Evaluation and Validation of a Decision Support System for Selection and Placement of BMPs in the Mississippi Delta

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Prevention and reduction of surface water pollution has been a matter of concern for decades, which has promoted the implementation of best management practices (BMPs) to ensure the protection of water resources. A considerable number of structural and non-structural BMPs have been developed to control hydrological processes and enhance pollutant load reduction at field and watershed scales. However, the selection of a specific BMP or the best combination of these practices and BMP placement are major challenges faced by decision makers. Recently, modeling tools have been presented as an effective alternative to support those challenges and to achieve cost-effectiveness in addressing environmental quality restoration and protection needs in different scenarios. USEPA has presented The System for Urban Stormwater Treatment and Analysis Integration (SUSTAIN) model to be used by watershed and stormwater professionals to develop, evaluate and select optimal BMPs combinations, at multiple watershed scales, and to achieve targeted water quality objectives based on cost and effectiveness. This tool incorporates algorithms from the Storm Water Management Model (SWMM), the Hydrologic Simulation Program FORTRAN (HSPF) model and other BMP modeling techniques. In order to evaluate and validate the application of the SUSTAIN model in an agricultural scenario, a case study is developed for a midsize drainage area (307 ha) located in the Mississippi Delta. The agricultural watershed includes a surface drainage ditch in which three low grade weirs have been installed and monitored for water level and pollutants concentrations since July 2010. The objective of this study is to assess the performance and capability of the SUSTAIN model in the context of a real agricultural scenario where BMPs are implemented. The study also attempts to determine the cost-effectiveness curve for the implementation of BMPs in the study area (considering the number of weirs installed as a variable) using total suspended sediments and total phosphorus as control targets.

INTRODUCTION

The Mississippi River/Gulf of Mexico Hypoxia task force released the Gulf Hypoxia Action Plan for Reducing, Mitigating, and Controlling Hypoxia in the Northern Gulf of Mexico and Improving Water Quality in the Mississippi River Basin in June 2008 (FTN Associates, 2009). A Planning Team co-led by Delta F.A.R.M and the Mississippi Department of Environmental Quality (MDEQ) and formed by about 30 representatives from agencies organizations and stakeholders groups identified 12 critical elements for a Delta nutrient reduction strategy. This document is a component of the activities orientated to the evaluation and selection of appropriate analytical tools that can be used to develop the most efficient and effective action plans for areas within the Mississippi Delta Region.

Different models involving Management Decision Support Frameworks have been developed in the past years including a new model released by the USEPA in 2009 called SUSTAIN (System for Urban Stormwater Treatment and Analysis Integration). The SUSTAIN model (version 1.0) has been presented as an efficient tool that facilitates the selection of strategic placement of best management practices (BMPs) and Low Impact Development (LID) in watersheds at multiple scales. The model is expected to help in the development and implementations of plans for flow and pollution control in water systems, and to aid to identify the best cost effective solution helping managers or decision makers to identify the most efficient design of a BMP. The SUSTAIN model was developed and has being tested for urban stormwater treatment. This study evaluated the SUSTAIN model in an agricultural sub-watershed where BMPs were implemented for the reduction of sediment and nutrients. The objective of this study was to evaluate the performance and capability of the SUSTAIN model in the context of a real agricultural scenario in the Mississippi Delta, where BMPs were implemented.

What is the System for Urban Stormwater Treatment and Analysis Integration - SUSTAIN ?

The SUSTAIN model (Version 1.0) is a decision support system developed by the USEPA to facilitate the selection and strategic placement of best management practices (BMPs) and Low Impact Development (LID) techniques in watersheds at multiple scales (local and larger scale). The major purpose of this model is to aid in the development and implementation of plans for flow and pollution control in water systems. Specifically, the SUSTAIN model was designed to evaluate a BMP effectiveness.

The SUSTAIN Model has six components built on a base platform interface using ArcGIS (ArcView 9.3 and Spatial Analyst extension). The ArcGIS Framework Manager serves as the command center of SUSTAIN, facilitates the linkages between the system components (BMP sitting tool, watershed module, BMP module, conveyance module, post processor, and optimization tools) and coordinates external inputs as well as provides output information to the post-processor (Figure 1).

The application of the SUSTAIN model starts with the definition of a study objectives, followed by data collection, project/model setup, formulation of the optimization problem, and analysis of results (Figure 2). To setup the model, each component needs to be considered and usually applied in a series of steps, as follows:

Step 1. The BMP sitting tool is applied using the ArcGIS platform and user-guided rules to determine site suitability for a variety of BMP options.

Step 2. The watershed and conveyance module is used to generate runoff time series data to drive the BMP simulation and to provide routing capabilities between land segments, BMPs or both. The SUSTAIN model has the option to use externally generated land use-associated flow and water quality time series data, or internally generated data from BMP contributing areas, routing them through the BMPs to predict flow and water quality time series data at selected downstream locations.

Step 3. The BMP module is applied to provide simulation of management practices by using a combination of processes for storage retention, open-channel controls, filtration, biological purification and mechanical structure facilitated separation.

Step 4. Assessment locations are defined in the watershed where results are analyzed or compared.

Step 5. The cost database is organized according to BMP construction components (e.g., grading, backfilling, filter fabric) and populated with unit costs for each component.

Step 6. Optimization module compiles results from other modules in the framework for evaluating and selecting a combination of BMP options that achieve the defined pollutant targets at minimum cost.

Step 7. A post-processor tool is used to present the optimization results in a cost-effectiveness curve.

Model Evaluation

The main objective of this study was to evaluate the performance and capability of the SUSTAIN model in the context of a real agricultural scenario in the Mississippi Delta, where BMPs were implemented. The model evaluation used general and monitoring information from the Harris Bayou North Ditch Project, which was established and monitored by Dr. Robert Kröger, Assistant Professor at the Department of Wildlife, Fisheries and Aquaculture of Mississippi State University. The project was set up in August 2010 and samples have been collected since December 2010. The model evaluation considered monitoring information collected between January and July 2011.

MATERIALS AND METHODS

Study Area Description

The Harris Bayou North Ditch project is located at the Mississippi Delta area within the Harris Bayou watershed (Figure 3), which was placed on the Mississippi 2006 Section 303(d) list of impaired water bodies due to sediments and nutrients. The project has a total area of 758.9 acres including a ditch of approximately 931.93 ft length. Agricultural crops production (corn/winter wheat and soybean/winter wheat) represents the 80% of the entire area complemented by an extension of forest land located at the upper part of the watershed. Overland flow was drained from the agricultural fields to the ditch by 11 pipes (Ø=20 in) established at the end of the fields along the channel length. The ditch has a two-stage trapezoidal shape, which first stage depth is always lower than 1 ft. Three low grade weirs, a BMP method used as an alternative water control structure in drainage ditches, were built at the upper, middle and lower part of the ditch. Each low grade weir (h=1.4 ft) was built using rip-rap (Ø≈8.0 in) following a trapezoidal design (Figure 4). The construction of the weirs included excavation, engineering fabric, and installation of the rip-rap, information that was taken in consideration when computing costs for the SUSTAIN model setup. Four monitoring stations were located along the ditch length, one at the upper part of the ditch before the location of the first drainage pipe and other three near each weir. Each monitoring station included two water samplers each one at a different level, one water level logger and a sediment level ruler.

Methodology

To determine the effectiveness of SUSTAIN to represent the Harris Bayou North Ditch system the model was initially setup to run in internal simulation mode. A second instance in the application of the model referred to its evaluation by running it in external simulation mode. Suspended sediments and phosphorus were defined as the pollutants of interest for this analysis.

The SUSTAIN model was setup using the monitoring dataset from the Harris Bayou North Ditch Project and additional information collected by field observation and GIS application. The monitoring dataset included information of water level, water quality and channel geometry. Based on field recognition, aerial photography available at Google Earth® and personal communication with Dr. Kröger, a GIS dataset for land use, channel network, BMP location, monitoring points' location, soil series/hydrological group and area delimitation was generated using ArcMap 9.3.1. Since the project was already established, the SUSTAIN's BMPs sitting tool was not used to identify the BMP locations within the area. Instead, each BMP location was considered as established at the original project design. The three low grade weirs were represented in the model as dry ponds and the total cost of their construction was considered as $3,000 per unit. The entire area (watershed) was subdivided in nine major fields or drainage areas (subcathments) contributing their overland flow to each one of the three low grade weirs (Figure 4). A full description of sizing and weir configuration was included, as well as substrate properties (depth, porosity, field capacity, wilting point, and infiltration). A distribution of five combinations of hydrological unit responses (HRUs) that capture the land use and physical texture of the watershed were determined. The initial values for the parameters involved in the estimations of overland flow and infiltration were defined as the representative values for each soil texture present on each field.

A weather file including daily air temperature and evaporation data was prepared. The format for the climate file followed the input format required by the SWMM model. Temperature values were obtained from the NOAA National Climatic Data Center. The closest weather station from the study area was the Clarksdale Station (GHCND: USC00221707; 34.1864°N and -90.5573°E). A period of record from January 2010 to July 2011 was compiled in the SUSTAIN's climate file. A separate file was compiled containing a 15-min precipitation time series dataset from a USGS station located near to the Harris Bayou North Ditch area (USGS 341550090391300 Overcup Slough Tributary No 2 near Farrell, MS). Daily evapotranspiration rates were estimated by using the ETo Calculator Version 3.1 (FAO, 2009). The records from April 2010 to July 2011 were included in the file to setup the SUSTAIN model application.

A routing network, which connected the established BMPs within the system, was built as a two stage level channel considering the conduit cross section as an irregular shape. A Manning's roughness coefficient value of 0.03 was assigned to the entire length of the conduit. The values for the pollutants decay factors and sediment transport parameters were initially considered as the default values included in the model. Infiltration was estimated by using the Green-Ampt equation and its parameters values were considered for each soil texture class as suggested by Rawls et al., (1983). SUSTAIN's default values were initially assigned to the values of the pollutants properties and concentrations and the land use properties used to estimate sediment erosion from pervious lands.

After setting up all the modeling components and parameters, two land simulation input files were compiled by SUSTAIN before performing the land simulation running. The activity of a computational bug, which limited the compilation of the input files by SUSTAIN, was solved by including the "SC" text before the catchment ID in all the sections wherever a catchment ID was present. Assessment points for running current scenario conditions were defined at the location where each field monitoring station was established. SUSTAIN would generate flow, sediment and phosphorus concentration time series at these points, which would be compared with the monitoring dataset. The optimization component that makes SUSTAIN to search and identify the optimal solutions was setup by establishing a number of three optimal solutions for output.

The Harris Bayou North Ditch system was evaluated in SUSTAIN under the external land simulation option. The combination of water level and flow time series, sediment and phosphorus concentration datasets from stormflow and grab sampling events were used to generate sediment rating curves and linear relationships between sediment loads and phosphorus loads (Figure 5). Continuous time series of flow, sediment loads and phosphorus loads were generated for the period between December 16, 2010 and July 9, 2011. The entire area was subdivided in three major fields (subcatchments). Flow and pollutants time series were built for each contributing area to be routed through each one of the three low grade weirs. The routing network was built as a two stage level channel considering the conduit cross section as an irregular shape with a Manning's roughness coefficient value of 0.03 for the entire length of the conduit. The values for the pollutants decay factors and sediment transport parameters were considered as the default values included in the model. Assessment points were setup at each BMP location to develop the BMP simulation under current scenario and optimized conditions. For each type of evaluation an input file was created and the results were observed and analyzed. The criteria selection to minimize the BMPs implementation costs at the Harris Bayou North Ditch system was based on the reduction of the annual average load of sediment and phosphorus in a 50% of the value under existing conditions. Another criteria, searched for the opportunity to reduce the concentration of phosphorus in runoff to a daily level of 1 mg L^{-1}.

RESULTS AND DATA ANALYSIS

The manual calibration procedure, based on a trial and error process of adjusting selected parameters, resulted on inaccurate and poor calibrated results for the internal land simulation option. Results showed that the SUSTAIN model underestimated the flow volumes, the peak flow and the duration of the receding time on each stormflow event (Figure 6).

Under the external simulation procedure, modeling results from running SUSTAIN to compare the current conditions scenario (agricultural land with BMPs established along the ditch) with a pre-development scenario (agricultural land with no BMPs established) showed that the BMPs could reduce the sediment and phosphorus concentrations delivered by the Harris Bayou North Ditch system in up to 55% and 53%, respectively (Figure 7). The figure 8 summarize the predicted values of average daily sediment and phosphorus concentrations in the water flow running trough the Harris Bayou North Ditch system. Under the pre-development scenario conditions, the SUSTAIN model predicted constant values for sediment and phosphorus concentrations along the entire segment of the ditch. Those concentrations were higher than the concentrations estimated by the generation of the time series from the monitoring dataset (in at least 2 times), which represented the existing conditions in the study area. The phosphorus concentrations (TP) in the water flowing along the ditch, which can be considered as agricultural runoff, were favorably reduced by the effect of the BMPs.

The use of SUSTAIN to determine the best probable scenario with minimized costs in the establishment of BMPs showed that the current scenario was the best probable arrangement to be established to reduce sediments and nutrients at the estimated percentage of control (50%). However, this arrangement was not capable to reduce phosphorus concentrations to the targeted level of 1 mg l^{-1}. The procedure to develop the cost effectiveness curve for the conclusion of this study was limited due to a bug in the Microsoft Excel spreadsheet that accompanied the SUSTAIN model, which did not identify some needed components that the estimation routine required. By the end of this report, the authors were unable to obtain an updated or modified version of the spreadsheet from the group of the model developers.

Model Application Analysis

Based on the application of the SUSTAIN model in the study area, the following considerations were found to be a limitation of this new tool and for being evaluated in the context of a real agricultural scenario. The considerations were classified in two groups based on their incidence for the model application. For instance, issues related with the model setup were considered as operational subjects and issues related with the model performance were classified as technical subjects.

Operational Issues. The first limitation that the SUSTAIN model (version 1.0) can present is the availability and incompatibility of the model's GIS interface platform. The current version of the model runs only under a specific previous version of the ESRI ArcGIS® software (ArcGIS 9.3 or 9.3.1) and the Spatial Analyst extension, which is not compatible with posterior releases of this GIS commercial software.

During the evaluation of the SUSTAIN Model, the modeling setup and running processes were delayed due to a lack of knowledge and published information regarding the model operation and guidance. A tutorial guide prepared by the model developers is available; however, a significant number of steps that were not included in that document were needed during the model setup to properly apply some of the model tools and solve programming problems (bugs) the model engine and the postprocessor spreadsheet included. The programming problems or "bugs" that make the model crash when creating an input file was one of the conditions that more time consumed during the evaluation of SUSTAIN for this study. After a failed run in SUSTAIN, the entire project was gone and the model had to be setup from the beginning. SUSTAIN only generated an "error message" that did not explain the specific problem and the identification of the specific error was not possible until getting in contact with the technical support team at TetraTech. The problem was identified to be a bug on SUSTAIN, which prevented the model for having a unique subcatchment ID when using the internal simulation mode. The solution to this problem was to internally modify in the input file each subcathcment ID by adding the prefix "SC" before the ID number. Additionally, this programming error caused that any change on the value of a parameter or property made during the calibration process required to properly modify and create a new input file before performing a new run.

Changes on a layer component of the model could be performed and included in the geo-database file of the project. However, that change was not reflected on the creation of a new input file.

Technical Issues.

- SUSTAIN does not handle the possible interaction between the groundwater system and the channel system to properly represent the occurrence of baseflow or water retention conditions along a channel.
- The SUSTAIN model does not represent conditions like "back water" caused by floods that increase the time of reduction in water level after a storm or rainfall event. The model does not have any hydraulic option to add a structure that allows the user to represent it.
- The optimization tool spreadsheet recognizes all the configuration parameters and files containing the outlet information under the different scenarios of evaluation. However, the macro routines were not able to generate time series results or to create the cost effectiveness curve for the evaluated system.

Some of the technical and operational issues previously mentioned were discussed and solutions were given as reported through electronic (email) and telephonic communication (until March 2012) by the SUSTAIN technical support team at Tetra Tech. For some cases, the support team said they are working on a new version of the SUSTAIN model, which will include a solution to the identified programming errors and technical issues.

CONCLUSIONS

- For different studies performed by the technical support team at TetraTech in urban watersheds, the SUSTAIN model has been a very useful tool capable to help decision makers to select the best combination of practices to implement among the many options available that also result in the most cost-effective achievable. However, the evaluation of the SUSTAIN model in an agricultural environment by a user that was not part of the technical support team some limitations on its application were found. Important operational problems were an enormous time consuming condition that limited the opportunity to evaluate all the potential capabilities of the model.
- Non-accurate results were obtained in this study when trying to perform the prediction of water flow under the internal land simulation option included in the model. Additionally, the need to repetitively perform changes on the input files to avoid the model to

crash, made the calibration process an expensive time consuming and ineffective process.

- The use of external datasets could have been a successful alternative to perform the evaluation of the SUSTAIN model at the Harris Bayou North Ditch project. However, the technical problems that the postprocessor spreadsheet presented were an additional factor that finally limited to achieve the study's objective.
- Because of the technical and operational limitations previously described in the document, the current version of the SUSTAIN model can not be satisfactorily considered as an appropriate tool at field and watershed scale to develop action plans to enhance the nutrient reduction strategy within the Mississippi Delta Region. The model has an enormous potential to satisfactorily support this enhancement if the reported operational and technical limitations are fixed and presented in a new version.

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Figure 1. SUSTAIN Model Components (Source: Shoemaker et al., 2009)

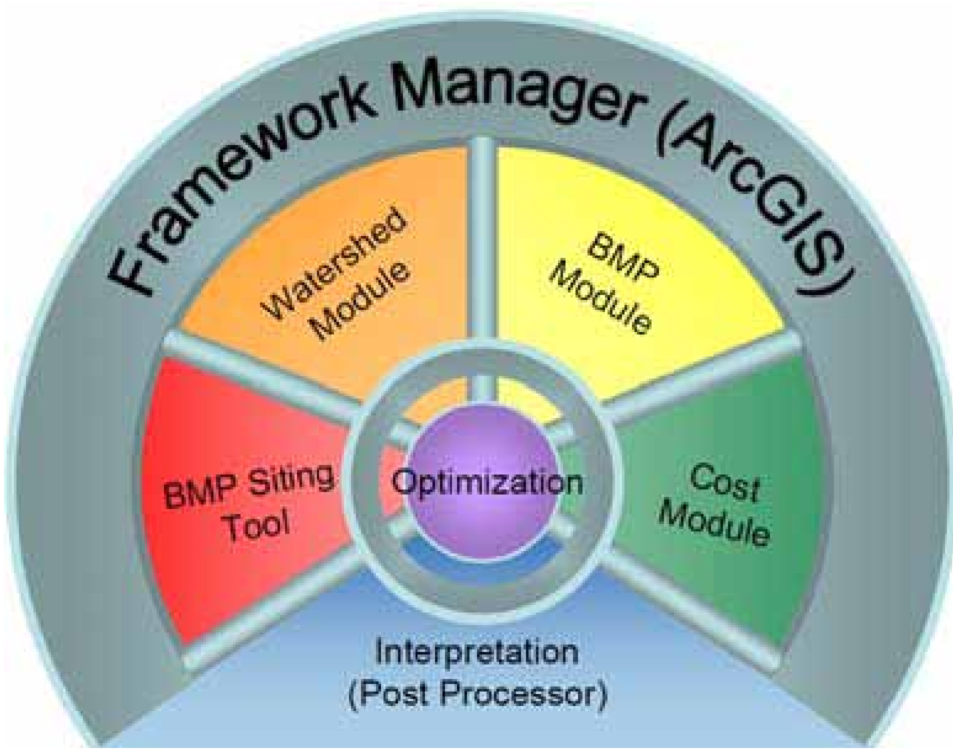

Figure 2. SUSTAIN Application Process (Source: Shoemaker et al., 2009)

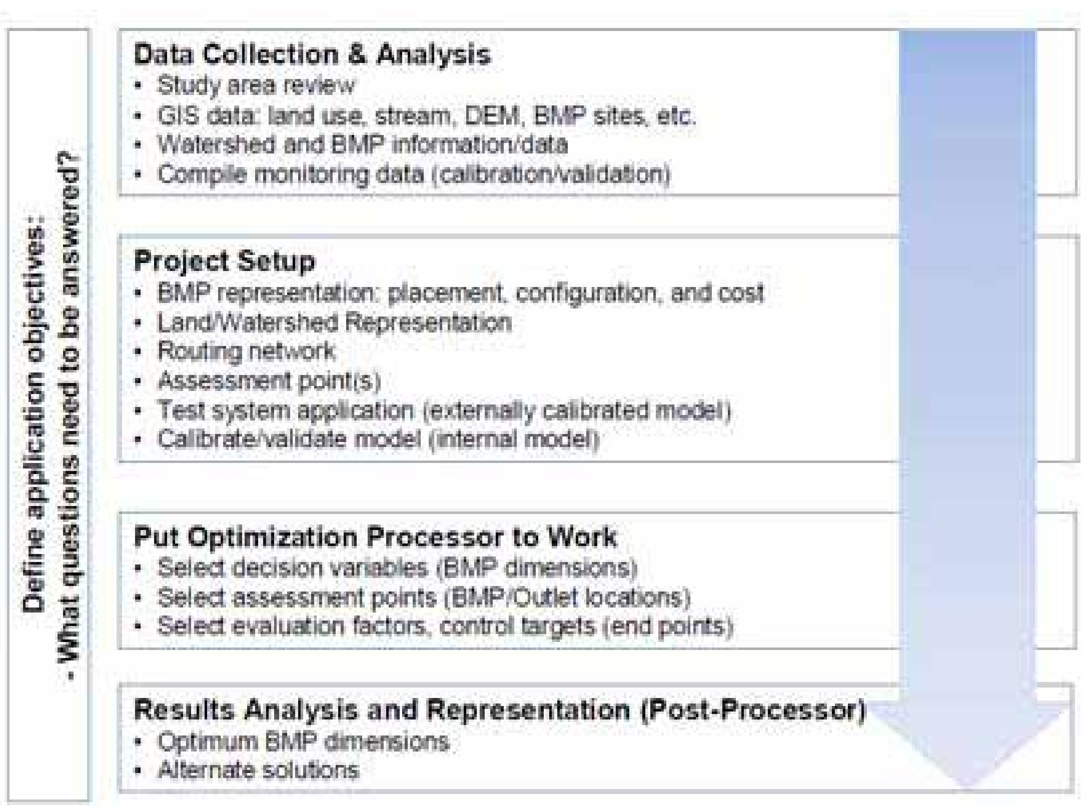

Figure 3 Harris Bayou Project Location

Figure 4. Low Grade Weir and Water Quality Monitoring Equipment

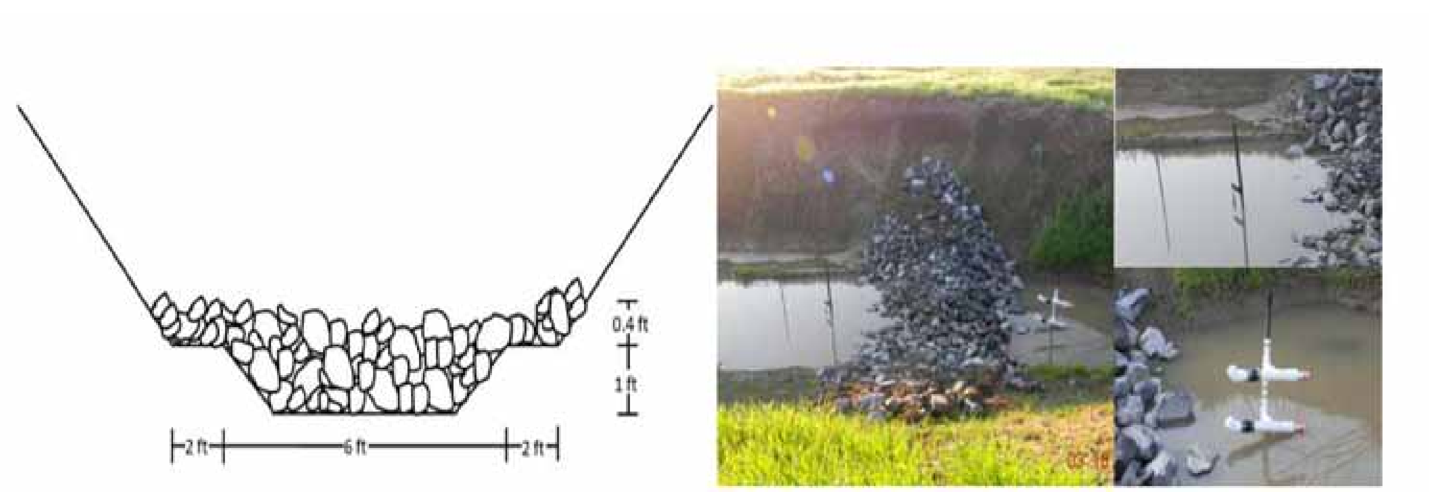

Figure 5. Runoff sediment rating curve (up) and relationship between suspended sediment load and phosphorus load in runoff (down) along the Harris Bayou North Ditch system

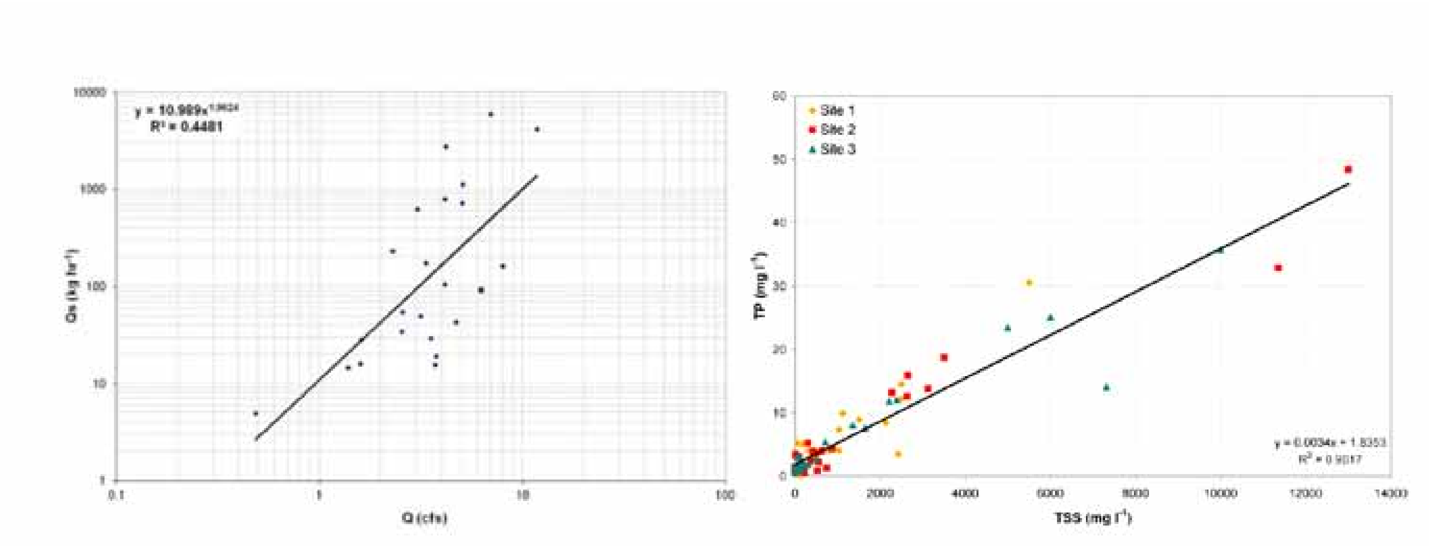

Figure 6. Estimated and simulated water flow along the Harris Bayou North Ditch system

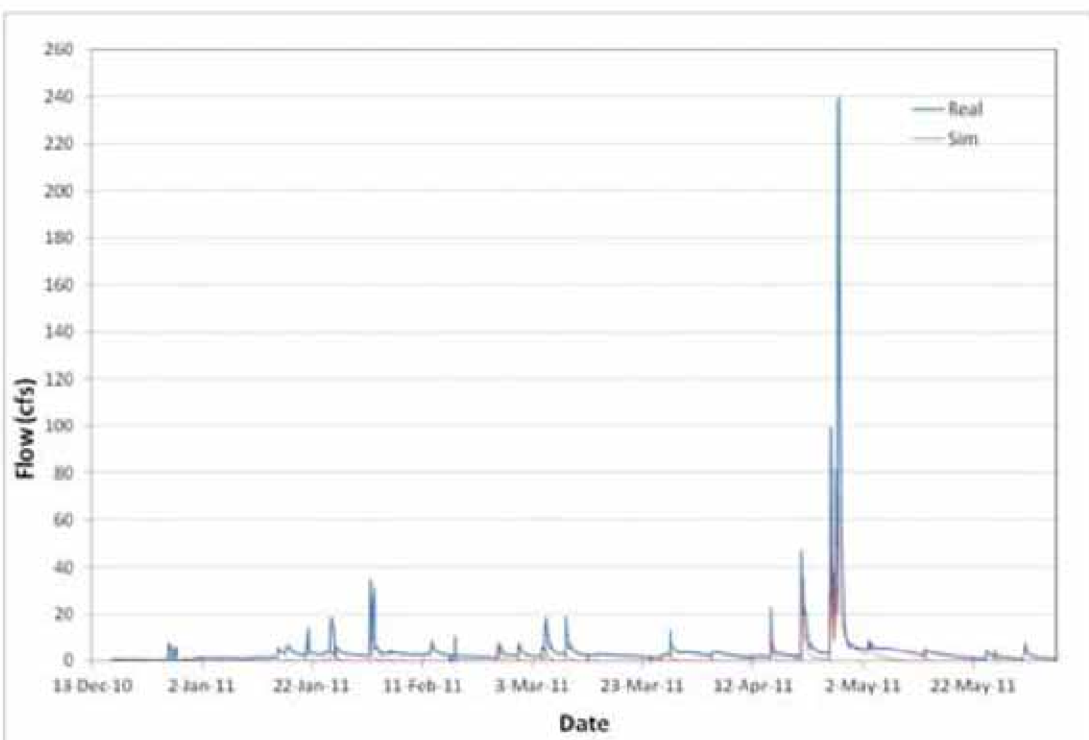

Figure 7. Time series of sediment (up) and phosphorus concentration (down) in water flow at the outlet of the Harris Bayou North Ditch system for two different.

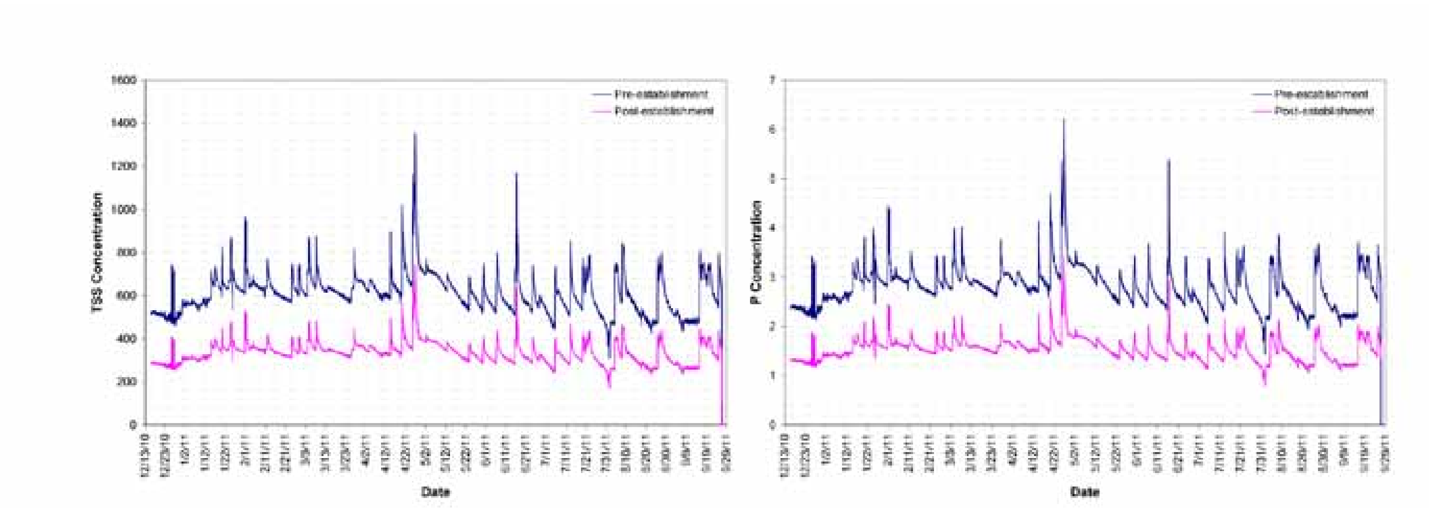

Figure 8. Mean annual concentration of TSS and TP at the lower BMP established along the Harris Bayou North Ditch system