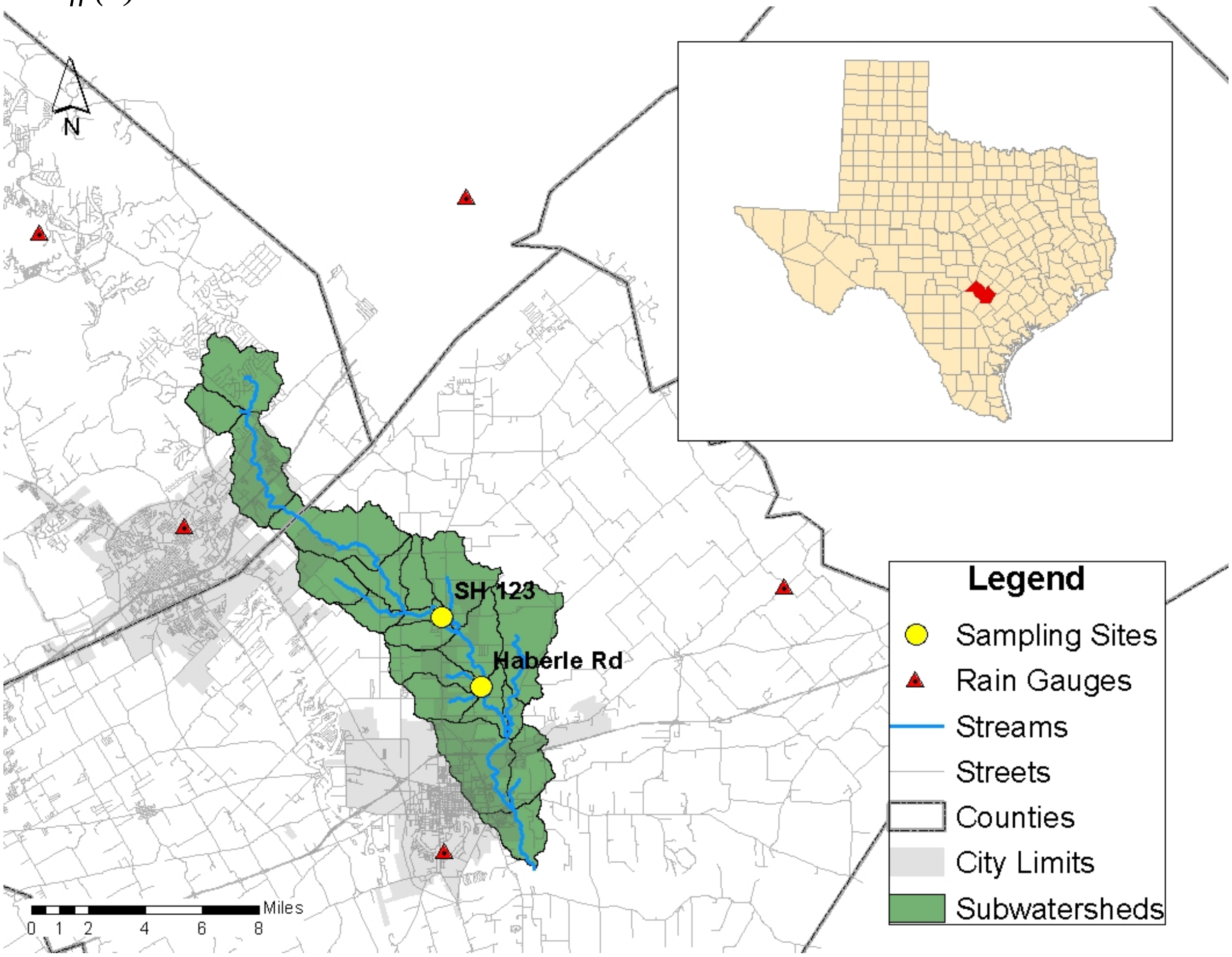


Figure 1. Geronimo Creek Watershed Study Area With Rain Gauges and Sampling Sites

Daily precipitation data was obtained at 5 sites, Canyon Dam, Kingsbury, New Braunfels, San Marcos, and Seguin, from the National Climatic Data Center (NCDC) for 1996 to 2010. The NCDC rain gauges shown in figure 1 were utilized to develop a daily precipitation grid.

The minimum rainfall to induce runoff was calculated using the SCS curve number approach by using the average area weighted curve number for the Geronimo Creek watershed. The watershed curve number grid was developed in ArcGIS 9.X. by intersecting the Soil Survey Geographic (SSURGO) hydrologic soil group with the land use type and using an NRCS lookup table. The area weighted curve number for the Geronimo Creek Watershed was calculated as 82. The minimum rainfall to induce runoff calculated using the area weighted curve number was 0.44 inches.

Runoff precipitation was assumed to occur in the watershed if one of the five rain gauges measured precipitation greater than the minimum rainfall to induce runoff. A precipitation grid was developed in ArcGIS 9.X. for each day with runoff precipitation occurring on the same day as when routine *E. coli* samples were taken from the Geronimo Creek sampling sites using the ArcGIS Spatial Analyst Extension. The interpolation method used will be inverse distance weighted (IDW). Inverse distance weighting assumes that observations closer to one another are more alike than ones farther apart (Zhang & Srinivasan, 2009).

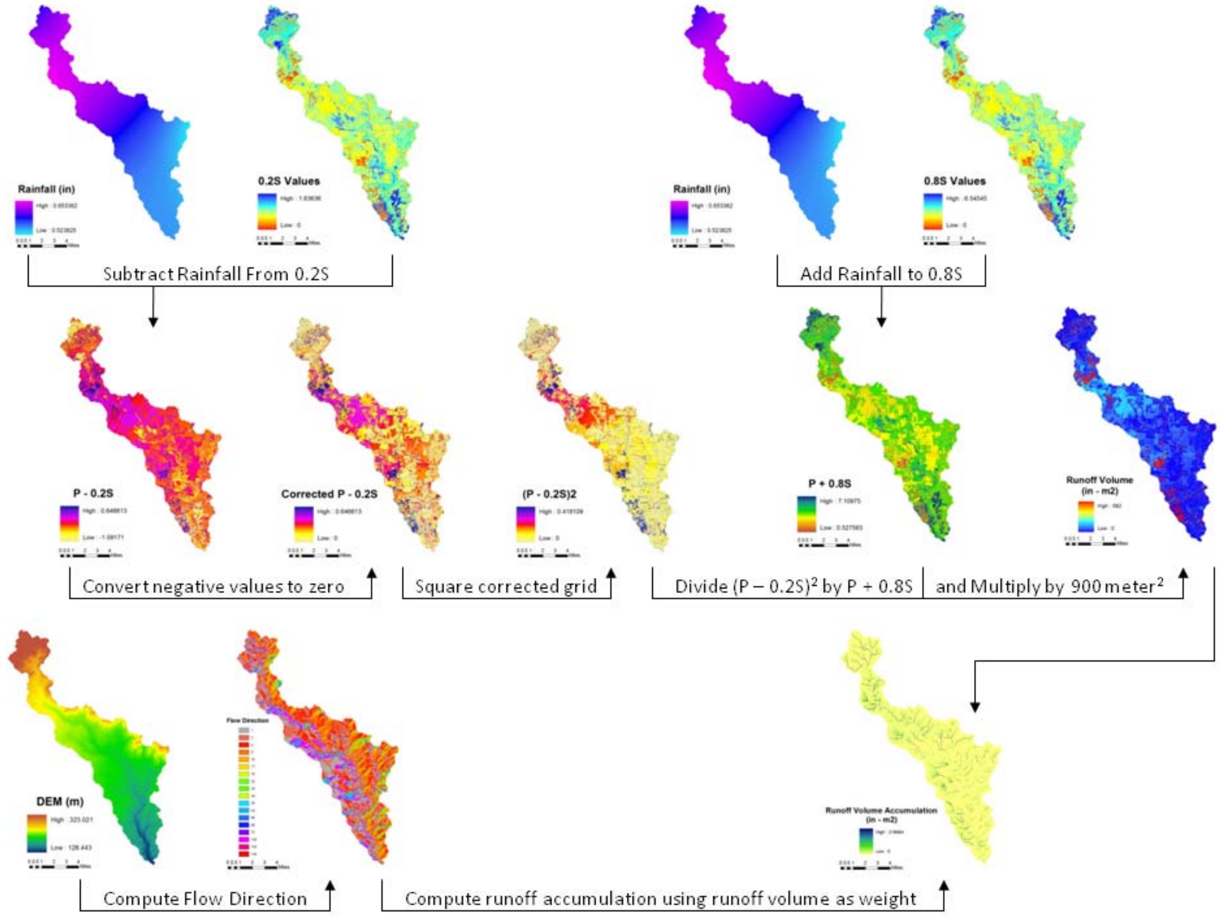


Figure 2. Flow chart illustrating the calculation of accumulated runoff volume

The runoff volume at a sampling site was then calculated from the precipitation grid (Figure 2). An automated tool was programmed into ArcGIS to calculate a runoff grid with the inputs being a rain gauge shapefile with the measured amounts of rainfall for each rain gauge as fields in the attribute table and an S grid calculated from the curve number grid. The runoff grid was calculated using the SCS curve number approach with the equation $Q = (P - 0.2S)^2/(P + 0.8S)$ where *Q* is the runoff depth in inches, *P* is the precipitation and *S* is the maximum soil water retention parameter derived from the curve number. The runoff equation requires that *P* must exceed 0.2*S* before any runoff is generated. The average runoff is first calculated for the entire watershed on a 30 meter grid cell basis. The curve number grid is calculated into an *S* grid using the equation, $S = (1000/CN) - 10$ where *CN* is the curve number. For the results of (*P - 0.2S*), the negative values were given a value of zero so that runoff was not calculated for cells with *P* less than 0.2*S*. After the runoff depth was calculated, the runoff depth was then converted to a runoff volume per grid cell by multiplying by the cell area which was 900 square meters creating a runoff volume grid.

An additional part of the Arc GIS 9.X. tool was used to automatically calculate with flow accumulation grid for the watershed. The inputs to the tool were the previously generated runoff volume grid and a Digital Elevation Model (DEM) over the watershed area provided by the Texas A&M University SSL which had a 30 meter grid cell size. The result of the flow accumulation would be the total amount of runoff volume going through a specific grid. The runoff volume at a sampling site is estimated by identifying the runoff volume value grid cell at the sampling site drainage area outlet.

Potential E. coli Load (Y) Estimation using SELECT

Potential *E. coli* loads for Geronimo Creek were predicted using SELECT and input from stakeholders for stocking rates and possible sources. A custom land use classification (Figure 4) was provided by the Texas A&M University Spatial Sciences Laboratory (SSL) using 2008 National Agriculture Imagery Program (NAIP) imagery and a prior Texas Parks and Wildlife (TPWD) Classification.

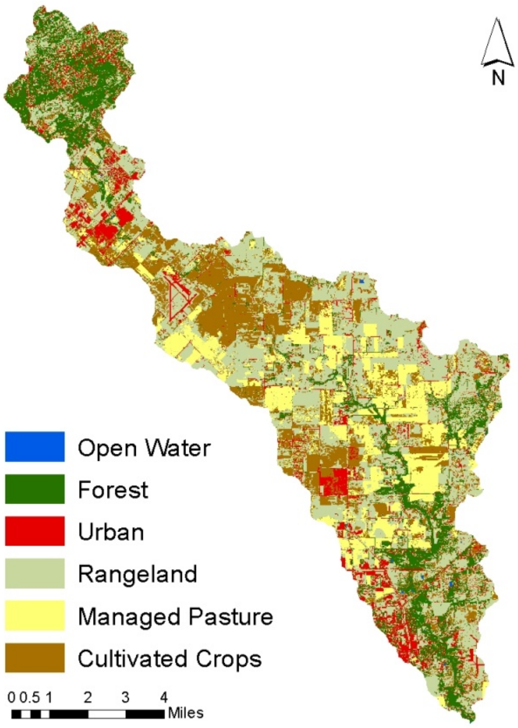


Figure 3. Geronimo Creek watershed land use classification

The SWAT model was used to delineate 21 subwatersheds as well as the watershed stream channel. In the Geronimo Creek watershed, it was determined that livestock sources for the watershed are goats, horses, and cattle. Wildlife sources are deer and feral hogs. Domestic sources consist of dogs and on-site wastewater treatment systems (OWTSs). A conversion of 0.63 fecal coliform to *E. coli* was used in the model. The conversion factor of 0.63 was decided using the USEPA's regulatory standards for fecal coliform and *E. coli* in recreational waters. The regulatory standard for fecal coliform was 200 organisms per 100 mL and is 126 organisms per 100 mL for *E. coli* (USEPA, 2003). The conversion factor was determined by taking the ratio of these two regulatory standards.

For livestock and wildlife, the number of animals is estimated with animal densities and stakeholder input. For cattle, the stakeholders determined a stocking rate of 20 and 10 acres per animal should be applied to Comal and Guadalupe Counties respectively with a suitable habitat of rangeland, forest, and managed pasture land use types. A density for horses was determined to be 132 acres per animal over the entire watershed with a total watershed population of 124 horses with a suitable habitat of rangeland. The animals are distributed evenly across suitable habitats and a fecal production rate is then applied per animal. Due to goats being raised on goat farms, 200 goats out of the total watershed population of 750 animals were distributed evenly in the watershed on rangeland, forest, and manage pasture land use types. The remaining animals were concentrated to specific watersheds which contained known goat farms for a specified number of animals. The potential *E. coli* load for the subwatersheds containing goats was calculated per subwatershed by multiplying the number of animals per subwatershed by the fecal production rate per animal. White-tailed deer had a population density of 10 acres per animal (Lockwood, 2005). The suitable habitat determined for deer were forest and rangeland with at least 20 acres of contiguous terrain available. Feral hogs had a population density of 26 acres per animal and were only distributed on suitable habitat within 100 meters of the main stem of Geronimo Creek which is perennial. Feral hogs were not distributed around Alligator Creek because it is an intermittent creek and is an unsuitable habitat for feral hogs. The suitable habitats for feral hogs as determined by stakeholders were forest, rangeland, managed pasture, and cultivated crops.

For dogs, the 2000 census data was used to calculate the contribution by using a dog density of 1 dog per household. The potential *E. coli* load for OWTSs was calculated by Espey Consultants. For OWTSs, spatially distributed point data of each household was collected from 911 address data and households within Certificate of Convenience and Necessity (CCN) areas were removed to not include households being serviced by a wastewater treatment facility. A failure rate was determined for the OWTSs using SSURGO soil limitation classes and the age of the system to calculate the percentage of *E. coli* contributing to the watershed due to septic failure. A fecal production rate was then applied to each household for dogs and OWTSs. Since SELECT divides the watershed into a raster grid with a 30 meter cell size, the potential load is calculated over the entire watershed at a 30 meter cell size. The individual raster files for each source are then added together spatially to create a total load raster (Figure 5) for the watershed that is divided into 30 meter grid cells.

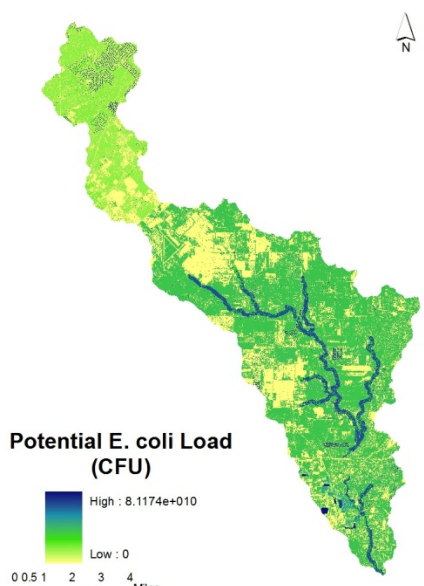


Figure 4. Total potential *E. coli* load calculated using SELECT for the Geronimo Creek watershed

The total load raster (Figure 4) estimates the potential *E. coli* load for the entire watershed based on a worst case scenario assuming the entire load calculated reaches the water body. Another part of the tool programmed in ArcGIS 9.X. was to calculate the *E. coli* load actually reaching a specific grid cell in the watershed.

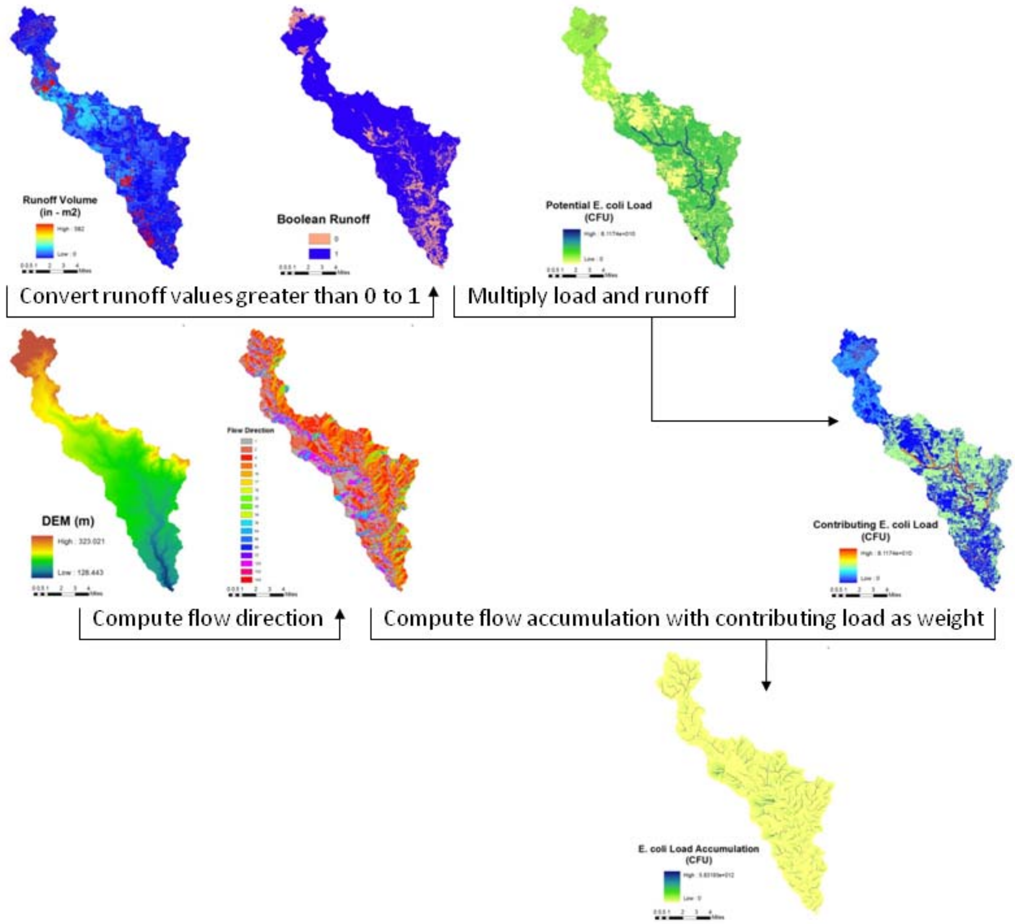


Figure 5. Flow chart illustrating the calculation of the contributing *E. coli* load

The inputs to the tool were the previously calculated runoff grid, the total load raster which was an output from running SELECT, and the DEM. The first step to estimating the *E. coli* load reaching the sampling site was to only consider the *E. coli* load grid cells that have runoff generated. A runoff SELECT grid was estimated for each runoff event in which the cells with no runoff generated had a contributing *E. coli* load of zero. The flow accumulation was calculated using the runoff SELECT grid as an input weight and the DEM. The output of flow accumulation would then represent the amount of *E. coli* load that would flow through each cell considering the upslope cells. The flow accumulation at a sampling site would then estimate the *E. coli* load reaching that site.

Calculation of Observed Runoff Volume

The observed instantaneous stream flow taken during the time the *E. coli* grab sample was sampled was converted to a runoff volume. The base flow was removed from the stream flow by subtracting the 100% exceedence flow. Flow duration curves were developed for the sampling sites SH 123 and Haberle Road using SWAT simulated flow rates ranging from 1998 to 2009. The 100% exceedence flow for the Haberle Road sampling site was determined as 1.89 cfs and 1.0 cfs for the SH 123 site.

The stream flow was converted to a runoff volume by multiplying by the lag time calculated for each sampling site using the SCS lag equation based on natural watersheds $t_L = L^{0.8}(S + 1)^{0.7}/1900Y^{0.5}$ where L is the hydraulic length of the sampling site drainage area in feet, S is the average maximum soil water retention parameter calculated from the curve number grid for the sampling site drainage area, and Y is the average land slope of the sampling site drainage area in percentage.

The SH 123 sampling site L parameter was determined by measuring the longest length for SWAT delineated stream channel to the drainage area outlet. The stream length measuring 78926 feet included the entire length of Alligator Creek and the length of Geronimo Creek from its confluence with Alligator Creek to the drainage area outlet. Although the Haberle Road sampling site is located downstream of SH 123, the flow accumulation showed due to slope that the Haberle Road site had about 1/5 of the area contributing of 1033 pixels compared to the SH 123 site's 5035 pixels. To remedy this difference, the hydraulic length for the Haberle Road sampling site was determined by measuring the longest stream length from the site determined with the flow accumulation grid which was 4738 feet. The lag time for the SH 123 site was 7.18 hours and 0.78 hours for the Haberle Road sampling site.

Delivery Factor (D)

The delivery factor is back calculated from equation 1 using observed *E. coli* concentration data. All factors influencing the processes affecting the runoff of the potential *E. coli* load into the creek are meant to be included in the delivery factor with the exception of runoff. Two separate delivery factors were calculated, one using the observed runoff volume converted from the observed stream flow. The other delivery factor is calculated from the simulated runoff volume.

A delivery ratio was calculated for all data points both using the observed and simulated runoff volume for each site separately. For each site, the average and the geomean was calculated for the separate delivery ratios. This resulted in the calculation of eight different delivery ratios to be applied to the data. For both sites, an observed and simulated delivery ratio was calculated with each type applying both an average and geomean.

Calibration

We obtained historical and routine stream flow and *E. coli* concentration sampling data ranging from 1996 to 2010 from the Guadalupe Brazos River Authority (GBRA). The SH 123 and Haberle Road sampling sites were both historical sites while the other 13 samplings sites in the watershed began sampling in September 2008. 84 Haberle Road samples were taken on a monthly basis beginning in September 2003 and ending in December 2010. For the SH 123 sampling site, monthly sampling began in October 1996 and ended in August 2003, but then resumed on September 2008 until August 2010. Out of the 105 data points taken at the SH 123 sampling site only 5 coincided with runoff precipitation. Only 12 data points out of the 84 for the Haberle Road site samples were taken when runoff precipitation occurred. The model was calibrated for both the Haberle Road site and the SH 123 site separately.

Statistics

The accuracy of the model was evaluated using the Nash-Sutcliffe efficiency (*E*), root mean square error (*RMSE*), and RMSE-observations standard deviation ratio (*RSR*). According to Nash and Sutcliffe (1970) the *E* value is an index of agreement or disagreement between observed and predicted values. The *E* value evaluates how consistently the predicted values agree with the observed values by applying linear regression analysis (Nash and Sutcliffe, 1970). *E* is computed with the equation: $E = 1 - [\sum_{i=1}^{n}(O_i - P_i)^2 / \sum_{i=1}^{n}(O_i - \bar{O})^2]$ where O_i is observed values, P_i is predicted values, and $\bar{O}$ is the mean of the observed values (Nash and Sutcliffe, 1970). The *E* value ranges from negative infinity to 1, where negative values are considered a biased model and values between 0 and +1 are considered an unbiased model (McCuen, et al., 2006). Model efficiencies were classificed similar to Moriasi et al. (2007) and Parajuli et al. (2009) as very good (*E* = 0.75 – 1), good (*E* = 0.5 – 0.74), fair (*E* = 0.25 – 0.49), poor (*E* = 0 – 0.24) and unsatisfactory (*E* < 0.0).

RMSE is an error index used in model evaluation and is valuable because the error is indicated in the units of the constituent of interest (Moriasi, et al., 2007). Legates and McCabe (1999) recommend including at least one relative error measure (*E* or R^2) and at lease one absolute error measure (*RMSE* or mean absolute error) for a complete assessment of model performance. *RSME* values close to 0 indicate a perfect fit but values half the standard deviation are still considered low (Singh, et al., 2004). The equation for *RMSE* is: $RMSE = \sqrt{\sum_{i=1}^{n}(O_i - P_i)^2 / n}$ where O_i is observed values, P_i is predicted values, and *n* is the number of samples.

RSR is a model evaluation statistic that standardizes RMSE with the observed data standard deviation (Moriasi, et al., 2007). Moriasi et al. (2007) developed *RSR* to fill the need of an error index with additional information provided for using *RSME* with the standard deviation recommended by Legates and McCabe (1999). The equation for *RSR* is: $RSR = [\sqrt{\sum_{i=1}^{n}(O_i - P_i)^2}] / \left|\sqrt{\sum_{i=1}^{n}(O_i - \bar{O})^2}\right|$ where O_i is observed values, P_i is predicted values, and $\bar{O}$ is the mean of observed values (Moriasi, et al., 2007). The value of RSR ranges from 0, which is the optimal value and indicates a perfect model, to a large positive value (Moriasi, et al., 2007). Model efficiences are classified by Moriasi et al. (2007) as very good (RSR = 0.00 – 0.50), good (RSR = 0.51 – 0.60), satisfactory (0.61 – 0.70), and unsatifactory (RSR > 0.70).

Moriasi et al. (2007) states that the model evaluation guidelines for both *E* and *RSR* values given apply to a continuous, long-term simulation for a monthly time step. The guidelines should be adjusted based on a multitude of factors including quality and quantity of measured data, single-event simulation, evalution time step, model calibration procedure, and project scope and magnitude (Moriasi, et al., 2007). Moriasi et al. (2007) continues to say that when a complete measured time series does not exist, such as when only a few grab samples per year are available, that the data may not be sufficient for analysis using the reccomended statistics.

Principal Findings

The runoff volumes and the *E. coli* concentrations were simulated for both the Haberle Road and SH 123 sampling sites.

Runoff Volume

The model was able to predict the runoff volume at the Haberle Road sampling site outlet with good agreement and at the SH 123 sampling site outlet with very good agreement. For the Haberle Road sampling site, both the *E* and *RSR* values (Table 1) had a good performance rating. The *RMSE* value is considered low because it less than half of the observed standard deviation as shown in Table 1. The SH 123 sampling site had a very good performance rating for both *E* and *RSR* values. The *RMSE* value for the SH 123 sampling station was considered low as well.

Table 1. Runoff volume model performance

Sampling Site	Statistic	Value
Haberle Road	E	0.74
	RSR	0.51
	RMSE	984
	Observed Average	1329
	Observed Standard Deviation	2015
SH 123	E	0.84
	RSR	0.40
	RMSE	1494
	Observed Average	3764
	Observed Standard Deviation	4128

For the Haberle Road sampling site, simulated runoff volumes were mostly underestimated with the exception of one point. This point may have been overestimated because it was taken during the driest season in a year (in August) whereas; the other points were taken in wetter months. The dataset does not include any data points taken in the fall months (October and November); September is not considered a fall month because the weather is still similar to the summer weather for this region. The dataset also has a gap for the 2009 year where no data points collected had contributing runoff occurring at the same time,

The runoff volumes for the SH 123 site were all underestimated for the five data points. The data was not taken continuously and there is therefore a gap between the years 2002 and 2010 with no data taken in 2001, where no data was collected where runoff occurred at the same time. The SH 123 site data points only include the fall and winter seasons with only one data point taken in the spring. This may skew the data some because the points do not include the summer season which is typically the driest season for the region.

E. coli Concentrations

For both the Haberle Road and SH 123 sampling sites, the model predicted *E. coli* concentrations with unsatisfactory agreement (Table 2) for all four methods of delivery factor calibration for both *E* and *RSR* values. The *RMSE* values for both sites using all four methods, were higher than the observed standard deviations and observed averages (Table 2) indicating an unsatisfactory agreement between the observed and predicted *E. coli* concentrations. The delivery factor estimated from the geomean of simulated runoff volumes performed the best for both the Haberle Road and SH 123 sampling sites. The Haberle Road site consistently performed better than the SH 123 site with the *E* and *RSR* values of -0.67 and 1 (Table 2) for the

Haberle Road site and value of -101.21 and 10.11(Table 2) for the SH 123 site, respectively, estimated using the geomean simulated delivery factor for both. The delivery factor estimated using simulated runoff volumes versus observed runoff volumes was able to better predict the *E. coli* concentrations because simulated runoff volumes were consistently under predicted for both the Haberle Road and SH 123 sampling sites. The runoff volume was meant to dilute the *E. coli* load to an *E. coli* concentration entering the stream.

Table 2. *E. coli* concentration model performance.

Sampling Site	**Statistic**	**Simulated Delivery Factor**		**Observed Delivery Factor**	
		Geomean	**Average**	**Geomean**	**Average**
Haberle Road	E	-0.67	-72	-1155	-54189
	RSR	1	9	34	233
	RMSE	21	138	646	4421
	Observed Average	12	12	12	12
	Observed Standard Deviation	20	20	20	20
SH 123	E	-101.21	-408.58	-54143	-84609620
	RSR	10.11	20.24	233	9198
	RMSE	8.00	16.01	184	7275
	Observed Average	1.79	1.79	1.79	1.79
	Observed Standard Deviation	0.88	0.88	0.88	0.88

The observed *E. coli* concentrations had values ranging from 0.46 to 57 CFU/mL. The *E. coli* concentrations predicted using the delivery factor estimated from the geomean of the simulated runoff volumes was the method that had the closest range of concentrations (0.54 to 42.32 CFU/mL) to the observed concentration range. The method predicting *E. coli* concentrations using the delivery factor estimated from the average of the observed runoff volumes performed the poorest and grossly over predicted with a range of concentrations from 187 to 14739 CFU/mL. The *E. coli* concentrations predicted using the delivery factor estimated from the average of the simulated runoff volumes had a closer range of 5 to 445 CFU/mL than the concentrations predicted using the geomean of the observed runoff volumes with a range of 27 to 2162 CFU/mL.

The prediction of *E. coli* concentrations for the SH 123 sampling site was poorer than the prediction for the Haberle Road sampling site. The SH 123 sampling site followed similar trends as the Haberle Road sampling site. As with the Haberle Road sampling site, for the SH 123 sampling site, the delivery factors computed using the simulated runoff volumes performed better than the delivery factors computed using the observed runoff volumes. The delivery factors computed using the geomean instead of the average of the respective runoff volumes performed better as well for the SH 123 sampling site. The range for the observed *E. coli* concentrations was from 1.12 to 3.2 CFU/mL. The *E. coli* concentrations predicted using the delivery factor estimated using the geomean of simulated runoff volumes had the closest range from 0.26 to 19 CFU/mL of predicted concentrations to the observed concentrations. Since the SH 123 site runoff volume was predicted more accurately than the Haberle Road site runoff volume, the *E. coli* concentration data should be better predicted as well. Since this is not the case, other factors influencing the transport of *E. coli* bacteria are not accounted for in the model.

Significance

In ungauged watersheds, historical bacteria data is sparsely available. It is expensive to collect more monitoring data. The USEPA estimates a cost of approximately seventeen million dollars a year for water quality monitoring to support the development of all national TMDL projects (USEPA, 2001). Current bacteria models require extensive monitoring data within the watershed for calibration or they cannot predict actual *E. coli* concentrations in the water body. A simple model that predicts actual bacteria concentrations in a water body is needed in order to develop TMDLs or WWPs within the state of Texas.

References Cited

Benham, B., Baffault, C., Zeckoski, R., Mankin, K., Pachepsky, Y., Sedeghi, A., et al. (2006). Modeling Bacteria Fate and Transport in Watersheds to Support TMDLs. *Transactions of the ASABE. 49(4)* , 987-1002.

Fraser, R. H., Barten, P. K., & Pinney, D. A. (1998). Predicting stream pathogen loading from livestock using a geographical information system-based delivery model. *Journal of Environmental Quality. 27* , 935-945.

Legates, D. R., & McCabe, G. J. (1999). Evaluating the use of "goodness-of-fit" measures in hydrologic and hydroclimatic model validation. *Water Resources Research. 35(1)* , 233-241.

Lockwood, M. (2005). *White-tailed Deer Population Trends.* Austin, Texas: Texas Parks and Wildlife Department.

McCuen, R. H., Knight, Z., & Cutter, A. G. (2006). Evaluation of the Nash-Sutcliffe efficiency index. *Journal of Hydrologic Engineering. 11(6)* , 597-602.

McElroy, A. D., Chiu, S. Y., Nebgen, J. W., Aleti, A., & Bennett, F. W. (1976). *Loading functions for assessment of water pollution from nonpoint sources, EPA-600/2-76-151.* Washington D.C.: USEPA Office of Research and Development.

Moriasi, D. N., Arnold, J. G., Van Liew, M. W., Bingner, R. L., Harmel, R. D., & Veith, T. L. (2007). Model evaluation guidelines for systematic quantifications of accuracy in watershed simulations. *Transactions of the ASABE. 50(3)* , 885-900.

Munafo, M., Cecchi, G., Baiocco, F., & Mancini, L. (2005). River pollution from non-point sources: a new simplified method of assessment. *Journal of Environmental Management. 77* , 93-98.

Nash, J. E., & Sutcliffe, I. V. (1970). River flow forecasting trhough conceptual models part 1 - A discussion of principles. *Journal of Hydrology. 10* , 282-290.

Parajuli, P. B., Mankin, K. R., & Barnes, P. L. (2009). Source specific fecal bacteria modeling using soila and water assessment tool model. *Biosource Technology. 100* , 953-963.

Sadeghi, A. M., & Arnold, J. G. (2002). A SWAT/microbial sub-model for predicting pathogent loadings in surface and groundwater at watershed and basin scales. *Total Maximum Daily Load (TMDL) Environmental Regulations.* St. Joseph, MI: ASAE.

Singh, J., Knapp, H. V., & Demissie, M. (2004). *Hydrologic modeling of the Iroquois River watershed using HSPF and SWAT. ISWS CR 2004-08.* Champaign, Ill: Illinois State Water Survery.

TCEQ. (2008, March 19). *2008 Texas Water Quality Inventory and 303(d) List.* Retrieved August 4, 2010, from Texas Commission on Environmental Quality: http://www.tceq.state.tx.us/compliance/monitoring/water/quality/data/08twqi/twqi08.html

Teague, A., Karthikeyan, R., Babbar-Sebens, M., Srinivasan, R., & Persyn, R. A. (2009). Spatially Explicit Load Enrichment Calculation Tool to Identify Potential *E. coli* Sources in Watersheds. *Transactions of the ASABE. 52(4)* , 1109-1120.

USEPA. (2003). *Bacterial water quality standards for recreational waters (freshwater and marine waters) status report, EPA 823-R-03-008.* Washington, D.C.: U.S. Environmental Protection Agency, Office of Water.

USEPA. (2001). *The National Costs of the Total Maximum Daily Load Program (Draft Report), EPA 841-D-01-003.* Washington D.C.: U.S. Environmental Protection Agency, Office of Water.

Zhang, X., & Srinivasan, R. (2009). GIS-based spatial precipitation estimation: a comparison of geostatistical approaches. *Journal of the American Water Resources Association. 45(4)* , 894-906.

Rainwater Harvesting as a Stormwater Best Management Practice

Basic Information

Title:	Rainwater Harvesting as a Stormwater Best Management Practice
Project Number:	2010TX364B
Start Date:	3/1/2010
End Date:	2/28/2011
Funding Source:	104B
Congressional District:	30
Research Category:	Climate and Hydrologic Processes
Focus Category:	Floods, Irrigation, Water Use
Descriptors:	None
Principal Investigators:	SaD Shannak, Bruce James Lesikar

Publications

1. Shannak, S. 2011. Investigating the influence of soil characteristics on total volumes of water runoff and potable water used for irrigation by utilizing a Rainwater Harvesting System. Applied Engineering in Agriculture. In Progress.
2. Shannak S. Lesikar B and Jaber F.2010. Rainwater harvesting as a stormwater best management practice. Texas Water Conference 2010, Corpus Christi, TX April 13-16 2010.
3. Shannak S. Lesikar B and Jaber F.2010. Investigating rainwater harvesting as a stormwater best management practice as function of irrigation water use. Handshake Across the Jordan: Water and Understanding investigating rainwater harvesting as a storm water bmp and as a function of irrigation water use.2010, Pella, Jordan Sep 26-28 2010 ISBN 978-3-902719-94-2.
4. Jaber F. H., Shannak S., Mohan S. 2011. Evaluating Low Impact Development Stormwater Practices in Texas. Texas Water Conference 2011, Fort Worth, TX April 5-8, 2011.
5. Jaber F.H., Shannak, S, and Lesikar B. 2010. The effectiveness of rainwater harvesting as a stromwater BMP as related to irrigation practices. Paper No. 10-9832, presented at the 2010 ASABE Annual International Meeting, Pittsburgh, PA, June 20-23, 2010. ASABE, St. Joseph, MI 49085.
6. Shannak, S. 2010. Investigating Rainwater Harvesting as a Stormwater Best Management Practice and as a Function of Irrigation Water Use. Master’s Thesis, Texas A&M University, Biological and Agricultural Engineering, College Station.

1- Title: Investigating Rainwater Harvesting as a Stormwater Best Management Practice and as a Function of Irrigation Water Use.

2- Project Number: 2010TX364B

3- Principal Investigator:
Sa'd A. Shannak
PhD Graduate Student
Texas A&M University
The Water Degree Program
213 Teague, MS 3408
College Station, TX 77843-3408
979-862-2164, sshannok@tamu.edu

4- Former Co-Principal Investigator:
Bruce J Lesikar, PhD.
Texas AgriLife Extension Service
b-lesikar@tamu.edu

5- Abstract

Stormwater runoff has negative impacts on water resources, human health and environment. In this research the effectiveness of Rain Water Harvesting (RWH) systems is examined as a stormwater Best Management Practice (BMP). Time-based, evapotranspiration-based, and soil moisture-based irrigation scheduling methods in conjunction with RWH and a control site without RWH were simulated to determine the effect of RWH as a BMP on a single-family residence scale. The effects of each irrigation scheduling method on minimizing water runoff leaving the plots and potable water input for irrigation were compared. The scenario that reflects urban development was simulated and compared to other RWH-irrigation scheduling systems by a control treatment without a RWH component. Four soil types (Sand, Sandy Loam, Loamy Sand, Silty Clay) and four cistern sizes (208L, 416L, 624L, 833L) were evaluated in the urban development scenario.

To achieve the purpose of this study; a model was developed to simulate daily water balance for the three treatments. Irrigation volumes and water runoff were compared for four soil types and four cistern sizes. Comparisons between total volumes of water runoff were estimated by utilizing different soil types, while comparisons between total potable water used for irrigation were estimated by utilizing different irrigation scheduling methods.

This research showed that both Curve Number method and Mass-Balance method resulted in the greatest volumes of water runoff predicted for Silty Clay soil and the least volumes of water runoff predicted for Sand soil. Moreover, increasing cistern sizes resulted in reducing total water runoff and potable water used for irrigation, although not at a statistically significant level. Control treatment that does not utilize a cistern had the greatest volumes of predicted supplemental water among all soil types utilized, while Soil Moisture-based treatment on average had the least volume of predicted supplemental water.

6- Problem and Research Objectives

Problem

Though different policies requiring the use of RWH as a BMP are already in place, little research has addressed the effectiveness of implementing RWH system as a BMP. Therefore, investigating possible runoff reductions and effectiveness of RWH system on a household scale is an important research question and will potentially become increasingly so in the future. Moreover, the type of irrigation scheduling plays a significant role in determining the effectiveness of RWH as a stormwater BMP. For instance, most of the irrigation practices involved overwatering which in turn results in increasing water runoff and all the negative effects associated with it, such as: increasing pollution, decreasing groundwater recharge, increasing flash floods, and stream deterioration. As a result, this study involved three different management irrigation methods with RWH system and a control site without RWH. A comparison between each irrigation method was conducted based on reducing stormwater runoff and potable water input for irrigation. These irrigation methods include: time-based irrigation scheduling, evapotranspiration-based scheduling, and soil moisture-based scheduling.

A limited number of RWH as BMP studies have been conducted in the United States and no research has been done in Texas, or the Southeastern United States. Therefore, very little data exists on the environmental and economic incentives from implementing RWH system. The lack of research pertaining to the effectiveness of RWH system as a stormwater BMP creates a need to do this study. Furthermore, most of the available research that have mentioned RWH system as a BMP analyzed the effectiveness of the system based on the storage size and other climatic factors. None examined the impact of RWH system combined with different irrigation management methods or the runoff volume.

Objectives

The goal of this research is to study the effectiveness of a RWH system in terms of reducing total volume of runoff leaving lawn areas as well as total volume of potable water (supplemental water) used to meet irrigation requirements. This goal is attained by studying the following objectives:

1. Determine the effect of utilizing Curve Number method and Mass-Balance method in estimating total volume of water runoff.
2. Determine the effect of soil types (Sand, Sandy Loam, Loamy Sands, and Silty Clay) on the total volume of runoff and total volume of supplemental water.
3. Determine the effect of using several irrigation scheduling methods (Time-based, Soil moisture-based, ET-based and a control treatment that does not utilize a cistern) on the total volume of runoff and the total volume of supplemental water by utilizing: different cistern sizes (0L, 208L, 416L, 624L, 833L), depletion ratio of 50%, and soil depth of 15.2 cm.

7- Materials and Methodology

A model was developed to simulate the daily water balance for four irrigation scheduling methods and to extent the results to other soil types and different storage capacities. This model was designed to simulate water balance data for a field area of the Urban Solutions Center of Texas A&M University system located in Dallas, TX. This center is located within the White Rock Creek watershed (Figure 1). Dallas –Fort Worth Metroplex is located North Central Texas at 32.78°N 96.78°W (Elev. 144m). The climate in the area is humid subtropical with hot summers. It is also characterized by a wide annual temperature range. Temperatures during the daytime of summer frequently exceed 100°F. The average length of warm season in this area is about 249 days. Precipitation ranges from 508 to more than 1270 millimeter (NOAA, 2010). Weather data for the period (April 2008- April 2010) for the Dallas Research Center were analyzed. The source of weather data was taken from a weather station on-site which is administrated by Biological and Agricultural Engineering Department of the Texas A&M University system (TexasET, 2010). The following estimated measurements based on weather data from the Dallas Research Center were considered:

o Volumes of water runoff leaving the roofs and the turfgrass irrigated area;
o Total irrigation demand;
o Volume of overflow from the cistern during storm events.
o Volume of rainwater captured and used for irrigation.
o Supplemental water used for irrigation.

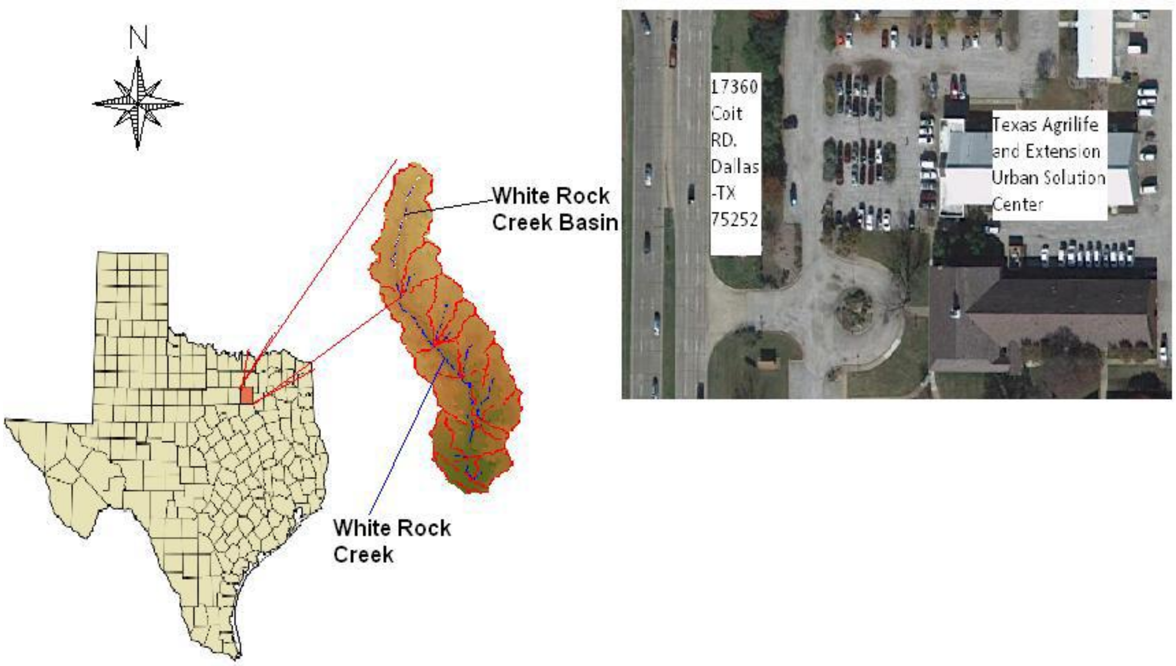


Figure 1. **Urban Solutions Center of Texas A&M University location.**

Several variables were considered as well in finding the previous measurements (Tables 1 and 2). First, four soil types were considered for this study; Sand, Sandy Loam, Loamy Sand, and Silty Clay. Second, four irrigation scheduling methods were considered; Time-based, Soil moisture-based, ET-based, and Time-based without a cistern. Third, five cistern sizes were studied; 0 L, 208 L, 416 L, 624 L, and 833 L which is equivalent to 0cm/ m^2 , 1.5cm /m^2 , 3.0 cm/ m^2 , 4.5cm/ m^2 , 6 cm/ m^2 respectively by considering 1 roof runoff coefficient. Fourth, three soil rooting depths were tested; 15.2 cm, 22.9 cm, and 30.5 cm. Fifth, four soil moisture allowable depletion ratios were studied; 40%, 50%, 60%, and 75%. The table below summarizes the considered variables:

Table1.Variables used in the simulation.

Soil type	Irrigation scheduling	Cistern size (L)	Depletion (%)	Soil depth(cm)
Sand	Time-based	0	40	15.2
Sandy Loam	Soil moisture-based	208	50	22.9
Loamy Sand	ET-based	416	60	30.5
Silty Clay	Time-based without cistern	624	75	
		833		

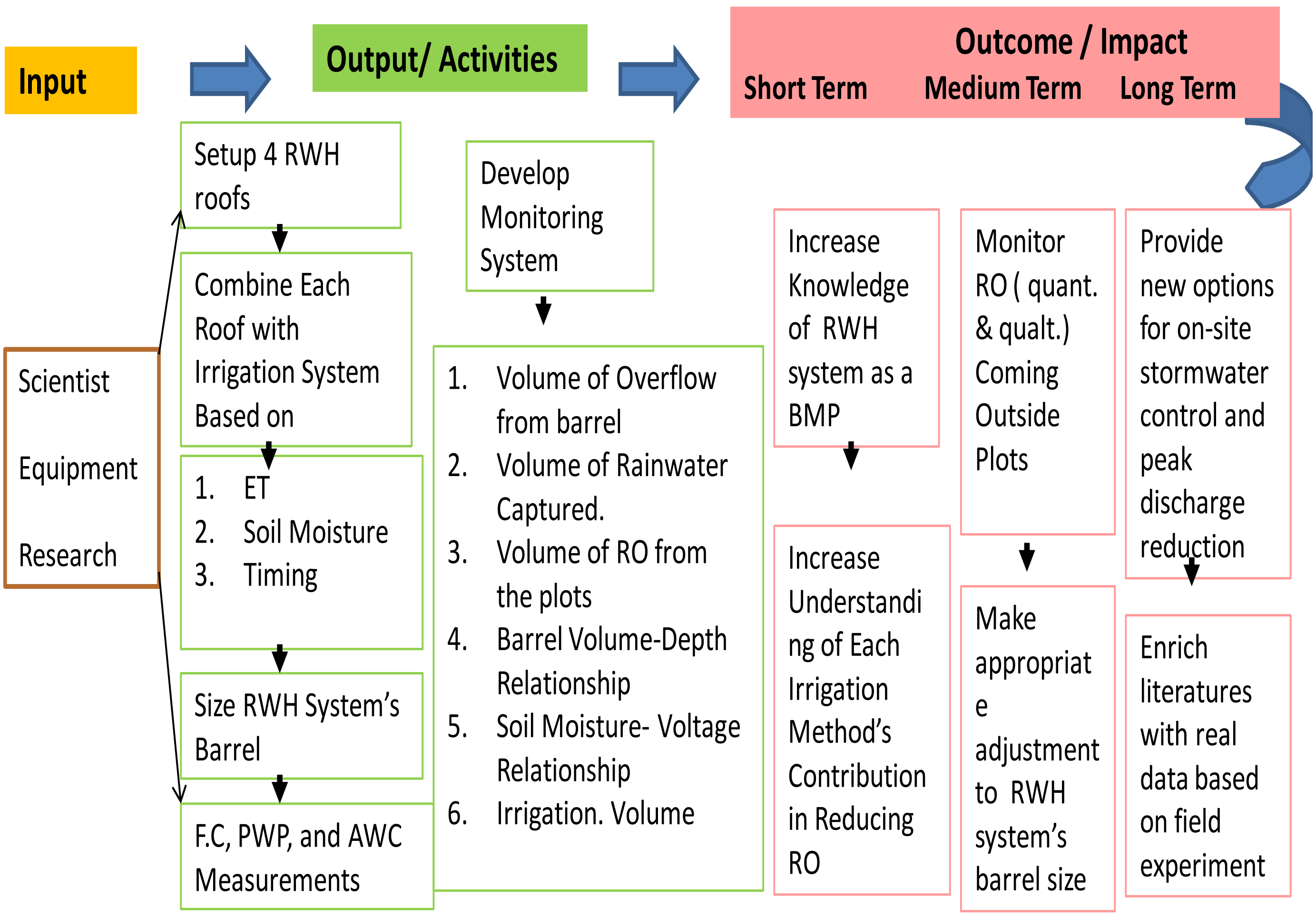
Table 2. Soil hydraulic properties considered as an input data in the simulation.

Parameter/ Soil Type	Sand	Sandy Loam	Loamy Sand	Silty Clay
Field capacity (%)	0.1	0.18	0.12	0.41
Permanent witling point (%)	0.04	0.08	0.05	0.28
Available water content (%)	0.06	0.10	0.07	0.14
Saturation (%)	0.45	0.46	0.47	0.54
Free drainage (%)	0.35	0.28	0.35	0.13
Roof runoff coefficient	0.95	0.95	0.95	0.95
Curve Number for lawns, good condition	55	71	65	80

The turfgrass which was used is a Crowne zoysia grass, this grass had been developed by Texas A&M University in cooperation with the United States Golf Association. The experimental name for this grass is (DALZ8512') and the scientific name is Zoysia japonica. This species is known for its tolerance to drought conditions and low water use, excellent cold hardiness, and rapid recuperative ability (Engelke et al., 1996).

A roof to lawn area ratio of 1:3 was used to reflect a typical residential area in the Dallas/Fort Worth Metroplex. Roof area considered in this study is 13.94 m^2 and a plot area of 20.9 m^2. Cistern sizes were developed based on a ratio of impervious surface area (rooftops) to total volume of rainfall and by assuming rainwater collection from half the roof. The total volume of runoff generated from rooftops is calculated by multiplying the Area of the roof, Roof Runoff Coefficient, and Rainfall depth. Therefore, the total volume of runoff from a roof during a 2.54 cm rainfall event was 0.35 m^3 (13.9 m2 0.0254 m) and a 1 roof runoff coefficient.

Research-Diagram



Assumptions

1. RWH system is sufficient in controlling small stormwater events.
2. Each irrigation method combining the RWH system has a different impact on the effectiveness of RWH system as a BMP.

8- Principle Findings

Figure 2 illustrates a graphical comparison between all irrigation scheduling methods and total supplemental water estimated. By utilizing 0L cistern, both Control and Time-based treatment ended with the same volume of predicted supplemental water and it was the least among the other treatment when utilizing all soil types. By utilizing all cistern sizes, Control treatment predicted the greatest volumes of supplemental water by considering: Loamy Sand, Sandy Loam and Silty Clay soil, while Soil Moisture-based treatment on average predicted the least volumes of supplemental water except when utilizing sand soil.

As it can be noticed from Figure 1; Control treatment that does not utilize a cistern had the greatest volume of predicted supplemental water as well among all cistern sizes utilized except when utilizing Sand soil, while Soil Moisture-based treatment on average had the least volume of predicted supplemental water. ET-based irrigation method comes in the second order in terms of least predicted supplemental water after the Soil Moisture-based treatment. Time-based treatment on average comes in the third order after both ET and Soil Moisture-based.

Figure 3 shows a comparison between all irrigation scheduling methods and total runoff estimated. As it can be noticed from this figure; Control treatment that does not utilize a cistern had the greatest volume of predicted runoff among all soil types and cistern sizes utilized, while Time-based treatment on average had the least volume of predicted runoff. ET-based irrigation method comes in the second order in term of least predicted runoff after the Time-based treatment. Soil Moisture-based treatment on average comes in the third order after both ET and Time-based.

By utilizing coarse soil texture such as sand among the four irrigation scheduling treatments, total volumes of water runoff estimated were the least, while utilizing fine soil texture such as silt clay estimates greatest volume of water runoff.

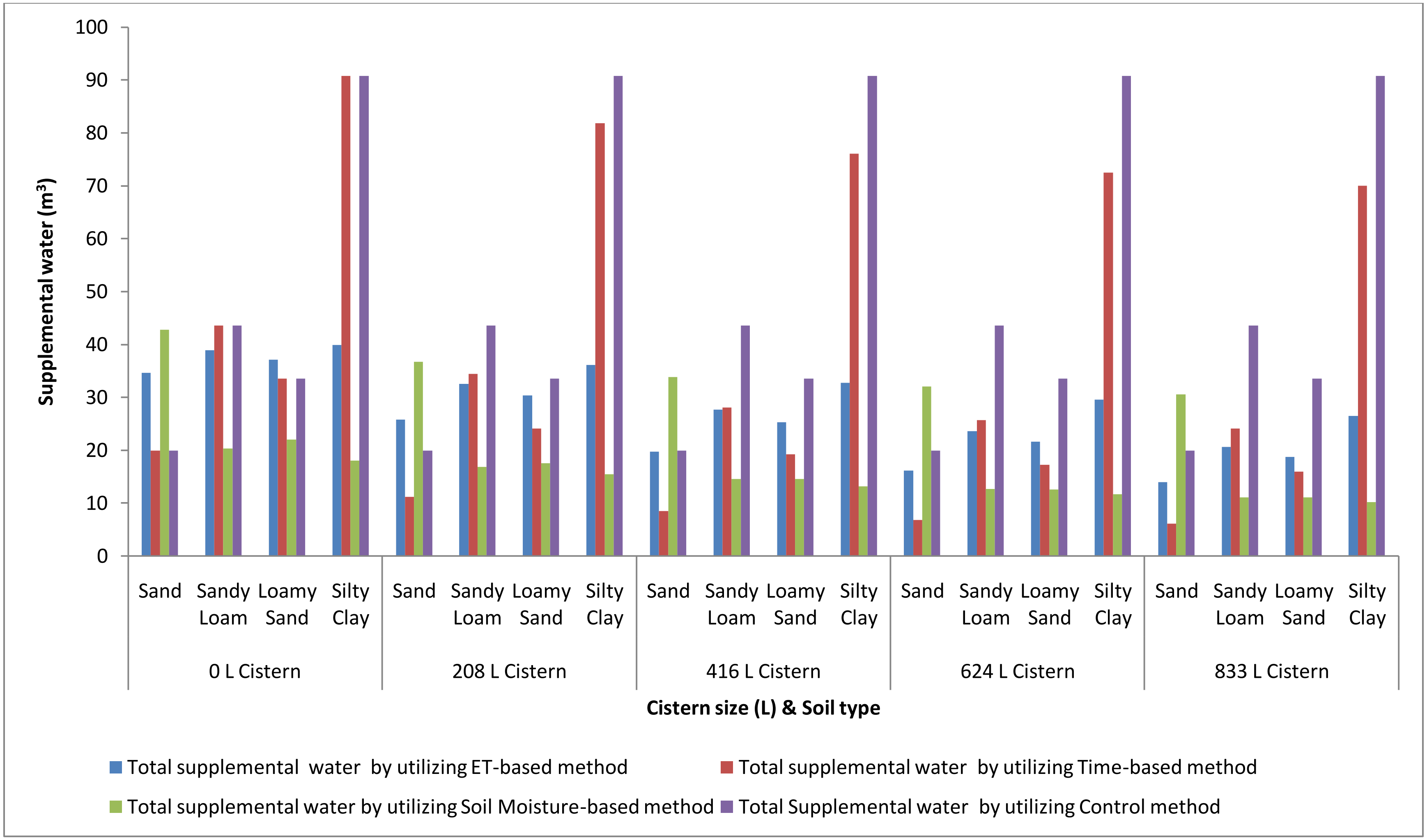


Figure 2. Comparison between different irrigation scheduling methods and total supplemental water by utilizing different cistern sizes.

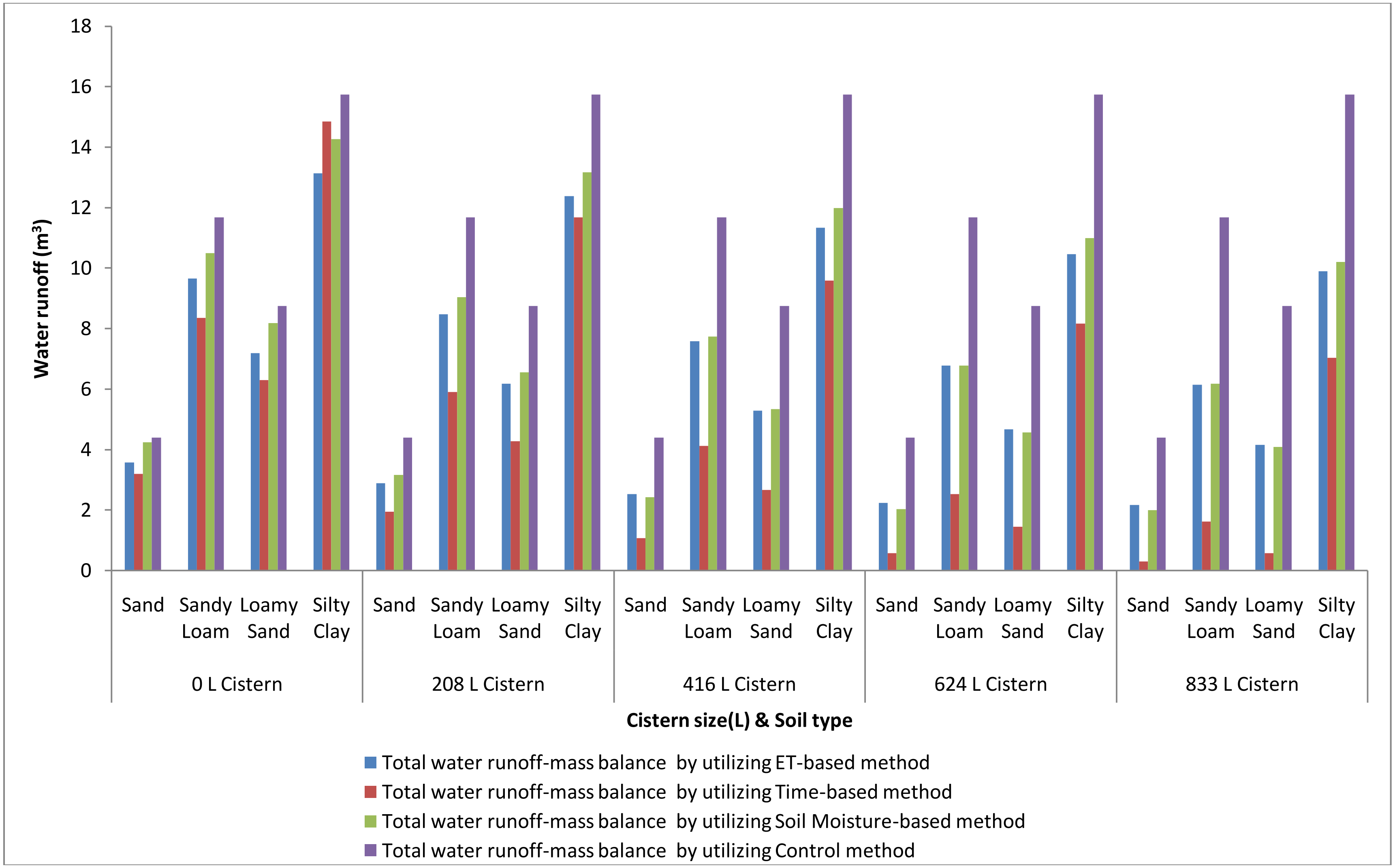


Figure 3. Comparison between different irrigation scheduling methods and total volumes of water runoff-mass balance method by utilizing different cistern sizes.

9- Significance

Developing a RWH model based on Mass-Balance method was a significant tool in predicting the total volume of water runoff leaving irrigated turfgrass and the total potable water used for irrigation (supplemental water). This model was developed by combining different irrigation scheduling methods with a RWH system and a control treatment that does not utilize a RWH system. Each irrigation scheduling method had different impacts on the total volumes of water used for irrigation and as a result the total volume of water runoff leaving plots. Cistern size as well was investigated as a factor influencing volume of rain water captured, total water runoff leaving plots and total supplemental water. Increasing cistern size reduced total supplemental water and water runoff, although not at a significant level as results showed in the previous section. Soil depth, soil type, and depletion ratio were other factors that this study investigated to determine the effectiveness of RWH system as a stormwater BMP.
Through this research the following conclusions were developed:

- Soil Moisture and ET based irrigation scheduling methods are water conservative practices and contributed in reducing total volumes of potable water used for irrigation.
- Soil Moisture-based irrigation scheduling method contributed in utilizing least volumes of water which was reflected on keeping RWH cistern full of water more frequently and in its turn resulted with greater volumes of water runoff.
- Time-based irrigation scheduling method utilized greater volumes of water than Soil Moisture treatment that contributed in keeping RWH cistern not full of water and that predicted least volumes of water runoff.
- By moving from coarse soil texture to fine soil texture; total water runoff predicted increased and total potable water predicted increased, while by moving in the opposite direction from fine to coarse soil texture, total water runoff predicted and total potable water predicted decreased.
- Based on all the comparisons conducted to investigate the influence of Curve Number method and Mass-Balance method in estimating total volume of water runoff; both methods resulted in the greatest volumes of water runoff predicted for Silty Clay and the least volume of water runoff predicted for Sand.
- When utilizing ET-based and Soil Moisture-based irrigation scheduling methods, the Curve Number method predicted greater volumes of water runoff for Silty Clay for all cistern sizes utilized than the Mass-Balance method, while Mass-Balance method predicted greater volumes of water runoff for Sandy Loam, Loamy Sand and Sand soil in respect to all cistern sizes utilized. By utilizing Time-based irrigation scheduling method, the Mass-Balance method predicted greater volumes of total runoff for all cistern sizes and soil types utilized except for Silt Clay where the Curve Number method predicted greater volumes. Finally, the Mass-Balance method predicted greater total volumes of water runoff than the Curve Number method for the control treatment (0L cistern).
- Irrigation scheduling method affected predicted total volumes of water runoff and supplemental water. Control treatment that does not utilize a cistern had the greatest volume of predicted runoff among all soil types utilized, while Time-based treatment on average had the least volume of predicted runoff. ET-based irrigation method comes in the second order in term of least predicted runoff after the Time-based treatment. Soil Moisture-based treatment on average comes in the third order after both ET and Time-based.
- Soil Moisture treatment had the least volume of predicted supplemental water by utilizing all cistern sizes and Silty Clay soil. Control treatment continues to have the greatest volume of

predicted supplemental water among all cistern sizes utilized and by considering Silty-Clay soil type.

- ET-based irrigation method comes in the second order in terms of least predicted supplemental water after the Soil Moisture-based treatment. Time-based treatment on average comes in the third order after both ET and Soil Moisture-based.
- Increasing cistern size resulted in decreasing total predicted volumes of water runoff and supplemental water, although not at a statistically significance level.

10- Reference Cited

Engelke, M. C., R. H. White, P. F. Colbaugh, J. A. Reinert, K. Marcum, B. A. Ruemmele, and S. J. Morton. 1996. Crowne Zoysiagrass. Dallas TX: Texas A&M University. Available at: http://dallas.tamu.edu/turf/crowne.html.

NOAA. 2010. Dallas/Fort Worth climate overview. National Oceanic and Atmospheric Administration. Available at: http://www.srh.noaa.gov/fwd/?n=dnarrative.

TexasET. 2010. Texas historic weather averages. College Station: Texas A&M University. Available at: http://texaset.tamu.edu/etinfo.php.

Design and evaluation of Best Management Practices (BMPs) for urban stormwater quality improvement in South Texas

Basic Information

Title:	Design and evaluation of Best Management Practices (BMPs) for urban stormwater quality improvement in South Texas
Project Number:	2010TX365B
Start Date:	3/1/2010
End Date:	2/28/2011
Funding Source:	104B
Congressional District:	28
Research Category:	Water Quality
Focus Category:	Surface Water, Water Quality, Wetlands
Descriptors:	None
Principal Investigators:	Xubin Pan, Kim D Jones

Publications

1. Xubin Pan, Kim D Jones*, Shuangzhen Wang, Javier Guerrero, Abel Garza. Design and Implementation of a Forebay-Pond-Wetland System for Urban Stormwater Treatment in South Texas, in American Ecological Engineering Society Annual Meeting, Québec City, Canada, June 13-17, 2010.
2. Xubin Pan, Kim D. Jones*, Shuangzhen Wang. Water-Quality Monitoring Evaluations in Semi-Arid South Texas (Arroyo Colorado Watershed) and Dataset Development Applications. in 2010 StormCon, San Antonio, TX, USA, August 1–5, 2010.

REPORT

Title (As it appears on the award document)
Design and evaluation of Best Management Practices (BMPs) for urban stormwater quality improvement in South Texas

Project Number (Assigned by the USGS system)
2010TX365B

Primary PI (Main principal investigator of the project, Student)
Xubin Pan, Ph.D candidate
Environmental Engineering, Texas A&M University – Kingsville
xubin.hu.pan@gmail.com, 281-935-3512
1004 South 18th Street, Kingsville TX 78363

Other PIs (Other principal investigators on the project, Professor(s))
Kim D. Jones, Professor and Chair
Environmental Engineering, Texas A&M University-Kingsville
Director, Institute for Sustainable Energy and the Environment
700 University Blvd. MSC 213, Kingsville, Texas 78363
Phone: 361-593-2338 Fax: 361-593-2069 kjones@tamuk.edu

Abstract

Urban stormwater runoff water quality is increasingly becoming a major contributor to nonpoint source water pollution for 21st century development. It can not only become a cause of flooding if not properly managed during storm events, but also is a cause of water pollution through runoff containing sediment and materials. The increase in population and fast social development at the border of US and Mexico imposes a serious water quality problem in the Arroyo Colorado area. The uncertain storm water runoff without treatment and management will potentially cause big impairments to the watershed. Therefore, a one year dataset (January 2004 through August 2005) for Green Valley Farm colonia was analyzed to assess the environmental effects of rural storm water runoff. Although the analysis period is short, the analysis showed that several important parameters of storm water quality run beyond the EPA standards, which would be addressed adequately if it had been covered by the related storm water management policy. Furthermore, more comprehensive and in depth analysis (including longer periods) of storm water run off in rural areas of South Texas are essential to trigger an adequate environmental regulation. Natural and semi-natural water and wastewater treatment technologies can provide effective water quality improvement and quantity control. Over the past several years, best management practices, including detention basins, biofilters and constructed wetlands, have been very successful in removing total suspended solids

and pollutants from wastewater. A sequential treatment system including a forebay, pond, and wetland has been proposed to incorporate the merits of these approaches and improve runoff water quality for South Texas. Hydraulic detention time, attached growth media and vegetation were three important parameters identified in the designs to help optimize system performance.

Problem and Research Objectives

Urban stormwater is a major non-point source of aquatic pollution, causing widespread environmental degradation and potential health risk (Novotny and Olem, 1994; Marsalek et al., 1999). The runoff contains significant loading of heavy metals, petroleum hydrocarbons, pesticides, sediment, and nutrients (Hall and Anderson, 1988; Davis et al., 2001). If contaminated stormwater is not properly managed during storm events, the pollutants such as non-biodegradable metals can accumulate in the local ecosystem, leading to adverse effects on human health and the environment, such as acute toxicity and potential carcinogenic damage (Wong, 2006; Wu and Zhou, 2009). Therefore, accurate characterization of frequency, volume and sediment load of urban storm water during rainfall events is vitally important for urban landscape development, drainage patterns design and water quality prediction.

Along the border of the US and Mexico, quick urbanization and population growth have triggered fast pace development of industrial and municipal sectors. These activities have imposed heavy environmental and ecological burdens in these areas and have thus caused serious air, water and solid waste pollution. The Arroyo Colorado and Rio Grande are important environmental and economic resources for South Texas. However, both were listed as impaired, identified in the 2008 Texas Water Quality Inventory and 303(d) listed for depressed dissolved oxygen, bacteria, mercury in edible tissue and PCBs in edible tissue (Texas Commission on Environmental Quality, 2008). Thus, as part of a prudent watershed protective plan, it is essential to implement some Best Management Practices (BMPs) for urban water quality improvement in South Texas to mitigate the impact of non-point pollution, such as urban stormwater, on watershed quality.

Even with this heightened awareness, the acquisition of adequate data for stormwater runoff for BMPs mitigation designs and modeling is still a challenge. It is until recently that some facts concerning storm water have been brought for the first time to academic discussion, for example, the first flush (Deletic, 1998; Stenstrom and Kayhanian, 2005). Currently, the complexities among land use, storm events and urban water quality are still poorly understood. Innovative approaches for developing comprehensive and field applicable datasets of stormwater quality management and in depth analysis are especially needed for South Texas (Leecaster et al., 2002).

In an elevated effort to improve our understanding of these storm events, this investigation studied the water quality at Green Valley Farm colonia, which was collected from January 2004 to August 2005. The analysis was designed to evaluate the adequacy of the current water monitoring plans, improvement of stormwater quality monitoring in the future and provision of more information for policy making. This research examines and evaluates analytical and statistical methods to accurately and effectively characterize this regional stormwater quality data, and its usefulness for design and model regional stormwater detention facilities for semi-arid coastal areas.

Thus, it is very important to accurately characterize the frequency, volume, sediment and materials loading of storm water during rainfall events for project design and policy making. In an effort to improve our understanding of these events, we propose to use continuous flow monitoring to survey the critical parameters including flows (flow rate, temperature), nutrients (nitrogen, phosphorus, chlorine, sulfate), bacteria (*Escherichia coli*, Enterococcus), and others (pH, dissolved oxygen, TDS and TSS) for the best management practices designs and model calibrations, and collect the data to make the time-flow, time-concentration and time-mass loading curves.

Based on these results, we will design some innovative best management practices for urban water quality improvement in South Texas, such as baffle box, free water surface wetlands, bioretention cells, treatment swales and others. Modeling of small scale urban BMPs presents challenges in the development of accurate models including fundamental water quality treatment processes. Thus, water quantity and quality will be monitored and evaluated after comparing the volume and concentration at the inlet and outlet of the BMP designs. A mathematical descriptive model of each BMP will be developed and validated using these data.

In order to improve the quality of large volumes of stormwater, various best management practices (BMPs) have been employed to control runoff volume and pollution loading, such as retention and infiltration systems used for collection, and infiltration and transport of stormwater into groundwater systems (Walsh, 2000). Performance evaluation and modeling of existing BMPs is critical for project management, public acceptance and future BMP designs. Although individual reports of BMPs are useful in specific locations, for various BMPs with a robust change of physical, chemical and/or biological operating processes, comparative analysis and dynamic modeling of water quantity and quality is needed to provide a more comprehensive knowledge basis for predicting and planning water quality treatment and innovation (Scholes et al.; Barrett, 2008).

The detention basin, retention pond, wetland basin and wetland channel are mainly structural types of BMPs. The differences among these types are the size and shape of pond and wetland. However, they have very similar structures: forebay, pond and wetland. Usually the forebay, as the first part of a pond and wetland system, is underestimated for its importance in the total water treatment process. Although the pond and wetland have different hydrologic, hydraulic and botanic characteristics

(Wong, 1999), they can be used sequentially in a complementary manner. At many northern temperate locations, pond-wetland systems have demonstrated reliable long-term performance (Kadlec, 2003). Thus, the extension to a forebay-pond-wetland system is proposed and investigated to illuminate the specific functions of different sections and their complementary performance toward water quality improvement, even with the challenges presented through a semiarid climate application such as South Texas

Materials/Methodology

Water quality monitoring evaluations in the semi-arid South Texas (Arroyo Colorado Watershed) and dataset development applications

The study area, near the US-Mexico border, is of the fastest growing urban areas in the nation. The largest city in Hidalgo County, Texas, city of McAllen, which is located in the Rio Grande Valley, is representative of this investigation. The population was 106,414 during the 2000 census, while the McAllen–Edinburg–Mission Metropolitan Statistical Area had a population of 569,463; rapid growth pushed the metropolitan area's population to 710,514 by 2007, which is about 25% population increase in 7 years' period (United States Census Bureau, 2007).

A dataset for the water quality monitoring is presented here. The precipitation information of McAllen was charted in Figure 1 and Figure 2 (National Weather Service, Mcallen, 1971-2000). McAllen has a distinct dry season (from November to April) and wet season (from May to October). Moreover, two high volume peaks (May or June, and September) provides the opportunity to examine seasonal variations in the first flush characteristic. Besides the study of extreme storm events, the impact of different storm intensity (precipitation >= 0.01, 0.1, and 1 inches) on the urban storm water quality is another important research topic.

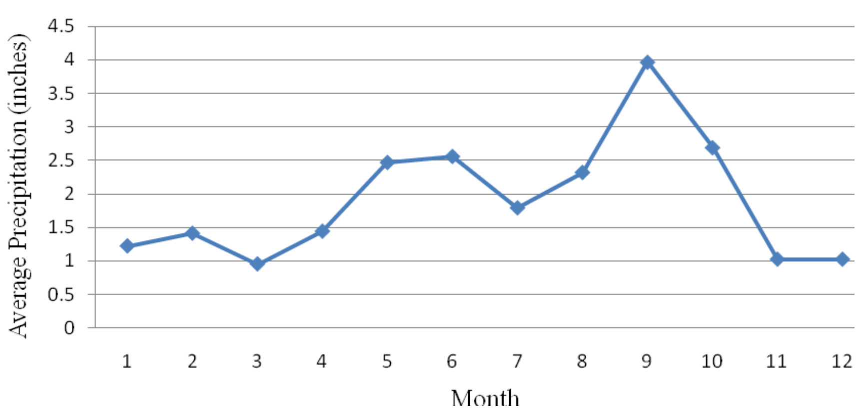


Figure 1. Monthly average precipitation (inches) in McAllen, Texas (National Weather Service, McAllen, 1971-2000).

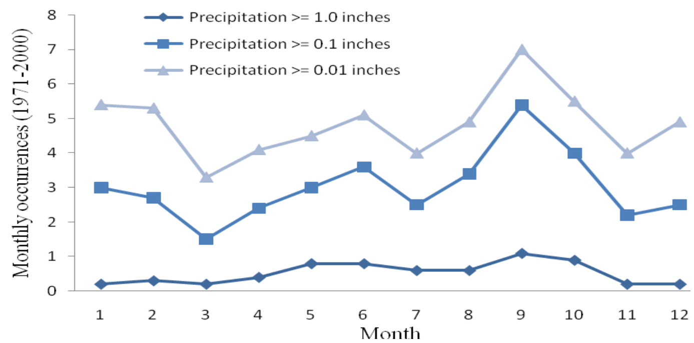


Figure 2 Average monthly occurrences when precipitation >= 0.01, 0.1 and 1 inches in McAllen, TX (National Weather Service, McAllen, 1971-2000).

Within the study area, a monitoring dataset from area within the Arroyo Colorado Watershed was evaluated. This dataset from Station 18196 (26.136862N, 97.54839W) during January 2004 through August 2005 was collected by a special research team of the Nueces River authority to monitor water quality in Green Valley Farms colonia in Cameron County, Texas (Fig. 3). The total base flow monitoring points are 19, and another two high flow events, high flow 1 on March 17, 2004, and high flow 2 July 21, 2005. The materials and methods of dataset collection can be found in a final report on the surface water monitoring and flow data collection study for the Cameron county special study (Sam, 2005).

Figure 3. Location of monitoring Station 18196 in Cameron County near McAllen, Texas USA from Google Earth.

Water quality monitoring follows the protocol of the latest version of TCEQ's Surface Water Quality Monitoring Procedures (2003) (Texas Commission on Environmental Qualify, 2003). Instantaneous field measurements in the selected monitoring database include three major categories that cover 35 parameters in the Table 1 (Sam, 2005).

Table 1. The monitoring parameters for the Cameron county special study

Categories	Parameters
Water flow rate	flow stream, flow, flow method
Water quality indexes	water temperature, transparency, turbidity lab; specific conductance, oxygen dissolved, pH, alkalinity; total non filterable, volatile non filterable, ammonia, kjeldahl; nitrite nitrate, total phosphorus, ortho phosphorus, total carbon; turbidity, chloride, sulfate, enterococcus, pheophytina, TDS; chlorophyll-a
Water environmental indexes	air temperature, days since precipitation event, rainfall in 1 day; rainfall in 7 days, wind direction, wind intensity, present weather; water surface, water color, water odor

Due to deep water and rapid current velocities, flow data from the two high flow events were determined by approximation (Sam, 2005). The flow rate of high flow event 1 was 146 cubic feet per second (cfs), and the flow rate of high flow event 2 was 40 cfs.

Design and implementation of a forebay-pond-wetland system for urban stormwater treatment in South Texas

A sequential treatment system including forebay, pond, and wetland has been proposed to incorporate the benefits of each natural system based treatment technique and develop optimization strategies for the entire system performance (Fig. 4).

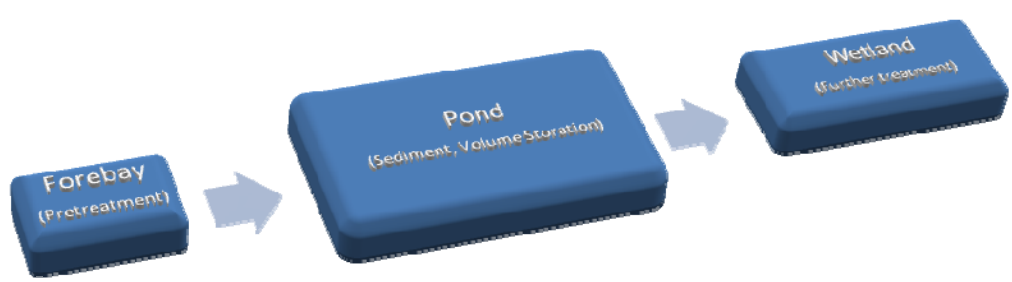


Figure 4. Schematic diagram of forebay-pond-wetland system

A forebay is a small reservoir connecting the channel and basin or other BMP facility. It serves to dissipate inflow energy, store some flow volume and trap coarse solids, and thus is usually used for pretreatment. In order to improve pollutant removal efficiencies, several accessory structures are often added such as oil and grit separators, and baffle boxes and screens. More important, the pretreatment function of forebay can reduce the sediment cleaning frequency of pond and wetland, make the maintenance easier and extend the operational life of BMPs. However, due to the small areas often available and the diversity of forebay design situations, there are no detailed accepted handbooks on forebay design and planning as of yet. Some findings from pond and wetland surveys in North Carolina have suggested that forebay designs should include separate energy dissipation and sedimentation sections (Johnson, 2007). For runoff pretreatment, the design must be flexible according to the specific location and objectives.

In stormwater management, ponds are constructed basins with greater depth and without the vegetation of wetlands. Ponds typically have two parts, a permanent pool and a temporary pool. This treatment approach has two main functions, water storage and solid sedimentation. Water interception with this system can decrease the impact of peak flow during heavy storm events on subsequent wetland structures, and balance the loss of pervious surface area for infiltration. The primary treatment process in ponds is physical sedimentation, but also biological and chemical uptake, and other pollutant transformations can be significant (Wong et al., 1999). Solid sedimentation is governed by particle size, flow velocity and hydraulic retention time. Some contaminants are heavily associated with solid particles such as phosphorous or carbonaceous materials.. When the solids settle, these contaminants are also removed from the water column. Some microbes in water and pond bottoms can digest these pollutants as substrates. However, the sediment accumulation and heavy metal enrichment at pond bottoms are important for the safety design, operation and maintenance (Färm, 2001).

The wetlands approach to water quality treatment includes the natural wetland and constructed wetland. This approach provides many ecosystem services, such as water management, biological habitat, aesthetics and educational parks (Costanza et al., 1997). Natural wetlands also play an important role in watershed water management and regional biodiversity protection. Constructed wetlands mimic natural wetlands, but their implementation avoids damage to natural wetlands. Due to the multi-functional nature of wetlands, more and more artificial wetlands are being constructed as one type of BMPs. Constructed wetlands also are often classified into two types: surface flow wetlands (SFW) and subsurface flow wetlands (SSF). Wetlands use a combination of physical, chemical and biological processes to remove pollutants. Similar to the pond, solids can be settled by gravity, and some contaminants can react or be taken up by biota.. Vegetation can stabilize the bed surface, provide a filtration effect, transfer the oxygen, influence the flow and particles and finally increase the removal rate (Brix, 1997). Fecal bacteria, BOD and suspended solids in the secondary effluent from domestic wastewater were removed effectively in the constructed wetland experiments located in Kentucky, USA (Karathanasis et al., 2003). Vegetation management, such as the use of hummocks and harvesting, can be important for achieving and maintaining the optimal treatment function of wastewater treatment wetlands (Thullen et al., 2005). The depth distributions and vegetation density are vital parameters in determining the mixing extent and treatment performance (Carleton and Montas, 2007). However, particle sizes and flow characteristics are important factors in influencing particle trapping efficiency (Deletic and Fletcher, 2007).

Principal Findings

Water quality monitoring evaluations in the semi-arid South Texas (Arroyo Colorado Watershed) and dataset development applications

The threshold between base flow and high flow is set as 20 cfs (Figure 5). Concentration and mass loading of some common index of water quality between the base flow and two high flow events are shown in Table 2 and Table 3. Storm events result in high flow and thus high mass loading, which brings the complex relationship between pollutant concentration and flow rate. Therefore, Event Mean Concentrations (EMCs), which is based on the bimodal or mixture distributions, were applied to estimate the total mass loading (Nueces River Authority). Due to the potential significant complexities, time effect is not included for this investigation.

Figures 6 and 7 illustrated the relationship between flow rate and five water quality indexes, dissolved oxygen, total nitrogen (Kjedahl), total phosphorus (Wet method), E nterococcus and TDS (Residue, total filterable dried at 180 °C, mg/L). In addition, the high flow doesn't bring high pollutant concentration as original imagine except dissolved oxygen and enterococcus, due to the accumulation effect of pollutant and dilution effect of high water flow. In other words, the pollutant accumulation speed during the dry period is constant and long-term, and storm event can't wash off the pollutant more than the total accumulation amount. In addition, the increase of total nitrogen, total phosphorus and TDS will boost the bacteria counts and deplete the dissolved oxygen.

According to site specific criteria established by the Texas Commission on Environmental Quality (TCEQ), enterococcus and TDS concentrations were always higher than the standard during base flow and high flow (Grum et al., 1997). Total nitrogen was lower than the criteria during base flow, however, the dissolved oxygen was lower than the criteria during high flow.

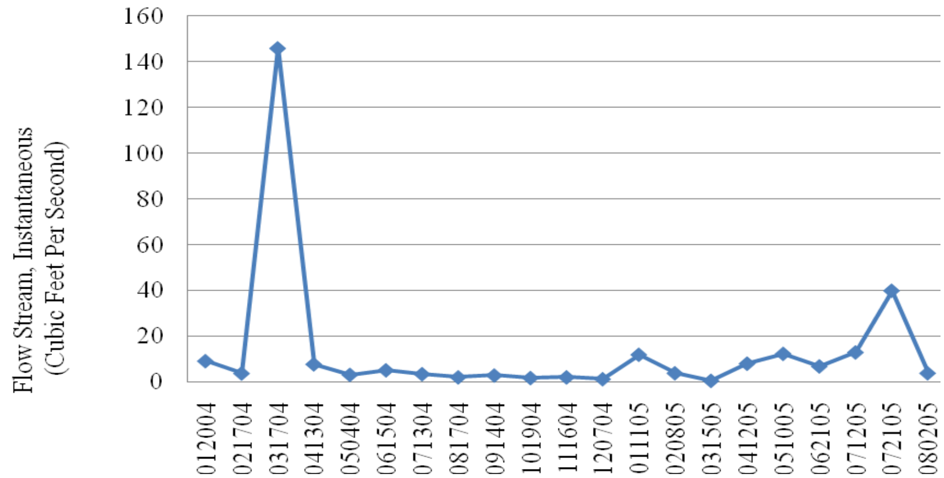


Figure 5. The instantaneous flow stream (cubic feet per second) from Jan. 2004 to Aug. 2005.

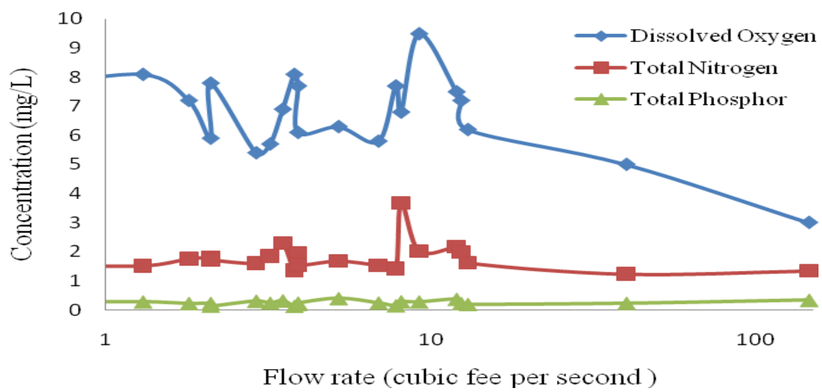


Figure 6. Dissolved Oxygen, Total Nitrogen and Total Phosphorus versus

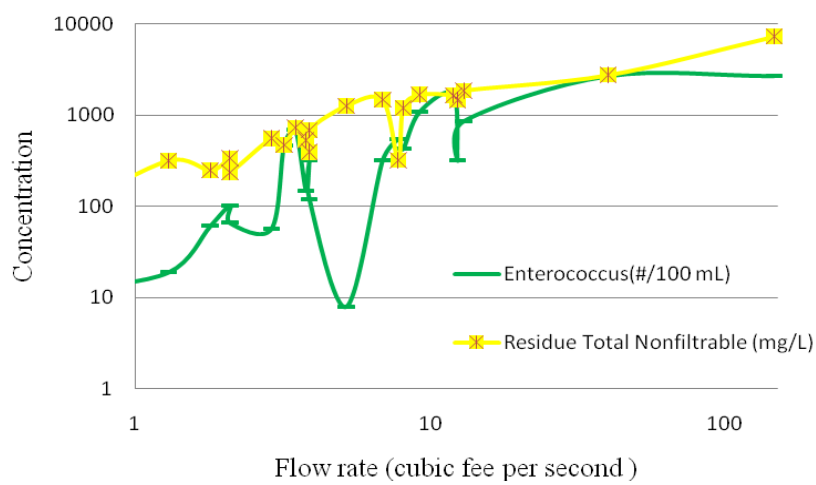


Figure 7. Enterococcus and TDS versus Flow rate

Software *Statistic 8* was employed to do the correlation analysis of the flow rate and other five indexes. Some data was adjusted, transforming >600 to 600 in enterococcus. Using the $p<0.05$ as the correlation analysis standard, the flow stream rate has a significant positive relationship with enterococcus and negative relationship with TDS at the base flow (Table 4). The data (just two high flow events) were not sufficient to complete a statistical analysis to show the difference between the base flow and high flow. However, Figure 5 preliminarily indicates that high flow leads to lower total nitrogen and dissolved oxygen concentrations; while Figure 6 indicates that high flow leads to higher enterococcus and TDS concentrations.

The purpose of this project was to provide hydrological and water quality data to monitor the effects of base and high flow storm events on the quality of flowing water in the drainage ditch in this rapidly developing area, and supply constructed wetland project for a treatment (Sam, 2005). However, there were several shortcomings in this available dataset which need elaboration.

The frequency of one sample per storm event is not sufficient to evaluate the storm. A more rigorous method for monitoring is to characterize sample adequately. However, time and cost will always restrict the amount of sampling. Some researchers proposed that sampling seven storms annually was the most efficient method for attaining small confidence interval width (Leecaster et al., 2002). However, more consideration needs to be given to the inherent sampling, storage and analytical uncertainties contained within these measurements (McCarthy et al., 2008). Thus, it is important to design monitoring programs for water quality based on field experience with realistic datasets (MacDonald et al., 2008). Furthermore, in order to identify the characteristics of runoff, the number of sampling events should be sufficient to illustrate the trend, especially in the period after the dry season to include the effect of first flush.

Runoff should be considered as the sum of base flow and rainfall on the ground (Figure 8). Therefore it is necessary to study the relationship of precipitation and stormwater flows. The rainfall gauges (weather station) should be established near the monitoring sites. The precipitation information from National Weather Service and US Geological Survey is critical but not enough. Basic statistics of storm events should comprise total rainfall, maximum intensity, antecedent dry day, event duration, and average rainfall intensity.

More importantly, stormwater link the atmosphere, land and river systems by precipitation and transportation (Figure 8). Therefore, in the project, factors such as weather, climate change, air quality, land cover and social-economic municipal, should be considered to investigate the relationship with the water quality and quantity.

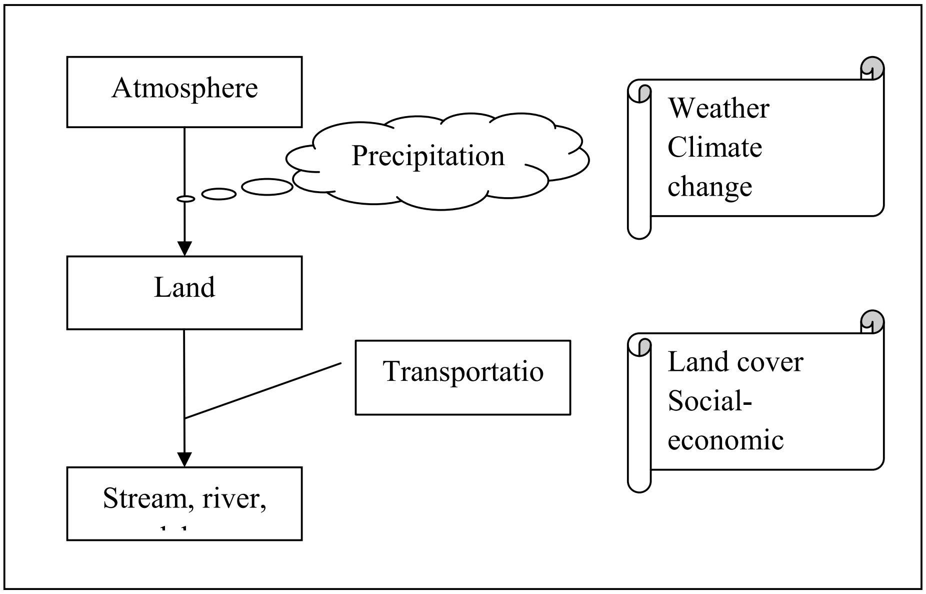


Figure 8. Schematic diagram of runoff complexities for sampling designs

Weather forecasting is a critical element for sampling planning. Based on the long term (5 day) forecasts by the US Weather Service, a research team can prepare to sample base flow and storm water quality. 24 samples of base flow (one hour interval) will be collected one day each month. If possible, one storm event per month will also be sampled. The procedure will cover the seasonal variation. The sampling interval before and after the rain is prepared for one hour, and then 10-15 minutes during the storm events. Different storm levels (precipitation >= 0.01, 0.1, and 1 inches) also will be considered in sampling. The selected water quality parameters for base flow include the total suspended solids, TDS, turbidity, conductivity, pH, chemical oxygen demand, dissolved oxygen, ammonia, total Kjeldahl nitrogen, total phosphorus, fecal coliform (Table 1). Mercury in edible tissue and PCBs in edible should also be given more attention (Texas Commission on Environmental Qualify, 2008). Without regard to the financial limitation, more organized data will support the statistic analysis and cover possible uncertainty and variation.

Complexities exist among the volume of runoff, concentration of (pollutants and time; furthermore, the uncertainties of rainfall and land use transformations also have significant influences. Therefore, a comprehensive and dynamic analysis should cover the influences of storm, flow rate, pollutants concentration and mass loading. Continuous monitoring of water quality will also add values. Typically, one piece of monitoring dataset or one storm event is not sufficient to characterize the water quality of runoff of the whole year. More modeling parameters, time-volume, time-concentration, and time-mass loading, should come into play.

The objective of monitoring determines the methods of data collection and sampling protocols. The original report of the Green Valley (Sam 2005) plotted the general water quality index against flow rate changing with time. However, this analysis did not illustrate the correlation analysis among the flow rate, water quality and environment factors. And it also lack enough data to identify the characters of storm water and its impact on the water quality, no matter the relationship between the stormwater quality and land use.

In addition, these data should be integrated into some application models, such as SWAT (soil water assessment tool), APEX (Agricultural Policy EXtender) and SWMM (Storm Water Management Model). However, most of these models usually focus on the flow rate change caused by storm event, the stormwater quality is less in such models. New samples strategies and deep data mining will be needed to provide useful information to control and manage the stormwater.

It is strongly recommended that necessary monitoring criteria be updated from the traditional water quality monitoring system. More data and higher frequencies of monitoring through the adequate modeling, supply more accurate characterization of the water quality of run off in the conditions of both routine dry and storm events.

Table 2. The concentration index of water quality for base flow, high flow 1 and high flow 2

Water quality index	Mean	Standard deviation	High flow 1	High flow 2	Criteria [8,9]
Flow rate (cfs)	5.4579	3.9185	146	40	
Oxygen, Dissolved (mg/L)	7.03	1.05	5	3	4.0
Nitrogen, Kjeldahl, Total, (mg/L as N)	1.85	0.51	1.23	1.34	0.44
Phosphorus, Total, Wet Method (mg/L as P)	0.25	0.07	0.234	0.34	0.8
Enterocci (#/100 mL)	387.37	444.64	> 600	600	200
TDS, Residue,Total Filtrable (dried at 180^{o}C, mg/L)	2863.16	1727.95	1730	1070	2000
Transparency, Secchi Disc (meters)	0.11	0.05	0.20	0.10	
Specific Conductance,Field (µmhos/cm @ 25 ^{o}C)	4856.84	2428.87	3160.00	2060.00	
pH (standard units)	7.87	0.19	7.90	7.20	6.5-9.0
Alkalinity, Total (mg/L as $CaCO_3$)	207.32	41.53	132.00	124.00	
Residue, Total Nonfiltrable (mg/L)	158.26	49.92	69.00	50.00	
Residue, Volatile Nonfiltrable (mg/L)	22.37	5.87	10.00	6.00	
Nitrogen, Ammonia, Total (mg/L as N)	0.07	0.05	0.08	0.11	
Nitrite Plus Nitrate, Total (mg/L as N)	1.85	2.66	0.98	1.69	
Phosphorus, Dissolved Orthophosphorus(mg/L as P)	0.00	0.01	0.00	0.23	
Carbon, Total Organic (mg/L as C)	6.68	1.87	8.11	11.10	
Chloride (mg/L as Cl)	1149.84	801.13	693.00	416.00	700
Sulfate (mg/L as SO_4)	611.47	312.84	395.00	199.00	700
Pheophytin-a (µg/L Fluorometric Method)	8.48	4.38	4.20	0.00	
Chlorophyll-a (Phytoplankton µg/L, Chromo-Flouro)	35.05	16.94	21.00	9.80	
Turbidity (Lab Nephelometric Turbidity Units, NTU)	151.65	54.02	68.50	61.20	

Table 3. The mass loading index of water quality for base flow, high flow 1 and high flow 2

Water quality index	Mean	Standard deviation	High flow 1	High flow 2
Oxygen, Dissolved (Mg/L)	38.67	29.26	200	438
Nitrogen, Kjeldahl, Total, (Mg/L As N)	10.60	8.89	49.2	195.64
Phosphorus, Total, Wet Method (Mg/L As P)	1.39	1.14	9.36	49.64
Enterocci (#/100 ML)	3297	5285	108000	87600
TDS, Residue,Total Filtrable (Dried At 180 ^{o}C),Mg/L	12204	7016	69200	156220

Table 4. The correlation between the flow rate and dissolved oxygen, total nitrogen, total phosphorus, Enterocci and TDS during base flow

Index	Flow rate	Dissolved oxygen	Total nitrogen	Total phosphorus	Enterocci	TDS
Flow rate	1.0000	.0748	.2794	.0933	.7164*	-.5336*
Dissolved oxygen	.0748	1.0000	.0130	-.1996	.2515	.1482
Total nitrogen	.2794	.0130	1.0000	.3263	.3058	-.2444
Total phosphorus	.0933	-.1996	.3263	1.0000	.2582	-.0277
Enterocci	.7164*	.2515	.3058	.2582	1.0000	-.3751
TDS	-.5336*	.1482	-.2444	-.0277	-.3751	1.0000

* It shown that the correlation analysis of two indexes was at $p<0.05$.

Design and implementation of a forebay-pond-wetland system for urban stormwater treatment in South Texas

There are two forebay-pond-wetland systems being constructed in the City of McAllen, Texas, USA. The construction of the McAuliffe School BMP is already complete (Fig. 9), and the design and implementation of the Morris School BMP is underway (Fig. 10).

The McAuliffe School BMP design has four parts, one forebay, two ponds and one wetland. The forebay is a small scale grass swale, with a screen inserted between the inlet and forebay. The two ponds have enough volume to detain a high intensity storm event. The wetland is primarily a subsurface flow wetland. Design draft of the McAuliffe school wetland is shown in Figure 11.

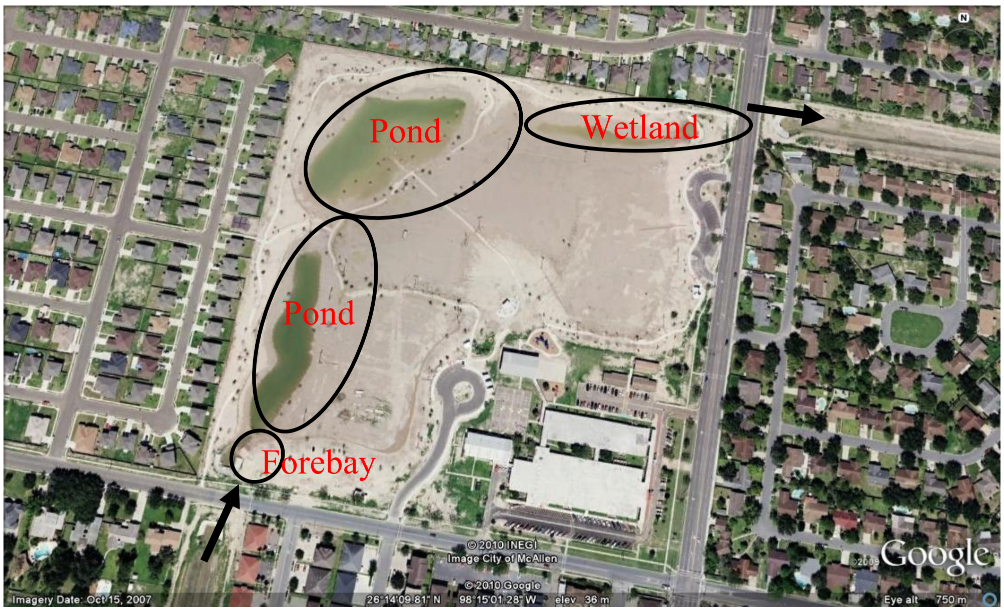


Figure 9. Aerial imagery of the McAuliffe School BMP, Feb. 10, 2009

The Morris School BMP is proposed to have three parts, one forebay, one pond and one wetland. One baffle boxes will be installed in the channel, which can remove sediment, floatables, suspended particles, and associated pollutants from storm water. The wetland will adopt the surface flow wetland type. Design draft of the Morris school wetland is shown in Figure 12.

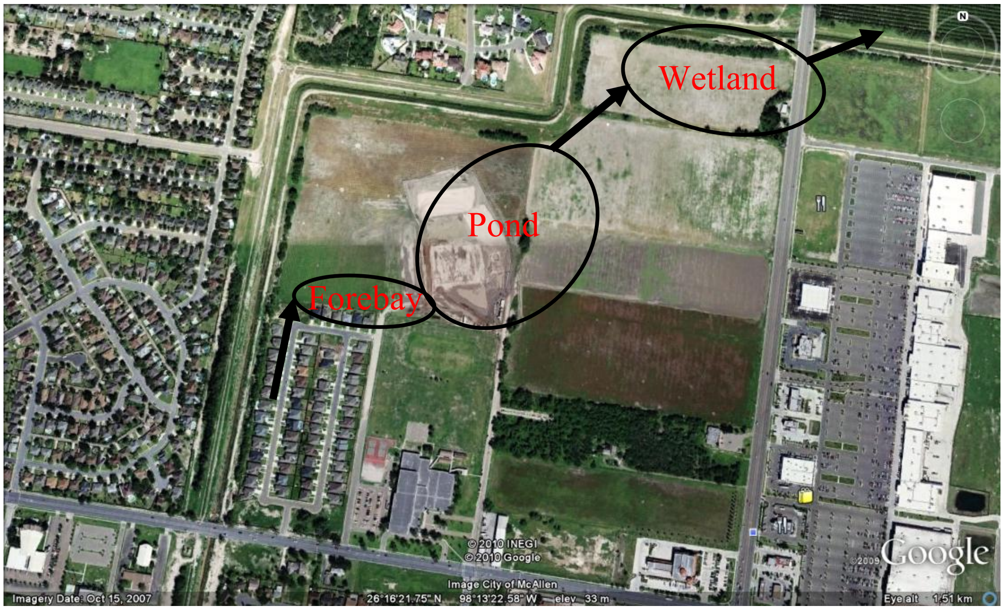


Figure 10. Aerial imagery of the Morris School BMP, Feb. 10, 2009

In order to remove contaminants in storm runoff, a forebay-pond-wetland system has been proposed and implemented at two locations in South Texas, USA. The forebay area is used as pretreatment step to increase the total performance and service life of pond and wetland. Both the ponds and constructed wetlands were designed to settle suspended solids and allow for some decay of active contaminants and nutrients. The ponds also have a significant volume storage function. Native vegetation has been planted in the wetland areas to enhance its positive role in the removal of sediment and pollution.

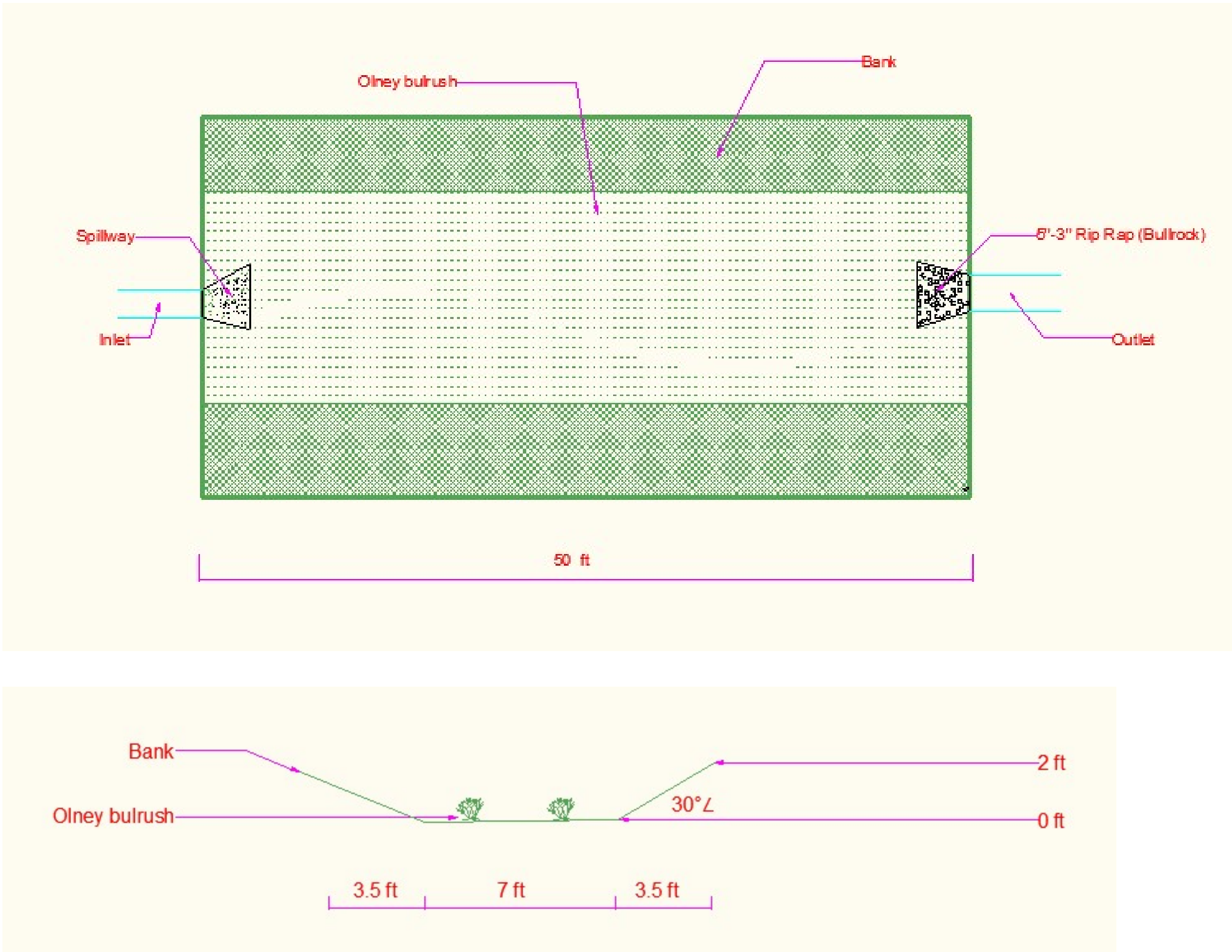


Figure 11. Design draft of the McAuliffe School Wetland

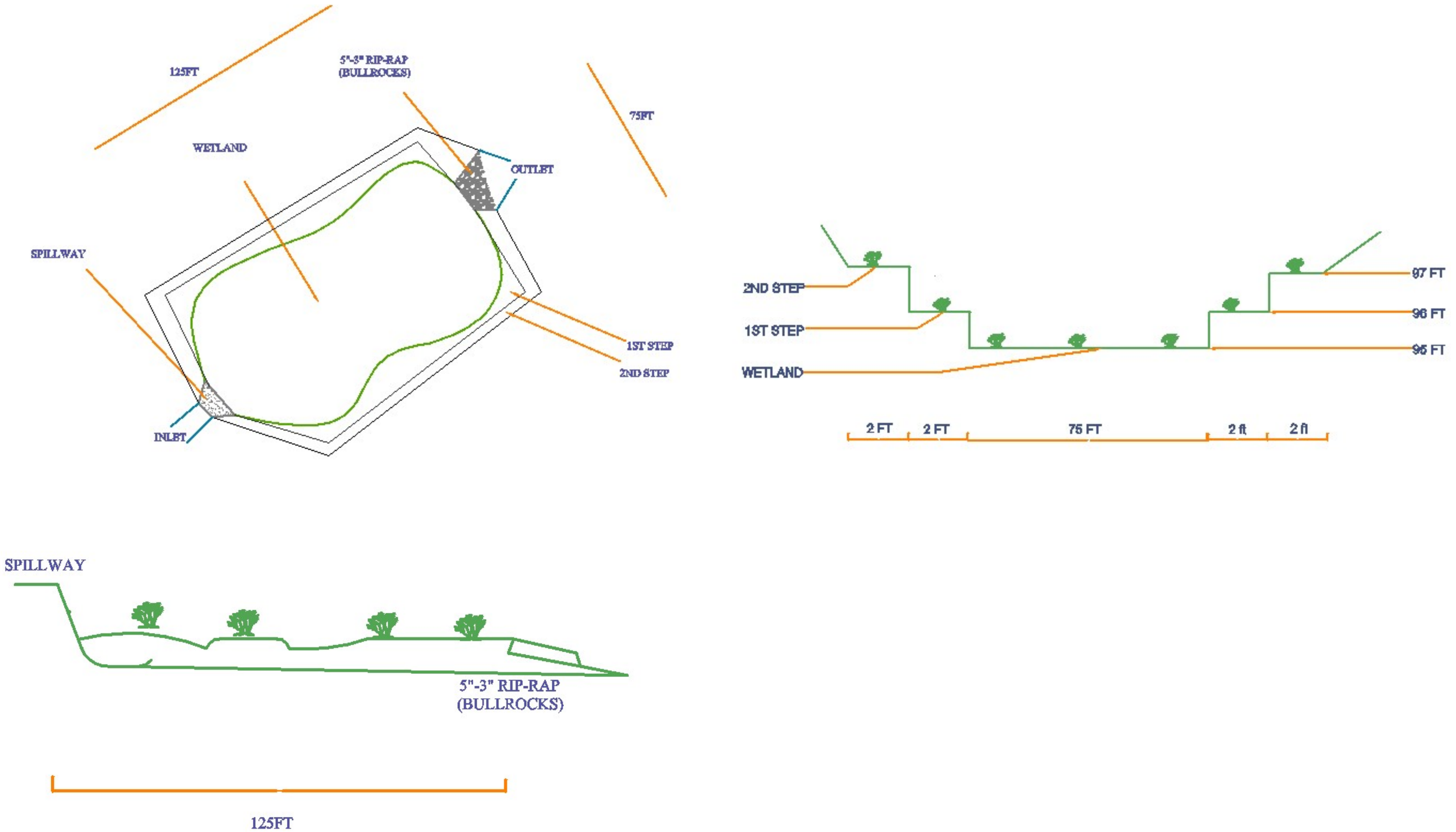


Figure 12. Design draft of the Morris School Wetland

Significance

The complete analysis of Green Valley Farm colonia dataset will provide a full picture for stormwater pollution in South Texas area. In addition, in the background of global climate change, proper management of urban stormwater also can decrease the risk of flood and increase the infiltration to groundwater. Thus, our project will be a pioneer work on the sustainable management and planning of urban stormwater in semi-arid area like South Texas.

Proposed of sequential treatment (forebay-pond-wetland) and design of some Best Management Practices (wetland) would be installed in McAllen city. Descriptive models of each BMP would be developed and validated using continuous flow monitoring data. The BMP designs and performance evaluation will be presented to stakeholders and recommended for incorporation into the South Texas Arroyo Colorado Watershed Protection Plan to improve regional water quality.

Acknowledgements

The author also want to thank the financial support from the South Texas Environmental Institute (Texas A&M University - Kingsville), Office of Research and Sponsored Programs (Texas A&M University - Kingsville), Texas Water Resources Institute (Texas A&M University), Spring Sunshine Plan grant (Ministry of Education, China) and China Scholarship Council (Ministry of Education, China). The authors also acknowledge the contributions Dr. Jianhong-Jennifer Ren, Dr. Lee W. Clapp, Dr. David Ramírez, Dr. Jingbo Liu, Nina Cortez, Abel Garza, Catherine M. Allen, Verna Walters and Don Marek at Texas A&M University - Kingsville.

References Cited

Barrett, M. E. 2008. Comparison of BMP performance using the international BMP database. J. Irrig. Drain. Eng. 134 (5): 556-561.

Brix, H. 1997. Do macrophytes play a role in constructed treatment wetlands? Water Sci. Technol. 35 (5): 11–17.

Carleton, J. N., and H. J. Montas. 2007. A modeling approach for mixing and reaction in wetlands with continuously varying flow. Ecol. Eng. 29 (1): 33-44.

Costanza, R., R. D'Arge, R. Groot, R. D. Groot, S. Farber, M. Grasso, B. Hannon, K. Limburg, S. Naeem, R. V. O'Neill, J. Paruelo, R. G. Raskin, P. Sutton, and M. V. D. Belt. 1997. The value of the world's ecosystem services and natural capital. Nature 387 (6630): 253-260.

Davis, A.P., M. Shokouhian and S. Ni. 2001. Loading estimates of lead, copper, cadmium, and zinc in urban runoff from specific sources. Chemosphere 44 (5): 997-1009.

Deletic A. The First Flush Load of Urban Surface Runoff. Water Research 1998, 32(8): 2462-2470.

Deletic, Y. L., and T. D. Fletcher. 2007. Modeling wet weather sediment removal by stormwater constructed wetlands: insights from a laboratory study. J. Hydrol. 338 (3-4): 285-296.

Grum M., Aalderink R.H., Lijklema L., Spliid H. The underlying structure of systematic variations in the event mean concentrations of pollutants in urban runoff. Water Science and Technology 1997, 36(89): 135-140.

Färm, C. 2001. Evaluation of the accumulation of sediment and heavy metals in a storm-water detention pond. Water Sci. Technol. 45 (7):105–112.

Hall, K.J., and B.C. Anderson. 1988. The toxicity and chemical composition of urban stormwater runoff. Can. J. Civ. Eng. 15 (1): 98–106.

Johnson, J. L. 2007. Evaluation of stormwater wetland and wet pond forebay design and stormwater wetland pollutant removal efficiency. A thesis published by the Graduate School of North Carolina State University, under the direction of Dr. William Hunt, III.

Kadlec, R. H. 2003. Pond and wetland treatment. Water Sci. Technol. 48 (5): 1-8.

Karathanasis, A. D., C. L. Potter, and M. S. Coyne. 2003. Vegetation effects on fecal bacteria, BOD, and suspended solid removal in constructed wetlands treating domestic wastewater. Ecol. Eng. 20 (2): 157-169.

Leecaster M. K., Schiff K., Tiefenthaler L. L. Assessment of efficient sampling designs for urban stormwater monitoring. Water Research 2002, 36(6):1556-1564.

MacDonald D.D., Clark M.J.R., Whitfield P.H., Wong M.P. Designing monitoring programs for water quality based on experience in Canada. I- Theory and framework. Trends in Analytical Chemistry 2008, doi:10.1016/j.trac.2008.10.016.

Marsalek, J., Rochfort, Q., Brownlee, B., Mayer T., Servos, M., 1999. An exploratory study of urban runoff toxicity, Water Sci. Technol. 39 (12): 33–39.

McCarthy D.T., Deletic A., Mitchell V.G., Fletcher, T.D. & Diaper, C. Uncertainties in stormwater E. coli levels. Water Research 2008, 42 (6-7), 1812-1824.

Novotny, V., and H. Olem. 1994. Water quality: prevention, identification, and management of diffuse pollution. Van Nostrand Reinhold, New York.

Nueces River Authority, Clean Rivers Program. Instantaneous Field Measurements. www.nueces-ra.org/CP/CRP/SWQM/docs/sparameters.doc

Sam Sugarek. A final report on the surface water monitoring and flow data collection study for the Cameron County special study. The Nueces River Authority, TX, 2005.

Scholes, L., D. M. Revitt, and J. B. Ellis. 2008. A systematic approach for the comparative assessment of stormwater pollutant removal potentials. J. Environ. Manage. 88 (3): 467-478.

Stenstrom M.K., Kayhanian M. First Flush Phenomenon Characterization. Final report prepared for the California Department of Transportation, Report No. CTSW-RT-05-73-02.6, Sacramento, CA, 2005.

Texas Commission on Environmental Quality. 2000 Texas Surface Water Quality Standards.

Texas Commission on Environmental Quality (TCEQ). Surface Water Quality Monitoring Procedures, Volume 1: Physical and Chemical Monitoring Methods for Water, Sediment, and Tissue, 2003.

Texas Commission on Environmental Quality (TCEQ). 2008 Texas Water Quality Inventory and 303(d) List, 2008.

Thullen, J. S., J. J. Sartoris, and S. M. Nelson. 2005. Managing vegetation in surface-flow wastewater-treatment wetlands for optimal treatment performance. Ecol. Eng. 25 (5): 583-593.

Walsh, C. J. 2000. Urban impacts on the ecology of receiving waters: a framework for assessment, conservation and restoration. Hydrobiologia 431 (2-3): 107–114.

Wu, P., and Y. Zhou. 2009. Simultaneous removal of coexistent heavy metals from simulated urban stormwater using four sorbents: A porous iron sorbent and its mixtures with zeolite and crystal gravel. J. Hazard. Mater. 168 (2-3): 674-680.

Wong T.H.F. Introduction. In: Wong, T.H.F. (Ed.), Australian Runoff Quality. Institute of Engineers, Australia, 2006.

Wong, T. H. F., P. F. Breen, N. L. G. Somes. 1999. Ponds vs wetlands – performance considerations in stormwater qualify management. Proceedings of the 1st South Pacific Conference on comprehensive stormwater and aquatic ecosystem management, Auckland, New Zealand, 2, 223-231.

Institutional Mechanisms for Accessing Irrigation District Water

Basic Information

Title:	Institutional Mechanisms for Accessing Irrigation District Water
Project Number:	2010TX375G
Start Date:	9/1/2010
End Date:	8/31/2012
Funding Source:	104G
Congressional District:	17
Research Category:	Social Sciences
Focus Category:	Law, Institutions, and Policy, Economics, Water Supply
Descriptors:	None
Principal Investigators:	Ron Griffin

Publications

There are no publications.

Institutional Mechanisms for Accessing Irrigation District Water
Project Number: 2010TX375G

Progress Report on

Achieving Water Use Efficiency in Irrigation Districts

Substantial effort has been made in reviewing literature pertaining to irrigation district structure and underlying economic and political factors affecting water reallocation decisions. The availability of organization level water use and water right data has been examined with the goal of undertaking empirical investigations regarding economics of water reallocation in American west.

Annual surface water use and water right data for irrigation organizations in different Western States have been searched. States of emphasis are Utah, Arizona, New Mexico, Texas, Nevada, and Colorado. Telephone and email inquiries have been made to state agencies such as State Engineers' Office (New Mexico), Division of Water Right (Utah), Division of Water Resources (Colorado and Nevada), Department of Water Resources (Arizona), Water Masters Office (Texas), and Texas Commission on Environmental Quality (Texas). Contacts have also been made to different irrigation districts (such as Bountiful Irrigation District, UT; Brownsville Irrigation District, TX; Riverside Irrigation District, CO), water conservancy districts (Colorado), and Bureau of Reclamation offices (Albuquerque and Denver). Organization level annual water use data are difficult to obtain. In Utah for instance, state engineer records more than 150,000 water rights; district rights are not distinguished; and actual water use is either self-reported or unreported. State-level water use reporting is by geographical boundary, not by organization, in states like Utah and Colorado, thereby complicating the task of identifying organization level water use in different sectors. In Arizona and Nevada there is no or rare central monitoring of surface water use by individual organizations. In New Mexico water use by county or river basin is performed on five-year basis rather than on annual basis and organization level water use database is unavailable. However, in Texas organization level time series water use data are found to be available. Data for different water rights are maintained by Texas Commission on Environmental Quality and Water Masters Office.

Information Transfer Program Introduction

In 2010, the Texas Water Resources Institute continued its outstanding communication efforts to produce university-based water resources research and education outreach programs in Texas.

Information Transfer

Basic Information

Title:	Information Transfer
Project Number:	2010TX367B
Start Date:	3/1/2010
End Date:	2/28/2011
Funding Source:	104B
Congressional District:	17
Research Category:	Not Applicable
Focus Category:	None, None, None
Descriptors:	None
Principal Investigators:	Bill L. Harris, Leslie Jordan, Danielle Supercinski, Courtney Swyden, Jaclyn Tech, Kevin Wagner, Ralph Wurbs, Kathy Wythe

Publications

1. Boyer, Christopher N., M. Edward Rister, Callie S. Rogers, Allen W. Sturdivant, Ronald D. Lacewell, Charles "Chuck" Browning, Jr., James R. Elium III, and Emily K. Seawright, 2010, Economies of Size in Municipal Water-Treatment Technologies: A Texas Lower Rio Grande Valley Case Study (TR-367), Texas Water Resources Institute, Texas A&M System, College Station, Texas, 101 pages.
2. Engler, Cady, Sergio Capereda, and Saqib Mukhtar, 2010, Assembly and Testing on an On-Farm Manure to Energy Conversion BMP for Animal Waste Pollution Control (TR-366), Texas Water Resources Institute, Texas A&M System, College Station, Texas, 23 pages.
3. Harris, B.L., Dan Roelke, Bryan Brooks, and James Grover, 2010, Lake Granbury and Lake Whitney Assessment Initiative (TR-392), Texas Water Resources Institute, Texas A&M System, College Station, Texas, 122 pages.
4. Lesikar, B, J. Mechell, B. Clayton, and R. Gerlich, 2010, Provide assistance to Improve Water Quality in Hood county final Report (TR-391), Texas Water Resources Institute, Texas A&M System, College Station, Texas, 12 pages.
5. Marek, Thomas, and Dana Porter, 2010, Energy Use and Irrigation Scheduling for Efficient Water Use (TR-2010), Texas Water Resources Institute, Texas A&M System, College Station, Texas, 46 pages.
6. Moench, Emily and Kevin Wagner, 2010, Educational Program for Improved Water Quality in Copano Bay Task Two Report (TR-347), Texas Water Resources Institute, Texas A&M System, College Station, Texas, 25 pages.
7. Miyamoto, S., 2010, Supplement to Diagnosis and Management of Salinity Problems in Irrigated Pecan Production: Salt Leaching (TR-387A), Texas Water Resources Institute, Texas A&M System, College Station, Texas, 13 pages.
8. Miyamoto, S., 2011, Updated Guidelines for Soil Selection and Improvements for Irrigated Pecan Production: Alluvial Soils (TR-394), Texas Water Resources Institute, Texas A&M System, College Station, Texas, 8 pages.
9. Swanson, Charles and Guy Fipps, 2010, Evaluation of Smart Irrigation Controllers: Year Two (2009) Results (TR-364) Texas Water Resources Institute, Texas A&M System, College Station, Texas, 21 pages.
10. Wagner, Kevin, 2010, Texas Watershed Planning Short Course Final Report (TR-290), Texas Water

Resources Institute, Texas A&M System, College Station, Texas, 87 pages.
11. Wagner, Kevin, Larry Redmon, and Terry Gentry, 2011, Bacteria Runoff BMPs for Intensive Beef Cattle Operations (TR-395), Texas Water Resources Institute, Texas A&M System, College Station, Texas, 38 pages.
12. Bryant, Gary, 2010 Rainwater Harvesting at the Marfa Activity Center (EM-106), Texas Water Resources Institute, Texas A&M University System, College Station, Texas.
13. Moench, Emily, 2010, Guide to Good Horsekeeping (EM-107), Texas Water Resources Institute, Texas A&M University System, College Station, Texas.

Texas Water Resources Institute
Information Transfer Activities
March 1, 2010 – February 28, 2011

In 2010, the Texas Water Resources Institute continued its outstanding communication efforts to produce university-based water resources research and education outreach programs in Texas.

The Institute publishes a monthly email newsletter, a quarterly newsletter specific for one project, and an institute magazine published three times a year. The Institute began publishing an online peer-reviewed journal in conjunction with a nonprofit organization and began using social media to publicize information.

New Waves, the email newsletter, publishes timely information about water resources news, results of projects and programs, and new water-related research projects, publications and faculty at Texas universities. The newsletter has a subscription of 1,271.

RGBI Outcomes is an 8-page newsletter specifically spotlighting research and education programs of the Rio Grande Basin Initiative, a federally funded project focused on increasing available water through efficient irrigation and water conservation. RGBI Outcomes has a subscription of more than 858.

txH_2O, a 30-page glossy magazine, is published three times a year and contains in-depth articles that spotlight major water resources issues in Texas, ranging from agricultural nonpoint source pollution to landscaping for water conservation. Over 2,433 individuals and entities received the magazine via subscription and approximately 1,000 more magazines are distributed.

The Texas Water Journal is an online, peer-reviewed journal devoted to the timely consideration of Texas water resources management and policy issues from a multidisciplinary perspective that integrates science, engineering, law, planning, and other disciplines. The Institute published its first issue in September 2010. It currently has 204 enrolled users, although registration is not required to view the journal.

The Institute began a Twitter account to promote the institute and water resources news and education throughout the state. The Institute's Twitter followers and engagement levels have steadily increased. It also began a project-specific blog and Facebook page.

Working to reach the public and expand its audience, the Institute generates news releases and cooperates with Texas A&M AgriLife Communications writers for them to produce news releases about projects as well. The Institute prepared numerous informational packets for meetings. TWRI projects or participating researcher efforts had at least 102 mentions in the media.

For each of the institute's projects, TWRI published a one-page fact sheet that explains the purpose, background, objectives, and, if applicable, accomplishments of the program.

In addition to the one-page fact sheets for its projects, the institute developed 23 other publications/brochures, including an accomplishment report for a major project and fact sheets about best management practices,.

In cooperation with research scientists and Extension education professionals, the institute published 11 technical reports and two educational materials publications, which provide in-depth details of water resource issues from various locations within the state.

TWRI continues to enhance its web presence by posting new project-specific Web sites and continually updating the information contained within the websites. The institute currently maintains 38 websites.

TWRI Program Sites:

Arroyo Colorado	arroyocolorado.org
Attoyac Bayou Watershed Protection Plan Development	attoyac.tamu.edu
Bacteria Fate and Transport	bft.tamu.edu
Big Cypress Creek Modeling and BST	bcc.tamu.edu
Buck Creek Watershed Protection Plan Development	buckcreek.tamu.edu
Caddo Lake Data	caddolakedata.us
Carters and Burton Creeks Water Quality	cartersandburton.tamu.edu
Center for Invasive Species Eradication	cise.tamu.edu
Consortium for Irrigation Research and Education	cire.tamu.edu
Copano Bay Water Quality Education	copanobay-wq.tamu.edu
Efficient Nitrogen Fertilization	n-fertilization.tamu.edu
Environmental Effects of In-House Windrow Composting of Poultry Litter	windrowlitter.tamu.edu
Evaluating BMPs to Reduce Poultry Odors	poultrybmps.tamu.edu
Fort Hood Range Revegetation	forthoodreveg.tamu.edu
Groundwater / Surface Water Interactions	waterinteractions.tamu.edu
Groundwater Nitrogen Source Identification and Remediation	groundwatern.tamu.edu
Lake Granbury Water Quality	lakegranbury.tamu.edu
Leon/Lampasas BST	leon-lampasasBST.tamu.edu
Little Brazos River Bacteria Assessment	lbr.tamu.edu
Lone Star Healthy Streams	lshs.tamu.edu
North Central Texas Water Quality	nctx-water.tamu.edu
Pecos River WPP Implementation Program	pecosbasin.tamu.edu
Rio Grande Basin Initiative	riogrande.tamu.edu
Rio Grande Basin Initiative Conference	riogrande-conference.tamu.edu
State BST Infrastructure Support	texasbst.tamu.edu
Texas Water Resources Institute	twri.tamu.edu
Texas Watershed Planning	watershedplanning.tamu.edu
Texas Well Owner Network	twon.tamu.edu
Water Resources Training Program	watereducation.tamu.edu

Completed Program Sites:

Dairy Compost Utilization	compost.tamu.edu
Environmental Infrastructures	bosque-river.tamu.edu
Improving Water Quality of Grazing Lands	grazinglands-wq.tamu.edu
Irrigation Training Program	irrigationtraining.tamu.edu

Other Sites:

Save Texas Water	savetexaswater.tamu.edu
Texas Congressional District GIS	congdistdata.tamu.edu
Texas Water Centers	txwatercenters.tamu.edu

Texas Water Journal journals.tdl.org/twj
WATER Scholars Program waterscholars.tamu.edu

USGS Summer Intern Program

None.

Student Support					
Category	**Section 104 Base Grant**	**Section 104 NCGP Award**	**NIWR-USGS Internship**	**Supplemental Awards**	**Total**
Undergraduate	0	0	0	0	0
Masters	6	0	0	0	6
Ph.D.	3	0	0	0	3
Post-Doc.	0	0	0	0	0
Total	9	0	0	0	9

Notable Awards and Achievements

Meghan Gallagher (2010TX354B): Received a Graduate Student Research and Presentation Grant in the amount of $400 for travel expenses to present at the 2011 Land Grant and Sea Grant National Water Conference in Washington, D.C. from January 31 to February 1, 2011.

Kyna McKee (2010TX363B): Received the Robert E. Stewart Graduate Excellence Award