Assessing the Efficiency of Alternative Best Management Practices to Reduce Nonpoint Source Pollution in the Saline Bayou Watershed, Louisiana

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Abstract

Identification of critical source areas (CSAs) helps to reduce best management practices (BMPs) adoption cost to meet the desired level of water quality in a given watershed. We used Soil and Water Assessment Tool (SWAT) to identify critical source areas within the Saline Bayou Watershed (HUC 11140208), Louisiana. SWAT model was calibrated and validated for discharge and sediment pollution. We then followed up with MAPSHED to assess the effectiveness of implementing different best management practices to reduce nutrient and sediment pollution. Optimization results show that nutrient management and agricultural land retirement can reduce most of the phosphorus runoff in the watershed at the lowest cost. Results are robust to change in parameter sensitivity and alternative weather (dry, normal, and wet) scenarios.

Keywords: Best management practices, cost, optimization, MAPSHED, phosphorus, SWAT

JEL classifications:

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1. Introduction

Surface water quality is of a significant concern in the United States. About 67% of reservoirs and 53% of the river systems in the U.S. are classified as impaired and need an immediate action (USEPA, 2013). The U.S. Environment Protection Agency also states that more than 40% of assessed waterways do not meet the minimum designated water use quality standard (USEPA, 2008). The impairment in the water is due to the accumulation of nutrients and sediment from the watershed. This accumulation could cause serious problems such as oxygen deficiency and instability in the ecosystem that results water being unsuitable for agricultural, industrial, and human uses (Carpenter et al, 1998).

Past efforts have been mainly focused on the management and control of point source pollution through regulatory approaches. Non-point source pollution control has not been properly addressed because of its spatial and temporal heterogeneity. Agricultural runoff contributes as much as 65% of the nitrogen pollution in the Gulf of Mexico (USEPA, 2000). The amounts of sediment and nutrient effluents from a watershed depend on physiographic characteristics such as soil type, land use & land cover, and gradient. There are some areas within a watershed which contributes a lion share of nutrients and sediment effluents. These areas, known as critical source areas (CSAs), are extremely important from the economic point of view for watershed management as best management practices adoptions in CSAs provide the minimum cost solution to pollution reduction. There are numerous studies which have taken the approach to control pollution in CSAs (Nonpoint source Task Force, 1984; Tim et al, 1992). CSAs could be identified either by water monitoring from the sub-watershed level or by simulation model or combinations of both (Sharply et al., 2002). Direct sub-watershed monitoring is cost prohibitive so a frequently used tool to identify CSAs in watershed is Soil and Water Assessment Tools (SWAT) (Arnold et al., 1998; Tripathi et al., 2005; Ouyang et al., 2008; Georgas et al; 2009).

SWAT has been used in different parts of the world for identification and prioritization of CSAs for sediment and nutrients control at the sub-watershed level (Tripathi et al, 2005; Ouyang et al., 2008; White et al., 2009; Ghebremichael et al., 2009; Panagopoulos et al., 2011; Shang et al., 2012; Niraula et al., 2012a). It has also been used for predicting stream flow, nutrient, and sediment from the watershed (Spruill et al.,2000; Kirsh et al., 2002; Veith et al.,2005; Shrivastava et al., 2006; Jha et al., 2007; Niraula et al., 2012a,b). Our objectives in this paper are to:

1. Identify CSAs in a watershed using SWAT and assess the effectiveness of different BMPs to reduce nutrient and sediment pollution using MAPSHED, and
2. Determine the most cost effective BMP combination under parameter and weather uncertainties.

2. Methods

2a. Study Area

We chose Saline Bayou Watershed (HUC 11140208) located in Bienville and Lincoln Parishes, Louisiana (Fig.1). This area is chosen for the study because Louisiana Department of Environmental Quality (LDEQ) has listed it as one of the priority watersheds to be comprehensively studied with respect to BMP adoptions. The watershed is located between longitude 92^{0}52’01” and 93^{0}04’44” W and latitude 32^{0}14’49” and 32^{0}34’48”N. Its area is 383.81 km^2 which is relatively flat land, varying from 46 m above the sea level to 163 m above the sea level. The total length of the stream in this area is 66.4 km, out of which 3.3 km stream lies inside the agricultural area. This watershed has heavy concentration of poultry production in Louisiana. Watershed area is dominated by the temperate climate with temperature ranging from -2.2^{0}C (min) to 40.5^{0}C (max).

2.2 Modeling Approach

SWAT is a semi-distributed model which was developed in order to estimate the impact of land management practices on water, sediment, and agricultural chemical yields in large and complex watersheds. This model is embedded with Geographic Information System (GIS) which has made easier to incorporate spatial variation and predict the hydrological process including surface runoff, percolation, deep aquifer flow, evapotranspiration (ET), and channel routing (Wu and Xu, 2006). SWAT can simulate various factors like hydrology, weather, crop growth, soil temperature, nutrients and sediment. Runoff generation is an important part of the model which uses The Natural

Resources Conservation Service (NRCS), formally the Soil Conservation Services curve number (SCS-CN) method to calculate surface runoff and infiltration (USDA-SCS, 1972). The CN depends on soil type, land use and management practice which distinguishes amount of infiltration and surface runoff in particular rain event. Higher CN value infers higher runoff and less infiltration (Zhan and Huang, 2004). The total discharge at the outlet is the discharge accumulated from each HRUs, sub-surface flow, lateral flow, and return flow. The flow in SWAT is either routed through Muskingum or variable storage coefficient method. Similarly, sediment yield from each HRUs and erosion is estimated from Modified Universal Soil Loss Equation (MUSLE) which uses modification of Bagnold's sediment transport equation for routing through channel.

SWAT requires digital elevation model (DEM), soils, land use, and weather in the ARCSWAT interface as an input data. The model divides the watershed into number of sub-watersheds which are further divided into number hydrological response units (HRU) based on topography, land use, and soil input data and this model lumps the parameters into HRU. Traditionally, HRUs are defined by the coincidence of soil type (Hydrologic Soil Group, USDA 1972) and land use.

To perform effectiveness of BMPs to reduce nutrient and sediment pollution, we utilized MAPSHED, an open source biophysical simulation model developed by Penn State University (Evans et al., 2002). The MAPSHED model is embedded with ArcView Generalized Watershed Loading Function (AVGWLF), which generates all the necessary information to run the model. This Generalized Watershed Loading Function (GWLF) model can simulate runoff, nutrient, and sediment from different watersheds. This model simulates runoff by water-balance technique, based on daily precipitation, daily temperature, land use, and soil data. This model is known to be a distributed/lumped parameter model because of its characteristics of distribute in the surface loading by taking various land use covered scenarios while for a lumped parameter model it takes sub-surface loading. In GWLF, precipitation is separated between direct runoff and infiltration by using a form of the Natural Resource Conservation Service's (NRCS) Curve Number method (SCS, 1986). Erosion and sediment yield are computed in GWLF model based on Universal Soil Loss Equation (USLE). Sediment delivery ratio which is the key factor to compute sediment yield is based on watershed size and a transport capacity. The daily runoff volume which transports sediment is computed by using CN which is the function of soil and land use/cover. Dissolved nutrients load and sediment transporting through rural areas are computed by multiplying their respective coefficients with runoff. In GWLF, all the N and P from the urban areas are considered to be in solid state and the model uses exponential accumulation and wash-off function for estimation of urban loadings. The sub-surface loses in the watershed is estimated by using dissolved N and P concentrations where watershed is considered to be single lumped-parameter contributing area (Evan et al., 2002).

2.3 Data

The necessary input data layers are collected from various sources. Since this is a GIS based model, several raster and vector data are needed to run the model. Soil layers (ArcSWAT SSURGO) are downloaded from the SWAT site. Weather data is taken from the nearby stations comprising of min and max temperature, and total daily precipitation. SWAT site is the main source for weather data.

3. Results and Discussion

3.1 Calibration and Validation

Discharge data for the Saline Bayou outlet is obtained from the United Stated Geological Survey (USGS) for 2000-2010. To understand the uncertainty character of the watershed, data from 2000 to 2001 are used for warm up period and half of remaining data is used for calibration and validation of the model. Manual calibration technique is adopted. We used existing literature to determine the values for runoffs. Various parameters are changed within their range in order to get the best fit with the observed data. We obtained Nash-Sutcliffe efficiency criteria (64%), Deviation of discharge D (-9.73) and Root Mean Square Error (3.59) for calibration. Similarly, we obtained Nash-Sutcliffe efficiency criteria (45%), Deviation of discharge D (-7.91) and Root Mean Square Error (4.63) for validation. Figures 2 and 3 show the calibration and validation, respectively. Graphical presentation of simulated and observed sediment data is shown in fig.4. Table 2 reveals the list of parameters adjusted during calibration. Sol_Z was found most sensitive parameters followed by Slope, Slsubbsn and Sol_awc, respectively. Results presented here are from the calibration of model corresponding to the discharge data. Smaller size of the study area and location of weather stations outside of the watershed might have resulted in a low performance of the model.

3.2 Identification of Critical Source Area (CSAs)

Load generated by each sub-watersheds corresponding to weight per unit area are analyzed to identify the CSAs. Maps of sediments, nitrogen, and phosphorus are plotted separately in the sub-watershed level. In order to distinguish which sub-watersheds are CSAs they are ranked in descending order based on pollutant loads. A certain threshold value (10%) is taken in order to distinguish the CSA. This % reflects the cost of implementing best management practice. For example, lower threshold value is generally recommended when there is budget constraint. Based on the above criteria (10%), sub-watersheds 15, 20, 22, 23 and 25 are identified as CSAs. Among these CSAs, sub-watershed 15 has substantial agricultural land so this watershed is considered to identify the effects of implementing several BMPs using MAPSHED.

3.3 BMP Reduction Coefficients and Optimization Technique

We considered eight different best management practices for their abilities to reduce nitrogen, phosphorus and sediment pollution. These eight best management practices are Cover Crops (BMP1), Conservation Tillage (BMP2), Conservation Plan (BMP4), Nutrient Management (BMP6), Agland Retirement (BMP8), Stream Km with Vegetated Buffer Strips (BMP9), Stream Km with Fencing (BMP10), and Stream Km with Bank Stabilization (BMP11). BMP reduction coefficients determine its effectiveness. These coefficients indicate the amount of nutrient or sediment reduction by one unit (hectare for watershed area and meter for stream- based BMPs) increase in BMP adoption. To get the coefficients of each BMPs, regression analysis are carried out on simulation output. The simulation outputs are subtracted from the baseline output (no BMP) to obtain amount of nutrient reduction at each level of adopted BMP. The coefficients of BMP9, BMP10 and

BMP11 are calculated by varying 0.1 unit of stream length while the coefficients of remaining BMPs are calculated by varying 2% of corresponding BMPs values. A regression analysis is performed between the amounts of nutrients reduction for each level of adoption and the amount of land associated with their level which gives nutrient reduction coefficient. This coefficient indicates how many unit of nutrients or sediment are reduced per unit of land.

An optimization model adopted to determine the BMP activities at least cost under different levels of pollution reduction target is shown in fig.5. The objective of this optimization model is to achieve the maximum pollution reduction goal at the lowest cost. To achieve such a goal, constraints are placed on resource availability and minimum nutrient and sediment goals. Phosphorus is taken as a primary nutrient for reduction because of its role in water pollution, eutrophication and hypoxia in the Gulf of Mexico. Nitrogen and sediment reduction are also taken as secondary goals. In the sub-watershed identified as CSAs, the following model was developed for dry, wet and normal rainfall years.

$$\text{Min} \sum_i^j C_i Bi$$

Subject to,

$$\text{Nitrogen: } \sum_i^j n_i B_i \geq 0$$

$$\text{Sediment: } \sum_i^j s_i B_i \geq 0$$

$$\text{Phosphorus: } \sum_i^j p_i B_i \geq \alpha I_p$$

$$\text{Others: } \sum_i^j O_{i,k} B_i \leq R_k, \text{ for all } k = 1, \ldots\ldots\ldots\ldots K$$

$$B_i \geq 0$$

Here, the variables and coefficients are defined as:

B_i = BMP_i

C_i = Cost of BMP_i

n_i = Nitrogen reduction by BMP_i

s_i = sediment reduced by BMP_i

p_i = Phosphorus reduced by BMP_i

α = Fraction of total phosphorus reduced ($0 \leq \alpha \leq 1$).

I_p = Total phosphorus loading when adopting no BMPs

$O_{,i,k}$ = Coefficient associated with k^{th} resource used in adopting BMP i

R_k = Maximum availability of resource k

3. Result and Discussion

Optimization results are obtained for various levels (Table 3) of desired phosphorus reduction under normal, wet and dry weather conditions. The baseline nutrients and sediment loading in the watershed without adopting any BMPs were 5.5 tons of nitrogen, 0.48 tons of phosphorus, and 144 tons of sediment. In the wet weather condition, higher amounts of nutrients and sediment can be reduced effectively by adopting BMPs. In the dry weather condition, BMPs do not reduce nutrient load as much as normal or wet weather scenarios. This outcome can be attributed to rainfall and runoff situations.

Nutrient management is the preferred BMP in the normal weather condition. It can reduce up to 30% phosphorus load from the watershed at the cost of \$3594 which translates to nitrogen reduction cost per kg \$8.24 and phosphorus reduction cost per kg at \$24.9/kg. As the desired level of phosphorus reduction was increased, Ag land retirement and vegetative buffers are added as the optimal BMP mix. It is possible to reduce up to 51% phosphorus load from the watershed which costs $20,058. At this level, the cost of reducing nitrogen is $33/kg, the cost of reducing phosphorus is $81.9/kg and the cost of sediment reduction is $336 per ton.

Similar to normal weather condition, nutrient management comes out to be the effective best management practice to reduce nutrient pollution. This BMP is effective in reducing 30% phosphorus loading from the watershed at $3,488. At this level, per kg cost of reducing nitrogen and phosphorus is $5.05 and $15.43, respectively. The maximum amount of phosphorus loading reduction under the wet weather scenario is 53% and it would cost $24,908. BMPs selected were cover crop, nutrient management, agricultural land retirement, and vegetative buffer. The cost per kg of nutrient reduction is $23.7 for nitrogen and $62.3 for phosphorus. The cost per ton of sediment reduction is $283.

In the dry scenario, at the lower level of phosphorus reduction goal, nutrient management comes out to be as an effective BMP. At a 30% level of phosphorus reduction, nutrient management and ag land retirement are two BMPs chosen. Notice, in wet and normal scenarios, only BMP selected to reduce this level of phosphorus was nutrient management. The cost to reduce 30% phosphorus is $4,226 in a scenario when dry weather prevails. Per kg cost for nitrogen and phosphorus reduction was $22.5 and $46.5, respectively. The maximum amount of phosphorus load reduction if dry weather prevails is 41% which costs $179.2/kg for nitrogen and $114/ kg for phosphorus.

The relationship between phosphorus reduction per unit cost for all the three conditions like normal, wet, and dry are also plotted (Fig.5) to checking their effect on the Saline Bayou watershed.

5. Conclusions

Nonpoint source water pollution has been identified as one of the main contributors of water pollution in the United States. Our study showed that focusing on agricultural BMPs can reduce water pollution in rural watersheds such as Saline Bayou Watershed studied here. We used SWAT, MAPSHED and economic optimization model to identify minimum cost solution to meet alternative levels of phosphorus reduction.

Rather than focusing on the entire watershed, we focused on CSAs to adopt best management practices. Obviously, it may not be possible to reduce all the phosphorus loads from a watershed by focusing on only CSAs. However, this approach picks the low hanging fruits first before embarking on other costly approach or expansion of BMPs adoption to more costly or less effective areas. It is generally costly to reduce phosphorus in dry years compared to normal and wet years. Although it is possible to reduce phosphorus more in wet scenario, the per unit cost of reducing phosphorus in the watershed continues to increase from low $15 per kg to $62 per kg. In normal year, the cost ranged from $25 per kg at low level of phosphorus reduction (48 kg of phosphorus reduction) to $82 (245 kg of phosphorus reduction).

Identification of the most effective best management practices in CSAs also helps state environmental agencies or Natural Resource Conservation Service to identify how much cost share should be paid to farmers to adopt these practices. Equipped with this information, the next step may be to conduct willingness to pay cost share information by farmers.

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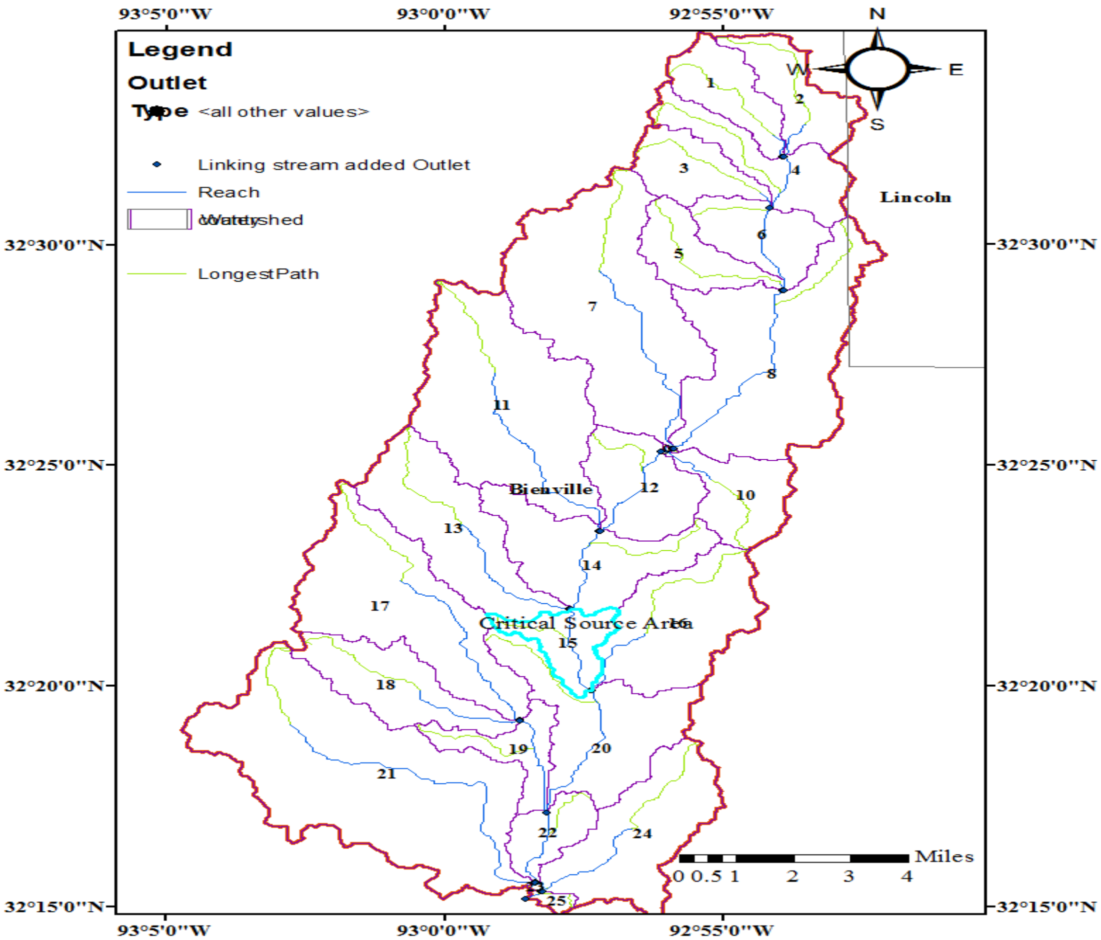
Fig.1: Saline Bayou Watershed



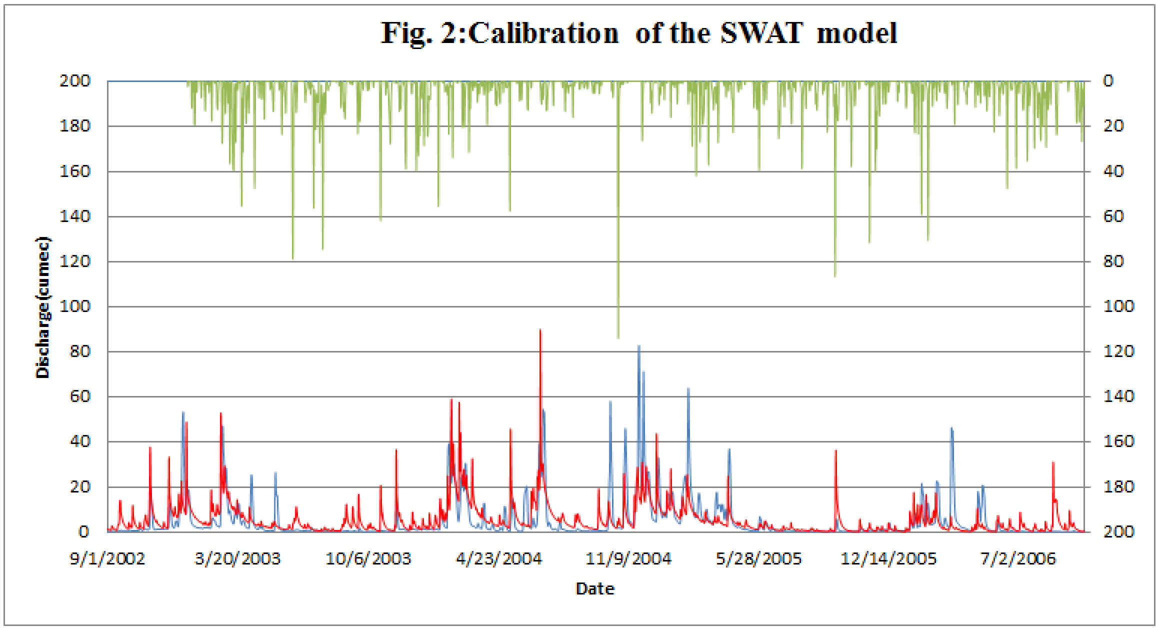


Fig. 2:Calibration of the SWAT model
200
180
160
140
120
100
80
60
40
20
0
0
20
40
60
80
100
120
140
160
180
200
Discharge(cumec)
9/1/2002
3/20/2003
10/6/2003
4/23/2004
11/9/2004
5/28/2005
12/14/2005
7/2/2006
Date

Fig.:3 Vaidation of SWAT model

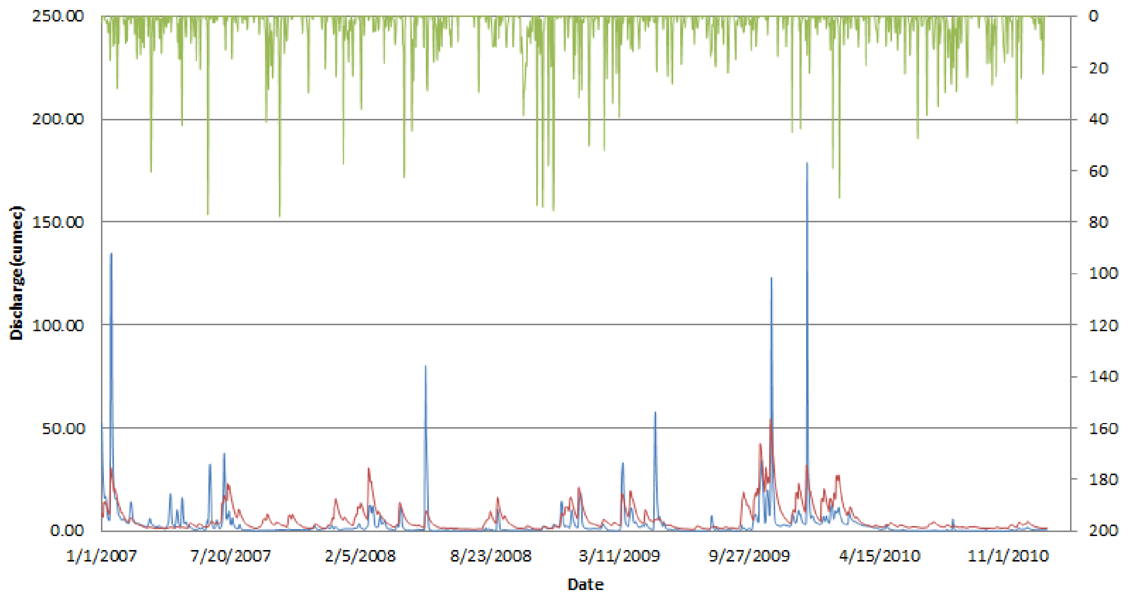


Fig. 4 : Measured and Simulated sediment concentration at sub-watershed no.3

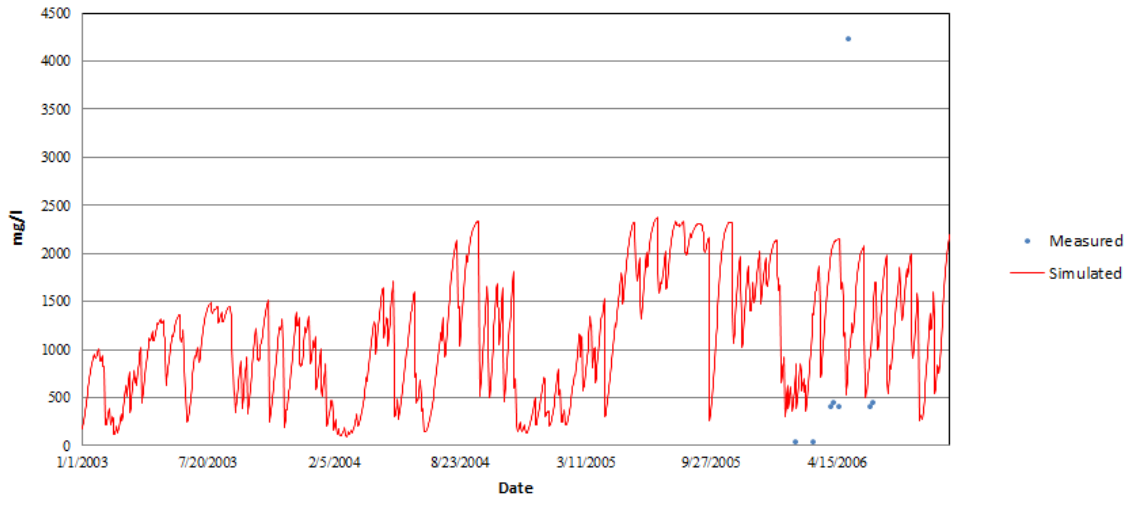


Fig.5: Phosphorus reduction per unit cost at Saline Bayou sub-watershed #15

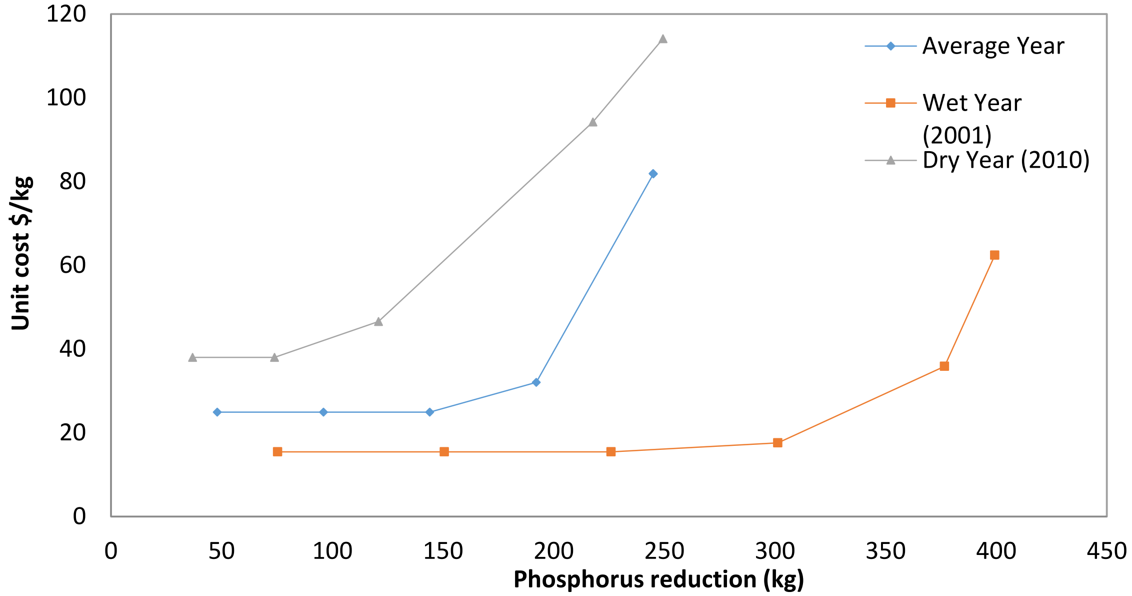


Table 1: Information of hydrological,meteorological, and othere data used in the study

S.Nos.	Station ID	Type	Longitude	Latitude	Elevation (m asl)	Duration	
1	P329-928	Rainfall	-92.813	32.94	61	2000	2010
	P329-925	Rainfall	-92.5	32.94	45	2000	2010
2	T329-928	Temperature	-92.813	32.94	61	2000	2010
	T329-925	Temperature	-92.5	32.94	45	2000	2010
3	7366200	Discharge	-92.65	32.9	25	2000	2010
4	DEM (30 m resolution)						
5	Soil (ARCSWAT SSURGO) for SWAT						
6	Landuse source USGS						
7	Counties from LSU GIS center						
8	Physiographic provinces from LSU GIS center						
9	Stream from LSU GIS center						

Table 2: Calibrated parameters of the SWAT model

Nos.	Parameters	Definition	Unit	Range	Calibrated value
1	CANMAX	Maximum canopy storage		0 to 100	20
2	CH_K2	Effective hydraulic conductivity in the main channel	mm/hr	0.1 to 150	80
3	CH_N2	Manning's roughness coefficient for the main channel		0.01 to 0.3	0.025
4	CN2	SCS runoff curve number		64 to 76	65
5	EPCO	Plant uptake compensation factor		0.4 to 0.9	0.8
6	ESCO	Soil evaporation compensation factor		0.7 to 1.0	0.8
7	GW_DELAY	Groundwater delay	day	0 to 500	10
8	GW_REVAP	Groundwater revap coefficient		0.02 to 0.2	0.1
9	GWQMN	Threshold depth of water in the shallow aquifer for return flow	mm	0 to 5000	1780
10	REVAPMN	Threshold depth of water for revap		0 to 500	0.2
11	SLOPE	Average slope steepness		-0.5 to 1	0.06
12	SLUSUBBSN	Average slope length	m	-0.5 to 1	55
13	SOL_AWC	Available soil water capacity	m/m	-0.5 to 1	0.29
14	SOL_K	Saturated hydraulic conductivity	mm/hr	-0.5 to 1	0.1
15	SURLAG	Surface runoff lag time	day	1 to 12	2
16	ALPHA_BF	Baseflow alpha factor for recession constant	day	0 to 1	1

Table 3: Summary of BMP adopted and Land Use in Saline Bayou sub-watershed #15

Average year (2001 to 2010)

Scenario	Cover crops (BMP1)	Coservation Tillage (BMP2)	Coservation Plan (BMP4)	Nutrient Management (BMP6)	Agland Retirement (BMP8)	Vegetative Buffer (BMP9)	Fencing (BMP10)	Bank Stabilization (BMP11)	Total Cost ($)	N Level (Kg)	P Level (Kg)	S Level (tones)	Unit cost ($) of N reduction	Unit cost ($) of P reduction	Unit cost ($) of S reduction
10%	0.00	0.00	0.00	28.81	0.00	0.00	0.00	0.00	1197.56	145.39	48.04	0.00	8.24	24.93	0.00
20%	0.00	0.00	0.00	57.61	0.00	0.00	0.00	0.00	2395.12	290.78	96.08	0.00	8.24	24.93	0.00
30%	0.00	0.00	0.00	86.42	0.00	0.00	0.00	0.00	3592.69	436.16	144.12	0.00	8.24	24.93	0.00
40%	0.00	0.00	0.00	90.90	10.10	44.24	0.00	0.00	6159.26	642.81	192.16	12.36	9.58	32.05	498.24
50%	56.40	0.00	0.00	34.50	10.10	360.00	0.00	0.00	20058.56	662.83	245.20	48.52	30.26	81.80	413.41
51% max	86.05	0.00	0.00	4.85	10.10	360.00	0.00	0.00	20058.56	605.51	245.00	59.61	33.13	81.87	336.47

Wet year (2001)

Scenario	Cover crops (BMP1)	Coservation Tillage (BMP2)	Coservation Plan (BMP4)	Nutrient Management (BMP6)	Agland Retirement (BMP8)	Vegetative Buffer (BMP9)	Fencing (BMP10)	Bank Stabilization (BMP11)	Total Cost ($)	N Level (Kg)	P Level (Kg)	S Level (tones)	Unit cost ($) of N reduction	Unit cost ($) of P reduction	Unit cost ($) of S reduction
10%	0.00	0.00	0.00	27.97	0.00	0.00	0.00	0.00	1162.70	230.03	75.36	0.00	5.05	15.43	0.00
20%	0.00	0.00	0.00	55.93	0.00	0.00	0.00	0.00	2325.41	460.05	150.72	0.00	5.05	15.43	0.00
30%	0.00	0.00	0.00	83.90	0.00	0.00	0.00	0.00	3488.11	690.08	226.08	0.00	5.05	15.43	0.00
40%	0.00	0.00	0.00	91.09	9.91	0.00	0.00	0.00	5303.28	1014.57	301.44	14.42	5.23	17.59	367.87
50%	9.80	0.00	0.00	81.10	10.10	360.00	0.00	0.00	13498.66	1255.68	376.80	44.53	10.75	35.82	303.17
53% max	90.86	0.00	0.00	0.04	10.10	360.00	0.00	0.00	24908.48	1051.53	399.41	87.95	23.69	62.36	283.23

Dry year (2010)

Scenario	Cover crops (BMP1)	Coservation Tillage (BMP2)	Coservation Plan (BMP4)	Nutrient Management (BMP6)	Agland Retirement (BMP8)	Vegetative Buffer (BMP9)	Fencing (BMP10)	Bank Stabilization (BMP11)	Total Cost ($)	N Level (Kg)	P Level (Kg)	S Level (tones)	Unit cost ($) of N reduction	Unit cost ($) of P reduction	Unit cost ($) of S reduction
10%	0.00	0.00	0.00	33.75	0.00	0.00	0.00	0.00	1403.1319	62.3257	36.95	3.31E-15	22.51	37.97	0.00
20%	0.00	0.00	0.00	67.50	0.00	0.00	0.00	0.00	2806.2638	124.651	73.9	3.31E-15	22.51	37.97	0.00
30%	0.00	0.00	0.00	100.75	0.25	0.00	0.00	0.00	4226.2997	187.536	120.85	0.090558	22.54	46.52	46669.43
40%	59.66	0.00	0.00	31.24	10.10	360.00	0.00	0.00	20517.064	195.236	217.8	24.82421	105.09	94.20	826.49
41% max	90.90	0.00	0.00	0.00	10.10	360.00	632.01	0.00	28465.523	158.848	249.495	30.41323	179.20	114.09	935.96