





AgriLIFE RESEARCH
Texas A&M System

Best Management Practice (BMP) Verification using Observed Water Quality Data and Watershed Planning for Implementation of BMPs

FINAL REPORT

TSSWCB PROJECT 04-18

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EXECUTIVE SUMMARY

The overall goal of this project was to verify the effectiveness of the best management practices (BMPs) implemented in the 5,157-km^2 Richland-Chambers watershed in north central Texas with water quality data and modeling. This report is organized in three parts. Part I describes the statistical trend analysis techniques applied on observed water quality data at several monitoring stations within the watershed. Part II describes the field and small watershed scale hydrologic/water quality (HWQ) modeling using the Agricultural Policy Environmental eXtender (APEX) model. Part III describes field and watershed scale HWQ modeling using the Soil and Water Assessment Tool (SWAT) model.

Water quality parameters including total suspended solids, nitrite + nitrate nitrogen, organic nitrogen, ortho phosphorus, and total phosphorus (TP) were analyzed for trend using exploratory data analysis, linear and Mann-Kendall's statistical tests on LOESS residuals from flow adjusted concentration values, and exceedance probability plots at eight different monitoring stations in the Richland-Chambers watershed. Exploratory data analysis indicated that most of the constituents analyzed showed departures from the normal distribution. Trend analysis showed statistically non-significant decreasing trend for majority of the constituents. A mixed result was noticed for nitrogen and phosphorus. Availability of water quality data at some of the stations for before and after BMP implementation facilitated plotting exceedance probability curves for pre-BMP and post-BMP periods. These plots complemented the results of statistical techniques. The available data analyzed in this study is perhaps not sufficient to prove that water quality is improving or degrading with time. However, decreasing trend noticed in most cases, though non-significant, is promising as there is likeliness of improving water quality with time.

The APEX model was used to simulate various structural and non-structural BMPs implemented in a 280-km^2 Mill Creek watershed, a subwatershed of Richland-Chambers watershed. The BMPs include pasture planting, nutrient management, brush management, clearing and range planting, prescribed grazing, critical area planting, conservation cropping, contour farming, terrace, ponds, grade stabilization structures, and waterways. Simulated annual average field level reductions obtained by these BMPs (considering only BMP areas) were 35% in runoff, 83% in sediment, 72% in total nitrogen (TN), and 58% in TP. At the subwatershed outlets, the reductions ranged from 2.9 to 6.5% in runoff, 6.3 to 14.8% in sediment, 11 to 15.1% in TN, and 6.3 to 8.6% in TP.

The SWAT model was used to simulate and assess the HWQ impacts of several BMPs in the entire Richland-Chambers watershed. The BMPs simulated included all those that were simulated using APEX (mentioned above) except ponds, grade stabilization structures, and waterways. In general, the BMPs achieved significant reductions at the field levels. Average annual reduction in sediment ranged from 32% to 100%, TN ranged from 33% to 97%, and TP ranged from 20% to 85%. At the Richland-Chambers watershed outlet, the reductions in sediment, TN, and TP achieved by the BMPs were 1%, 2%, and 3% respectively. It is to be recognized that a very small percentage (6%) of the watershed is under some type of BMP. With time, as more data becomes available and more area is implemented with BMPs, one can expect increased evidence of environmental benefits due to implementation of BMPs.

ACKNOWLEDGEMENT

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ACRONYMS AND ABBREVIATIONS

APEX	Agricultural Policy/Environmental eXtender
BMP	Best Management Practices
BREC	Texas AgriLife Blackland Research and Extension Center at Temple
C-factor	Channel Cover Factor
CN	Curve Number
EPIC	Erosion Productivity Impact Calculator
EQIP	Environmental Quality Incentives Program
HRU	Hydrologic Response Unit
HWQ	Hydrologic/ Water Quality
LUN	Land Use Number
Manning's N	Channel Manning's Roughness Coefficient
NAWQA	National Water Quality Assessment
NRCS	Natural Resources Conservation Service
NSE	Nash-Sutcliffe Modeling Efficiency
PEC	Conservation Support Practice Factor
SSL	Spatial Sciences Laboratory
SSURGO	Soil Survey Geographic
SWAT	Soil and Water Assessment Tool
TCEQ	Texas Commission on Environmental Quality
TMDL	Total Maximum Daily Load
TN	Total Nitrogen
TP	Total Phosphorus
TRWD	Tarrant Regional Water District
TSSWCB	Texas State Soil and Water Conservation Board
SWCD	Soil and Water Conservation District
USDA-ARS	United States Department of Agriculture-Agricultural Research Service
USEPA	United States Environmental Protection Agency
USLE	Universal Soil Loss Equation
USGS	United States Geological Survey

PROJECT BACKGROUND

Richland-Chambers watershed (Figure 1) has a drainage area of 5,157 km^2 and covers parts of Navarro, Ellis, Hill, Johnson, Freestone, and Limestone counties in Texas. The watershed drains into Richland-Chambers Reservoir, the largest among the five reservoirs maintained by TRWD that supplies water to a major portion of the 1.6 million people in the north-central Texas. During the 1960's and 1970's, the NRCS identified Chambers Creek as one of the tributaries contributing higher amounts of sediment to the Richland-Chambers Reservoir. In 2006 Texas Water Quality Inventory and 303(d) list, Chambers Creek was listed as category 5c with a rank D indicating that additional data and information will be collected before a Total Maximum Daily Load (TMDL) would be scheduled (Texas Commission on Environmental Quality (TCEQ), 2006). A TMDL is the maximum amount of a pollutant that a waterbody can receive and still meet water quality standards for the designated use. In the 2008 Texas Water Quality Inventory (TCEQ, 2008), orthophosphorus and TP in Chambers Creek are listed as parameters of concern, for general use, based on the screening levels. In 1993, a 3-year study initiated under the National Water Quality Assessment (NAWQA) program identified Mill Creek, a tributary of Chambers Creek with a drainage area of 280 km^2 as one of the major contributors of nutrient load to the stream and the Richland-Chambers Reservoir. The TRWD took a leading role in coordinating the development of a partnership of several stakeholders to implement a program aimed at reducing pollutant loads in the Richland-Chambers Reservoir. Development of this partnership enabled the application of $5 million in funding from NRCS to implement BMPs aimed at the reduction of sediments and nutrients from the Mill Creek watershed. Additionally, TRWD has provided funding to assist in partially satisfying the local match requirements associated with using the federal funds. As a result of these programs, there is an intensive implementation of BMPs within Mill Creek watershed, since 1996, coordinated by Navarro County Soil and Water Conservation District (SWCD) in order to reduce sediment and nutrient loadings. Also, BMP implementation in the watershed has been carried out under other programs such as Clean Water Act §319(h) and the Environmental Quality Incentives Program (EQIP).

The overall goal of this project was to verify the effectiveness of the implemented BMPs using observed flow and water quality and through hydrologic modeling approach. The specific objectives were to:

(1) Verify the effectiveness of BMPs implemented by analyzing observed water quality data using graphical and statistical techniques.
(2) Develop a modeling methodology to represent the BMPs and make quantitative assessment of their effectiveness at various spatial scales.

PART I: TREND ANALYSIS OF OBSERVED WATER QUALITY DATA

INTRODUCTION

An increasing investment has been made in the last two decades for implementation of agricultural BMPs to reduce nonpoint source pollution due to agricultural activities (Mausbach and Dedrick, 2004). Monitoring rivers and lakes provide information on ambient water quality and its suitability for the corresponding designated use. A long-term surface water quality dataset may be used to determine water quality impacts over time due to changes in landuse and land management as a result of regulation changes, industrialization and urbanization, BMP implementation, etc. Detecting and interpreting changes in water quality in complex watersheds can be challenging especially due to incremental implementation of BMPs, relatively small BMP implementation areas within the watershed, inadequate duration of data collection, gaps in data, and natural and anthropogenic variability (Meals, 1987). In the case of paired field/watershed studies, one can compare the measured data from the BMP implemented field/watershed versus a no-BMP field/watershed to determine the water quality impacts (for example, see Sharpley and Smith, 1994; Sharpley et al., 1996; Edwards et al., 1997; Chow et al., 1999). Due to the financial, labor, and time constraints involved in field measurements, simulation modeling using comprehensive distributed models is gaining significance in assessing the benefits of BMPs (for example, see Chen et al., 2000; Santhi et al., 2006, Bracmort et al., 2006; Secchi et al., 2007). Nevertheless, field monitoring data is essential to provide supporting field information to validate the simulation results. Several exploratory and statistical trend analysis techniques can be applied to the observed water quality data to determine water quality impacts of land management.

Most statistical analyses begin with understanding the underlying distribution of the data using exploratory data analysis techniques such as frequency distribution box-and-whisker plots (Meals, 1987; Ravichandran, 2003; Bouza-Deaño et al., 2008; Boyacioglu and Boyacioglu, 2008). Trend could be defined as the monotonic variation of the pollutant concentration with regard to time (Bouza-Deaño et al., 2008). Two categories of statistical tools are widely used to assess trends: parametric tests and non-parametric tests. For non-normal data and data with significant gaps, non-parametric methods such as Mann-Kendall's test and its variations (Mann, 1945; Kendall, 1975; Hirsch et al., 1982; Bouza-Deaño et al., 2008; Boyacioglu and Boyacioglu, 2008) and Sen's Slope Estimator (Sen, 1968; Boyacioglu and Boyacioglu, 2008; Bouza-Deaño et al., 2008) are generally used. Monotonic trend tests are preferred over discrete for instances where implementation of BMPs occurs gradually and water quality data is collected continuously during and after implementation (Walker, 1994).

MATERIALS AND METHODS

Monitoring stations and water quality

The tributary water quality is monitored at several locations in the watershed. The TRWD began routine water quality sampling in 1988 from stations on Richland Creek, Post-Oak Creek, and Chambers Creek (Figure 1). The stations were set up in order to gage nutrient and sediment loads entering the reservoir from each of the tributaries. The program was originally designed to capture major loading events from storm flows to the reservoir. However, around 2004, it was shifted to a more routine sampling program and samples have been collected two to six times per year. In addition to these stations, TRWD also has four fixed sampling stations on Mill Creek, established in 1996, for the purpose of monitoring erosion and BMP effectiveness implemented in the watershed. United States Geological Survey (USGS) stream gaging station on Chambers Creek also has long-term water quality data. The water quality parameters that were analyzed in this project include total suspended sediment and nutrients including nitrite + nitrate nitrogen, organic nitrogen, orthophosphorus, and TP.

The BMP implementation in the watershed has been carried out under different programs including TRWD, §319(h), and EQIP. The various BMPs implemented include terraces, contour farming, conservation tillage, pasture planting, range seeding, grade stabilization structures, grassed waterways, ponds, nutrient management, grazing management, critical area planting, brush management, and filter strips. The BMPs cover about 6% of the Richland-Chambers watershed (Figure 1).

Trend analysis

Box-and-whisker plots provide visually descriptive statistics of the data through their five-number summaries including the extreme values (smallest and largest observation) and three values in the interquartile range. In this study, box-and-whisker plots were used to explore water quality data subjected to further statistical analyses. Two statistical tests: linear regression (parametric) and Mann-Kendall’s (non-parametric) methods were used to quantify the trend in water quality. In addition, exceedance probability curves were plotted for individual water quality parameters considering pre- and post-BMP periods.

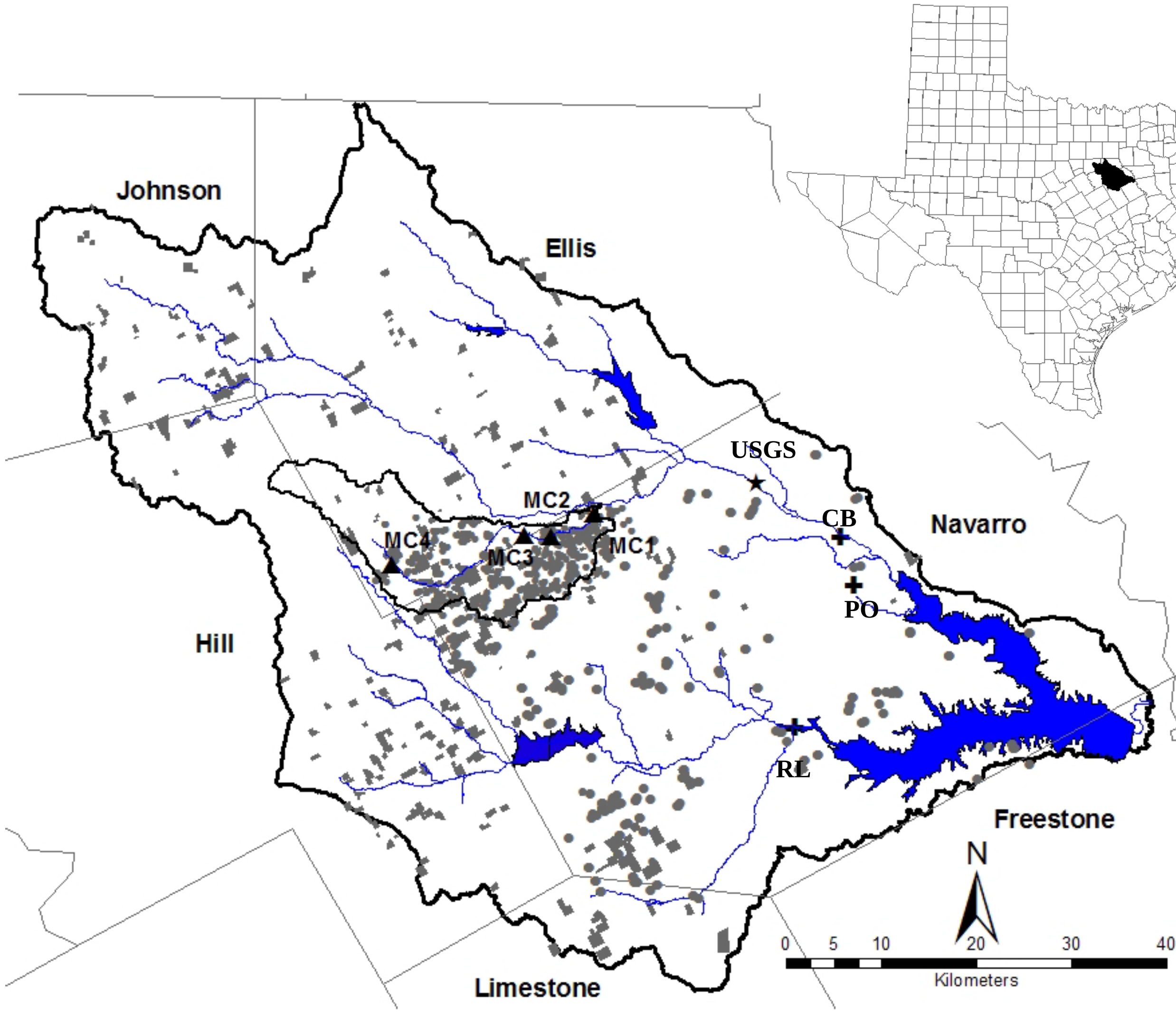


Figure 1: Monitoring stations including Mill Creek1 through Mill Creek 4 (MC1 through MC4), Richland Creek (RL), Chambers Creek (CB), Post Oak Creek (PO), and USGS and the implemented BMPs in Richland-Chambers Watershed.

Box-and-Whisker plots and Exceedance Probability plots

The concentration values of the individual constituents at each station were split into pre- and post-BMP periods and then plotted in box-and-whisker plots and exceedence probability plots. Box-and-whisker plots were used to compare the distribution of concentrations before and after BMP implementation. Exceedance probability plots were used to compare the number of observations exceeding a particular concentration value in pre- and post-BMP periods for the Richland, Chambers, Post Oak, and USGS monitoring stations. Where available, the water quality criteria/screening level is displayed on the exceedance probability plots to help identify the frequency of measured constituent concentration exceeding the standard criteria.

Linear regression and Mann-Kendall's methods

The entire period of record with concentration values and corresponding flow data available was considered for parametric and nonparametric trend analysis. Decreasing the variations in the data increases power and efficiency of any procedure of detecting and estimating the magnitude of trend (Hirsch et al., 1991). Therefore, statistical analysis was performed on flow-adjusted concentrations, which are the residuals resulting from the regression of constituent concentration and the corresponding streamflow values (Hirsch et al., 1982; Hirsch et al., 1991; Walker, 1994) in a 4-step process: (1) constituent concentration and streamflow values were log transformed to begin with; (2) these log-transformed data were fitted with LOESS (locally weighted scatterplot smoothing) line; (3) the difference (referred to as “residuals”) between the measured constituent concentrations and LOESS line were computed; and (4) linear regression and Mann-Kendall’s statistical tests were applied on these residuals versus time to determine the trend. The method of applying linear regression on LOESS residuals is similar to that described by White et al. (2004).

Mann-Kendall test is a non-parametric test. Non-parametric tests generally work with the rank of the data rather than the specific data and therefore less affected by outliers (Onoz and Bayazit, 2003; Walker, 1994). Such non-parametric tests are suitable for non-normal data, which is common in water quality data (Hirsch et al., 1991). Mann-Kendall’s test computes Kendall’s tau non-parametric correlation coefficient and its test of significance for any pair of X, Y data. When X is time, this is a test for trend in Y variable. This test is more applicable towards monotonic trends. Thus, the Mann-Kendall’s test can be stated as a test for whether Y values tend to increase or decrease with time (Helsel and Hirsch, 2002; Helsel and Frans, 2006). The test is somewhat less sensitive to seasonal effects. Some sensitivity to extreme events does pose a potential problem for smaller sample sizes.

For both linear and Mann-Kendall’s tests, the P-values were evaluated at 10% significance level. The trend with a negative slope indicates that the constituent concentration value is reducing with time and vice versa.

RESULTS AND DISCUSSION

Box-and-whisker plots (Figure 2) and exceedance probability (Figures 3-6) plots provide qualitative evidence whereas linear trend analysis and Mann-Kendall’s test provide quantitative evidence, in terms of significance, of the change in water quality over time. The screening levels are also displayed on exceedance probability plots for Nitrite+Nitrate N, Ortho P, and TP. The screening levels for TSS and Org N were not available. Results of these analyses are summarized in tables 1-5. Descriptive statistics in terms of minimum, maximum, mean, median, 25th percentile, 75th percentile, and outliers for the analyzed constituents at the four monitoring stations are presented in box-and-whisker plots in figures 2(a) through 2(e). Most of the constituents analyzed in this study showed departures from the normal distribution in both pre- and post-BMP periods. The station at Chambers Creek has a wider distribution of constituent concentration values compared to Richland Creek (Figure 2). This, more likely, could be attributed to the reservoir upstream of the station at Richland Creek (Figure 1) playing a role in arresting the pollutants and decreasing their transport downstream. Post Oak station has smaller drainage area (Figure 1) and less erosion causing agricultural activities, which is also indicated in figure 2(a). The USGS station showed the least variability (Figure 2). Overall, Mill Creek stations (MC1 through MC3) had a wide range of values compared to others. The area drained by Mill Creek has 35% cropland and 61% pasture compared to 20% cropland and 51% pasture in the entire Richland-Chambers Watershed. Higher proportion of cropland area in Mill Creek Watershed is most likely responsible for high erosion and higher nutrient losses indicated by larger mean and median values (figure not shown). Station MC4, like Post Oak station, has smaller drainage area and less erosion causing agricultural activities.

In general, these statistical analyses showed consistent results for a majority of constituents at most of the stations (Tables 1-5). All tests indicate an improvement (or decrease in concentration values) with time in TSS at all stations except MC2 and mixed results at station MC3. The improvement is significant in RL and PO stations (Table 1). Non-significant degrading trend is indicated for nitrogen components at RL and CB stations (Tables 2 and 3). The Nitrite+Nitrate N at MC1 and MC4 increased significantly (Table 2). There was a non-significant increasing trend in Ortho P at MC stations and significant increasing trend in USGS station (Table 4) whereas at RL, CB, and PO station, there was improvement though non-significant.

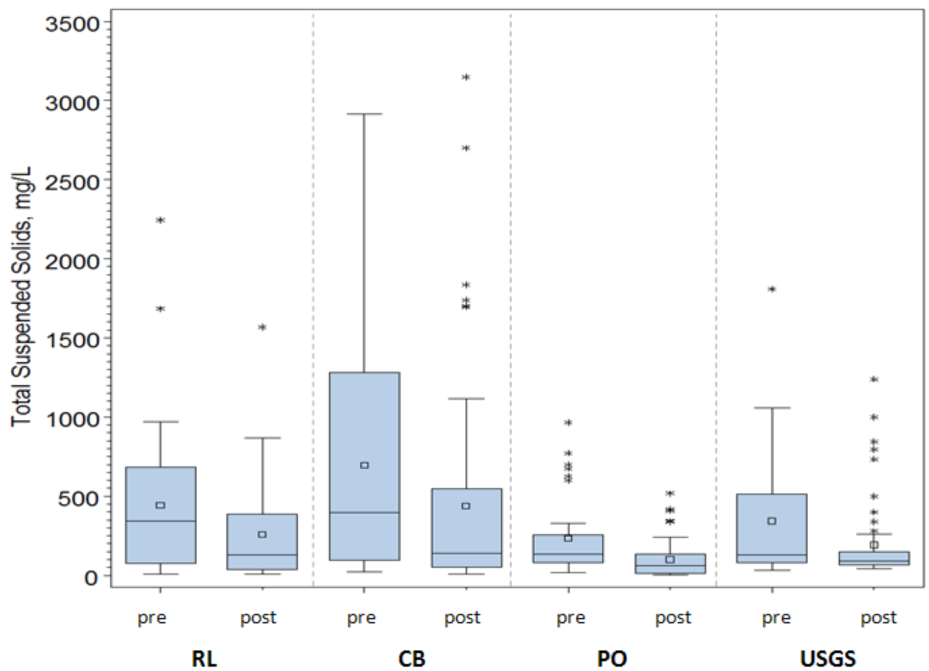
The TP at MC1, MC2, and MC3 declined significantly based on linear trend test but non-significant decreasing trend was indicated by Mann-Kendall test (Table 5). There was degradation of water quality in terms of significant increase in TP at USGS station. The additional flow from the tributary downstream of the USGS station and upstream of Chambers Creek, in part, decreased the phosphorus concentration as indicated by comparing the test results at these stations.

The exeedance probability curves in TSS concentration showed distinct difference in the frequency of occurrence of samples exceeding a particular concentration value (Figures 3(a), 4(a), 5(a), and 6(a)) between pre- and post-BMP periods. For example, 20% of the time, TSS concentration at Chambers Creek equaled or exceeded about 1400 mg/L during the pre-BMP period but equaled or exceeded only 700 mg/L during the post-BMP period (Figure 4(a)).

Improvement in water quality was clearly indicated by the exceedance probability plots at Post Oak station (Figure 5). Nitrite+Nitrate N and Org N concentration values in the post-BMP period exceeded the values in pre-BMP period at RL and CB stations (Figures 3(b), 3(c), 4(b), and 4(c)). From figure 3(d), it can be noted that there were some high values of Ortho P observed in post-BMP period compared to pre-BMP period. Except at USGS station, TP values were lower in the post-BMP period compared with pre-BMP period (Figures 3(e), 4(e), 5(e), and 6(d)).

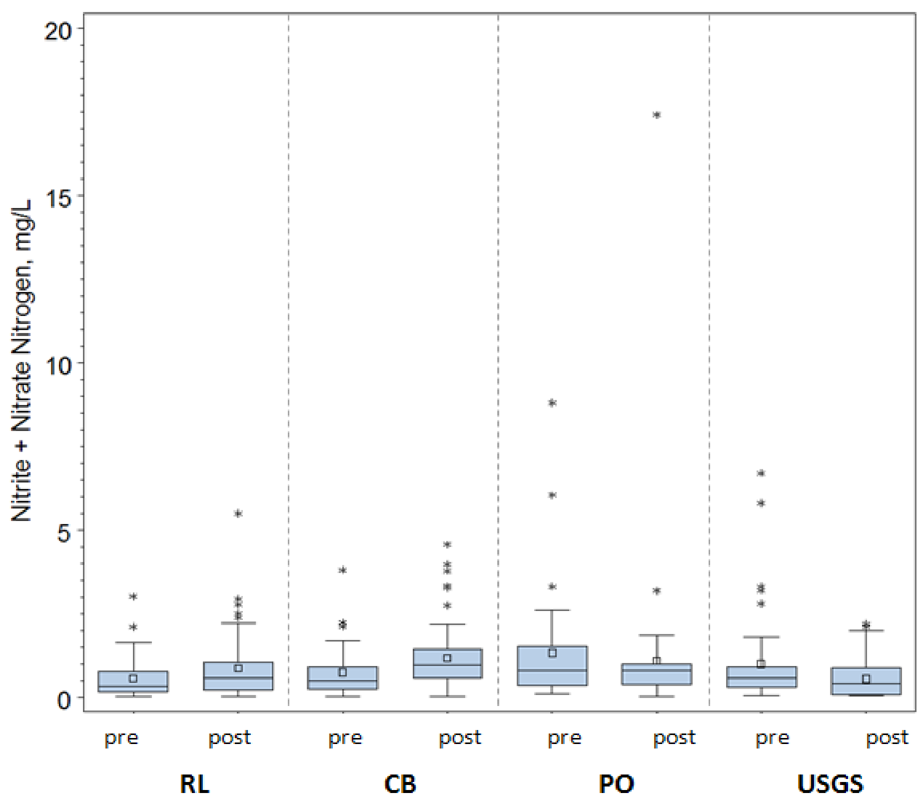
Relatively higher proportion of erosion control practices, especially in the Mill Creek watershed resulted in decreasing trends in sediment and corresponding decreases in sediment bound organic nitrogen. Previous studies (example, Sharpley and Smith, 1994) have shown that some management practices such as conservation tillage increased the mineral nitrogen (for example, Nitrite + Nitrate N in our case), which could also be the reasons for increasing trend in Nitrite+Nitrate N at RL, CB, MC1, and MC4 stations. Because of already limited data, this study did not consider separating the analysis for low and high flows. Although the tests give a general indication of trend, interpretation and reasoning of the direction of trend is challenging because of the large watershed area, variability in soils, landuse, and topography, and complex interactions between these elements. Moreover, we have no information about the condition and maintenance of the installed practices as most of the practices, especially the structural practices such as grade stabilization structures, terraces, grassed waterways, etc. have certain life span, unless well maintained, in which they are most effective (Bracmort et al., 2004). Uncertainty inherent in the measured water quality data itself could be overwhelming in some cases. As reported in Harmel et al. (2006), the uncertainty in measured water quality data can be due to one or more of: streamflow measurement, sample collection, sample preservation/storage, and laboratory analysis. Harmel et al. (2006) estimated that the uncertainty (±%) in TSS, nitrate nitrogen, Ortho P, and TP loads for typical scenarios ranged from to 7 to 53%, 8 to 69%, 11 to 104%, and 8 to 110%, respectively. The uncertainty estimates for measured constituent concentration was 2 to 3% less than the storm loads uncertainty reported above. Although Harmel et al. (2006) research focused on small watersheds, one could argue for the high possibility of such uncertainties in larger watersheds such as the one in the present study. A detailed analysis of effects of data uncertainty in trend analysis would be an interesting research.

The available data analyzed in this study is perhaps not sufficient to prove that water quality is improving or degrading with time. However, decreasing trend noticed in most cases, though non-significant, is promising as there is likeliness of improving water quality with time. It is to be recognized that a very small percentage (6%) of the watershed is under some type of BMP.



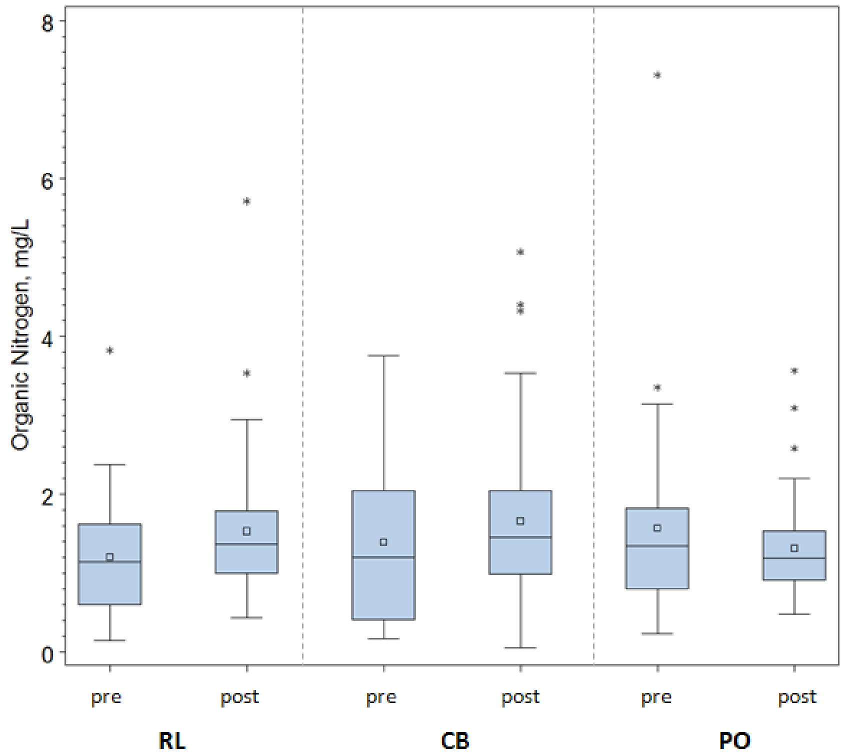
Total Suspended Solids, mg/L
3500
3000
2500
2000
1500
1000
500
0
pre
post
pre
post
pre
post
pre
post
RL
CB
PO
USGS

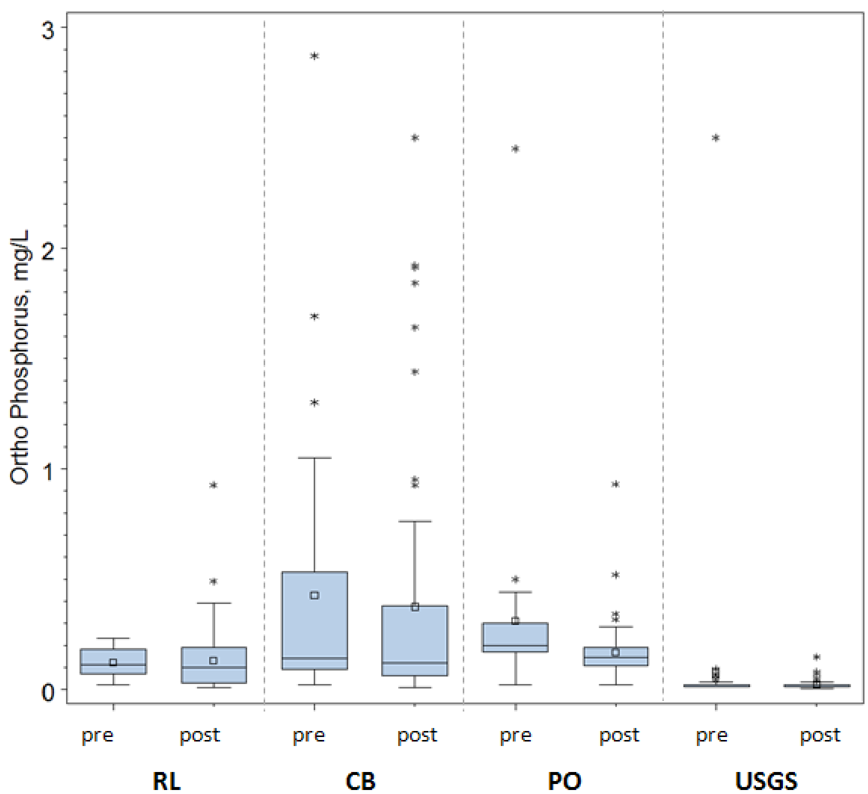
(a)

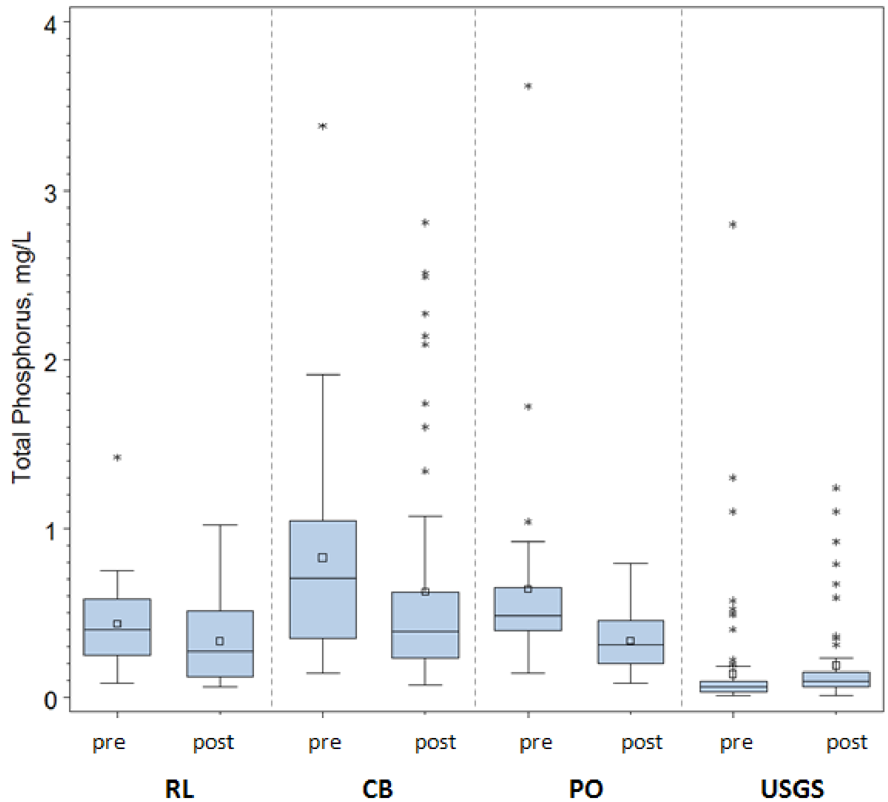


Nitrite + Nitrate Nitrogen, mg/L
20
15
10
5
0
pre
post
pre
post
pre
post
pre
post
RL
CB
PO
USGS

(b)


Organic Nitrogen, mg/L
8
6
4
2
0
pre
post
pre
post
pre
post
RL
CB
PO
(c)


Ortho Phosphorus, mg/L
3
2
1
0
pre
post
pre
post
pre
post
pre
post
RL
CB
PO
USGS
(d)



(e)

Figure 2: Box-and whihsker plots for (a) total suspended solids (b) nitrite plus nitrate nitrogen (c) organic nitrogen (d) ortho phosphorus, and (e) total phosphorus at Richland Creek (RL), Chambers Creek (CB), Post Oak Creek (PO), and USGS station during the pre- and post BMP periods.

Table 1: Summary result of statistical analysis on total suspended solids at all monitoring station within Richland-Chambers Watershed

	RL	MC4	MC3	MC2	MC1	USGS	CB	PO
Box-and-whiskers	Improving	‡	‡	‡	‡	Improving	Improving	Improving
Linear trend	Improving	Improving*	Degrading*	Degrading*	Improving*	Improving*	Improving*	Improving
Mann-Kendall	Improving	Improving*	Improving*	Degrading	Improving*	Improving*	Improving*	Improving
Probability exceedance	Improving	‡	‡	‡	‡	Improving	Improving	Improving

*nonsignificant (p>0.1); box-and-whiskers and probability exceedance analyses are qualitative
‡: no data

Table 2: Summary result of statistical analysis on nitrite plus nitrate nitrogen at all monitoring station within Richland-Chambers Watershed

	RL	MC4	MC3	MC2	MC1	USGS	CB	PO
Box-and-whiskers	Degrading	‡	‡	‡	‡	Improving	Degrading	No change
Linear trend	Degrading*	Degrading	Improving*	Improving*	Degrading	Improving*	Degrading*	Improving*
Mann-Kendall	Degrading*	Degrading	Improving*	Improving	Degrading	No change	Degrading*	Improving*
Probability exceedance	Degrading	‡	‡	‡	‡	Improving	Degrading	Improving

*nonsignificant (p>0.1); box-and-whiskers and probability exceedance analyses are qualitative
‡: no data

Table 3: Summary result of statistical analysis on organic nitrogen at all monitoring station within Richland-Chambers Watershed

	RL	MC4	MC3	MC2	MC1	USGS	CB	PO
Box-and-whiskers	Degrading	‡	‡	‡	‡	‡	Degrading	Improving
Linear trend	Degrading*	Improving*	Improving*	Improving*	Improving*	‡	Degrading*	Improving*
Mann-Kendall	Degrading*	Improving*	Improving*	Degrading	Improving*	‡	Degrading*	Degrading*
Probability exceedance	Degrading	‡	‡	‡	‡	‡	Degrading	Improving

*nonsignificant (p>0.1); box-and-whiskers and probability exceedance analyses are qualitative
‡: no data

Table 4: Summary result of statistical analysis on ortho phosphorus at all monitoring station within Richland-Chambers Watershed

	RL	MC4	MC3	MC2	MC1	USGS	CB	PO
Box-and-whiskers	No change	‡	‡	‡	‡	No change	Improving	Improving
Linear trend	Improving*	Degrading*	Degrading*	Degrading	Degrading*	Degrading	Improving*	Improving
Mann-Kendall	Improving*	Degrading*	Degrading*	Degrading*	Degrading*	Degrading	Improving*	Improving
Probability exceedance	--[a]--	‡	‡	‡	‡	--[b]--	Improving	Improving

*: nonsignificant (p>0.1); box-and-whiskers and probability exceedance analyses are qualitative

--[a]--: High values observed 10% of the time exceed preBMP concentration values

--[b]--: Data obstructed by a single outlier

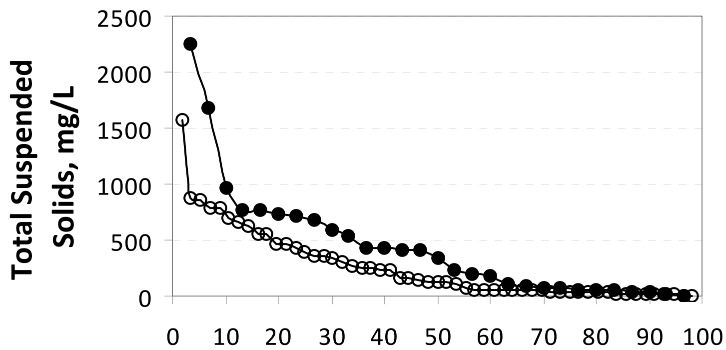
‡: no data

Table 5: Summary result of statistical analysis on total phosphorus at all monitoring station within Richland-Chambers Watershed

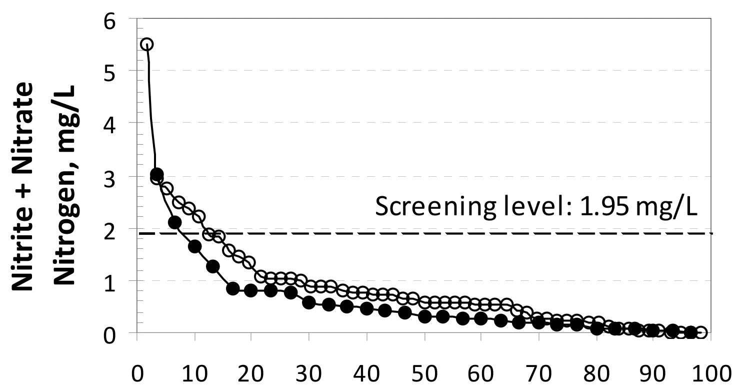
	RL	MC4	MC3	MC2	MC1	USGS	CB	PO
Box-and-whiskers	Improving	‡	‡	‡	‡	Degrading	Improving	Improving
Linear trend	Improving*	Improving*	Improving	Improving	Improving	Degrading	Improving*	Improving
Mann-Kendall	Improving*	Improving*	Improving*	Improving*	Improving	Degrading	Improving*	Improving
Probability exceedance	Improving	‡	‡	‡	‡	Degrading	Improving	Improving

*: nonsignificant (p>0.1); box-and-whiskers and probability exceedance analyses are qualitative

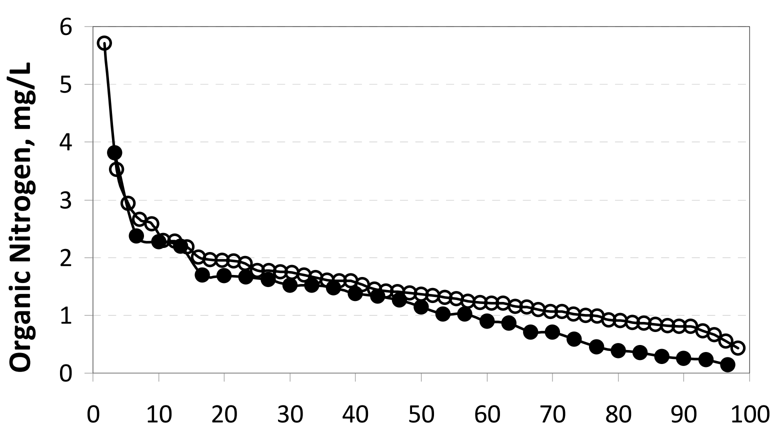
‡: no data


2500
2000
1500
1000
500
0
Total Suspended Solids, mg/L
0 10 20 30 40 50 60 70 80 90 100

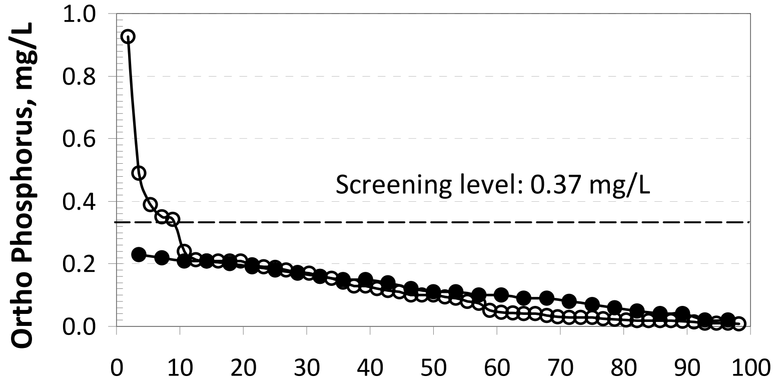
(a)


6
5
4
3
2
1
0
Nitrite + Nitrate Nitrogen, mg/L
Screening level: 1.95 mg/L
0 10 20 30 40 50 60 70 80 90 100

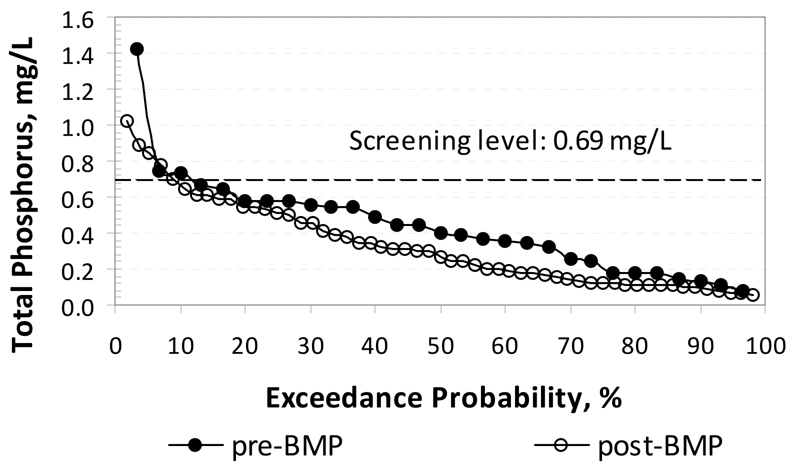
(b)


6
5
4
3
2
1
0
Organic Nitrogen, mg/L
0 10 20 30 40 50 60 70 80 90 100

(c)

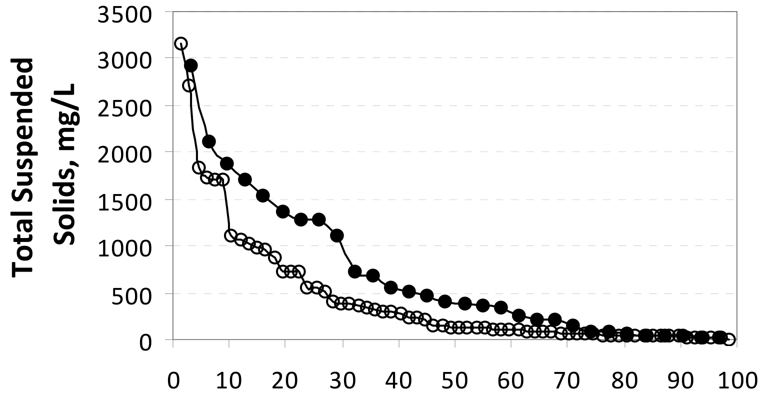


(d)

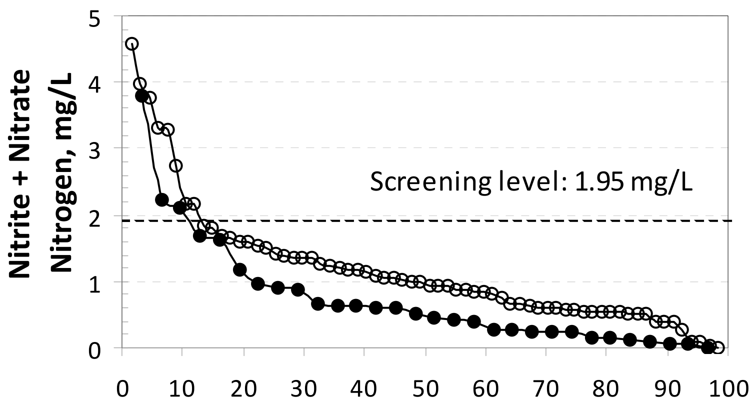


(e)

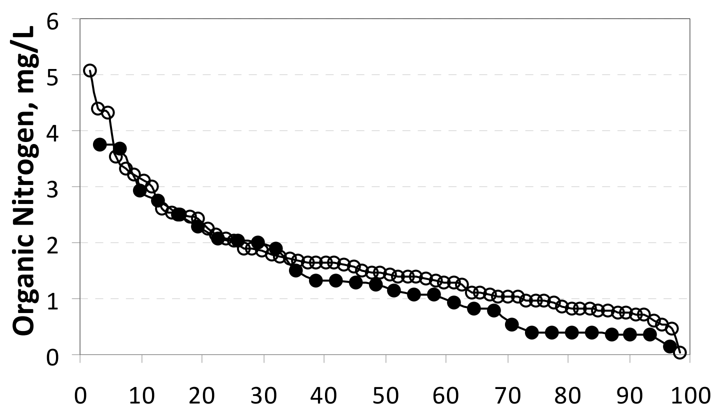
Figure 3: Probability exceedance plots (a) Total Suspended Solids (b) Nitrite + Nitrate Nitrogen (c) Organic Nitrogen (d) Ortho Phosphorus, and (e) Total Phosphorus at Richland monitoring station for the pre- and post-BMP periods


3500
3000
2500
2000
1500
1000
500
0
Total Suspended Solids, mg/L
0
10
20
30
40
50
60
70
80
90
100

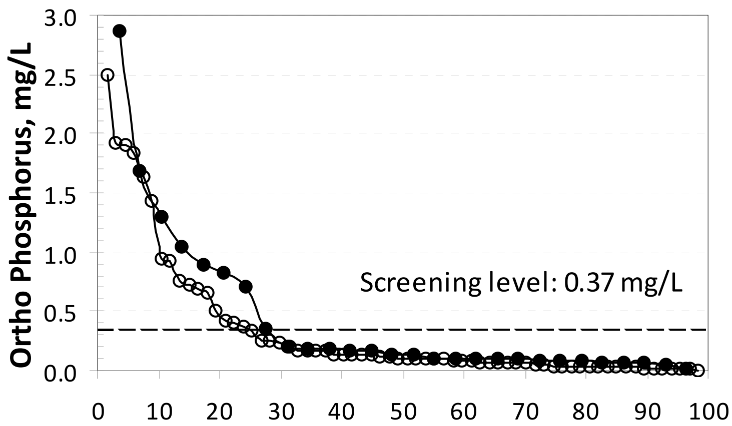
(a)


5
4
3
2
1
0
Nitrite + Nitrate Nitrogen, mg/L
Screening level: 1.95 mg/L
0
10
20
30
40
50
60
70
80
90
100

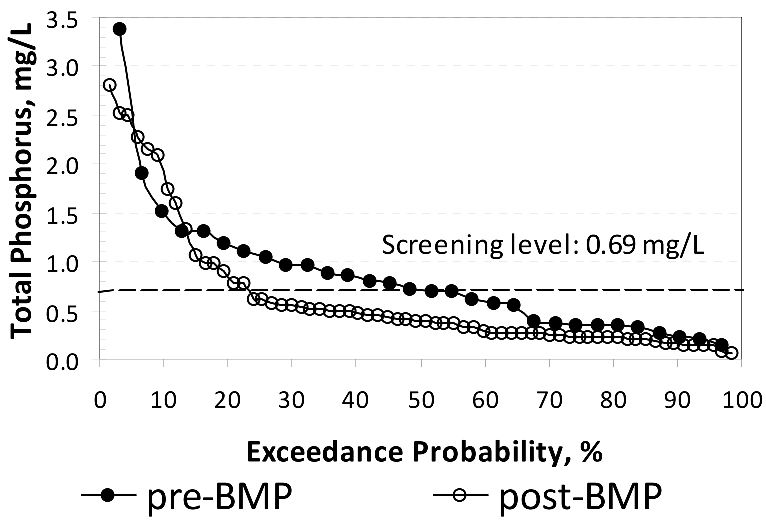
(b)


6
5
4
3
2
1
0
Organic Nitrogen, mg/L
0
10
20
30
40
50
60
70
80
90
100

(c)

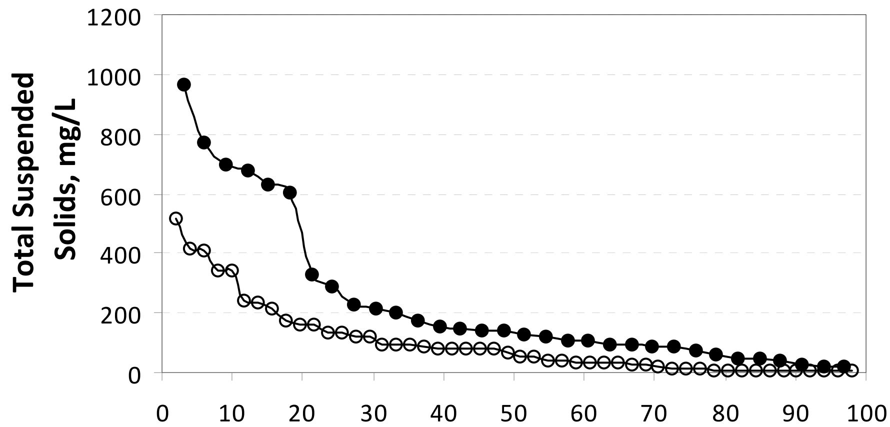


(d)

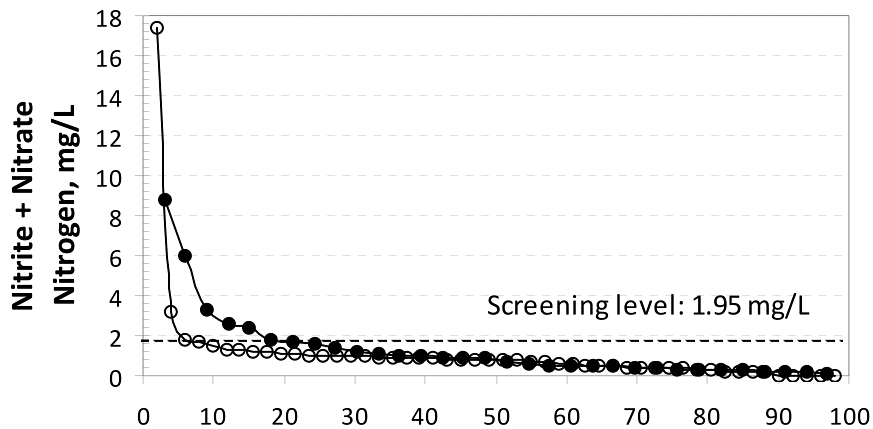


(e)

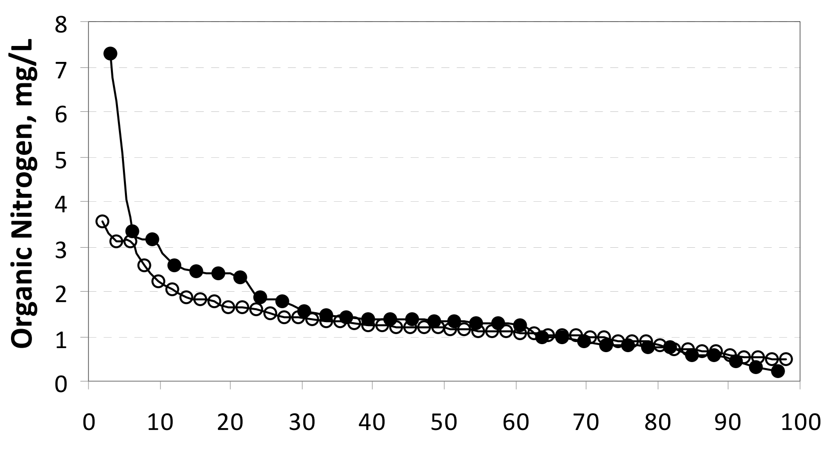
Figure 4: Probability exceedance plots (a) Total Suspended Solids (b) Nitrite + Nitrate Nitrogen (c) Organic Nitrogen (d) Ortho Phosphorus, and (e) Total Phosphorus at Chambers Creek monitoring station for the pre- and post-BMP periods


Total Suspended Solids, mg/L
1200
1000
800
600
400
200
0
0 10 20 30 40 50 60 70 80 90 100

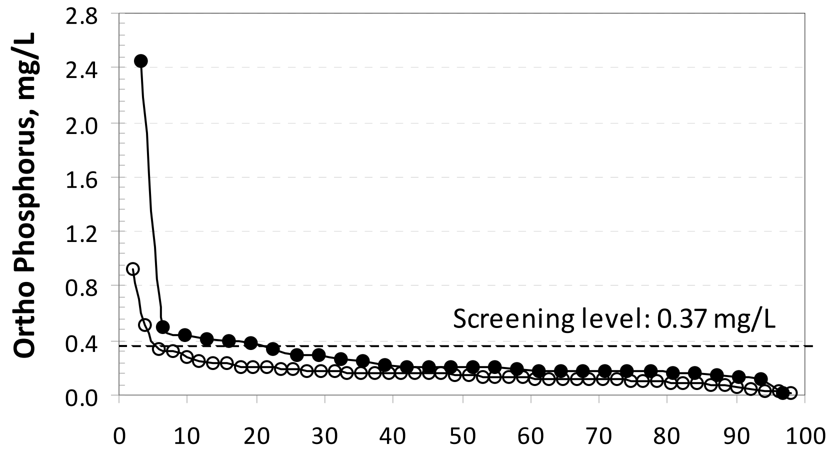
(a)


Nitrite + Nitrate Nitrogen, mg/L
18
16
14
12
10
8
6
4
2
0
Screening level: 1.95 mg/L
0 10 20 30 40 50 60 70 80 90 100

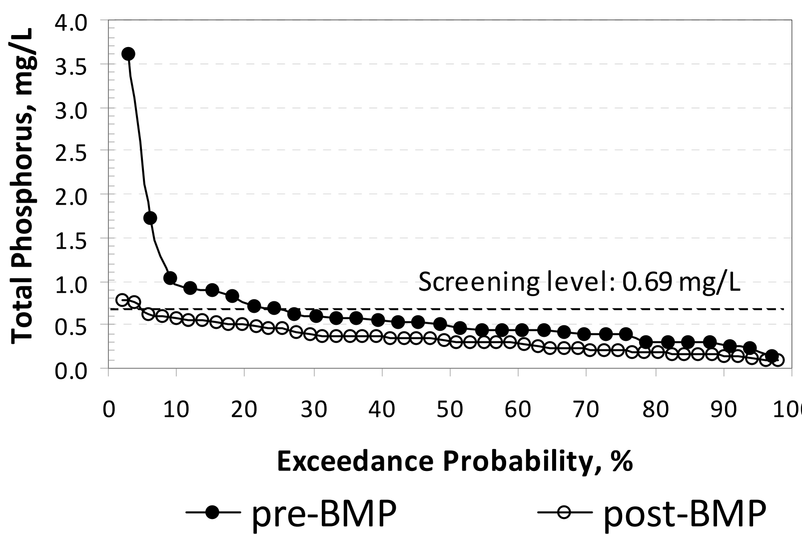
(b)


Organic Nitrogen, mg/L
8
7
6
5
4
3
2
1
0
0 10 20 30 40 50 60 70 80 90 100

(c)

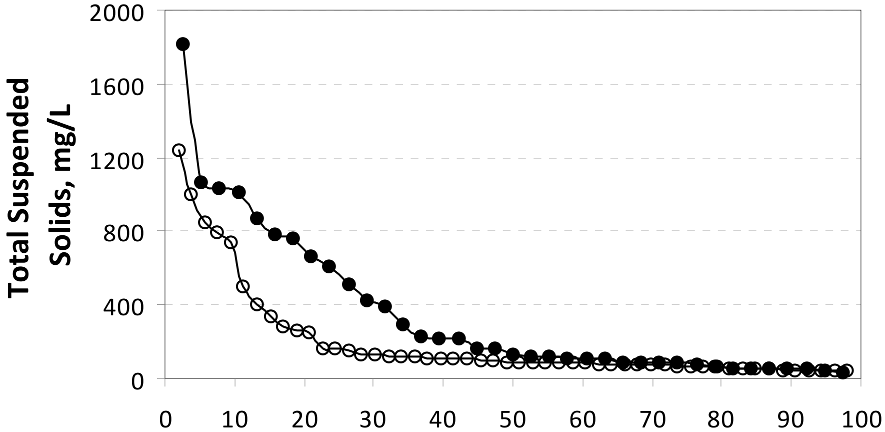


(d)

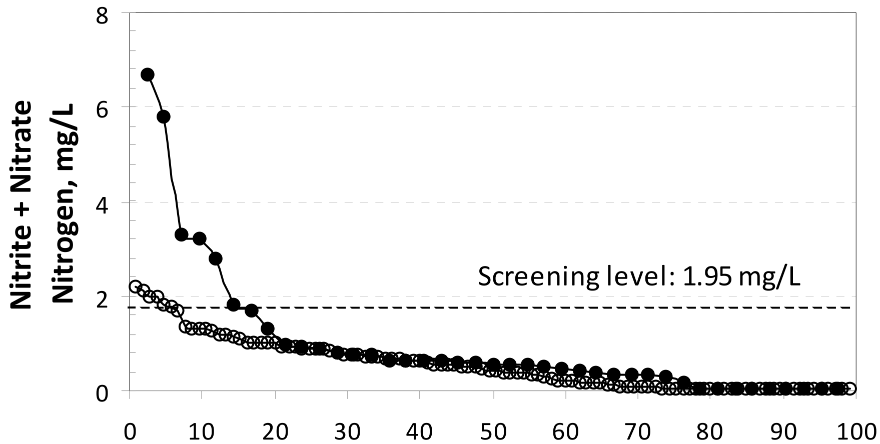


(e)

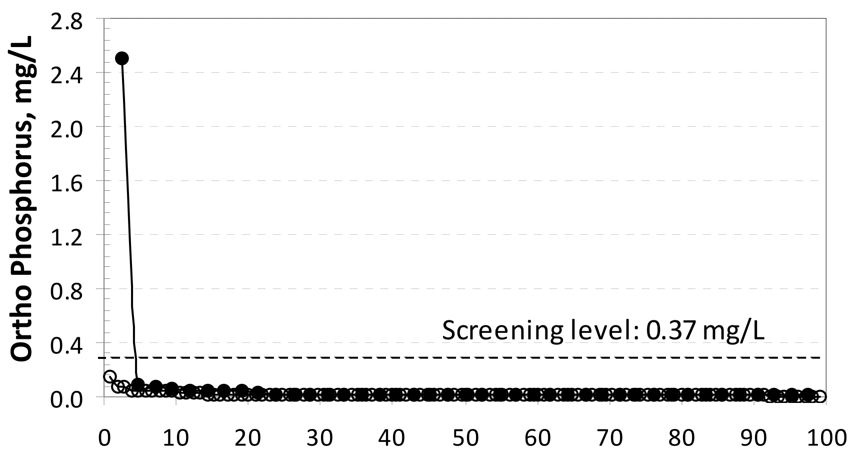
Figure 5: Probability exceedance plots (a) Total Suspended Solids (b) Nitrite + Nitrate Nitrogen (c) Organic Nitrogen (d) Ortho Phosphorus, and (e) Total Phosphorus at Post Oak Creek monitoring station for the pre- and post-BMP periods.


Total Suspended Solids, mg/L
2000
1600
1200
800
400
0
0 10 20 30 40 50 60 70 80 90 100

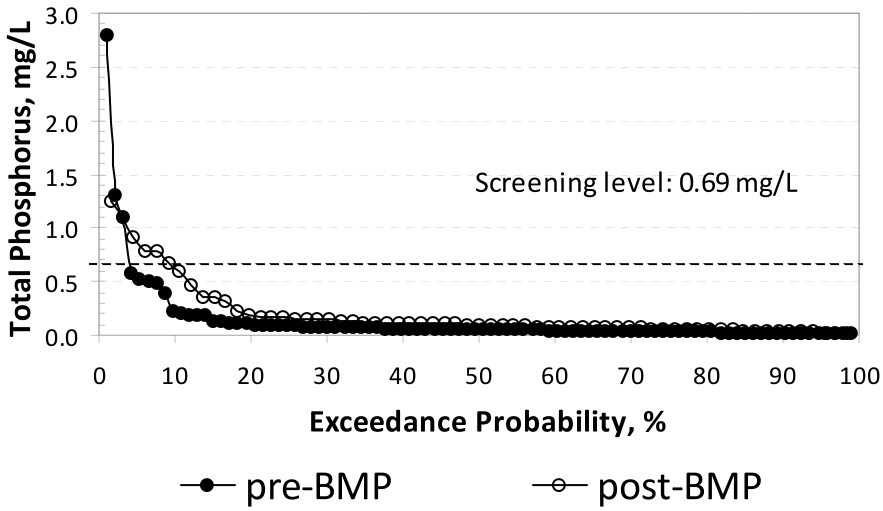
(a)


Nitrite + Nitrate Nitrogen, mg/L
Screening level: 1.95 mg/L
8
6
4
2
0
0 10 20 30 40 50 60 70 80 90 100

(b)


Ortho Phosphorus, mg/L
Screening level: 0.37 mg/L
2.8
2.4
2.0
1.6
1.2
0.8
0.4
0.0
0 10 20 30 40 50 60 70 80 90 100

(c)



(d)

Figure 6: Probability exceedance plots (a) Total Suspended Solids (b) Nitrite + Nitrate Nitrogen (c) Ortho Phosphorus, and (d) Total Phosphorus at USGS station monitoring station for the pre- and post-BMP periods.

CONCLUSIONS

Different techniques including exploratory data analysis, linear and Mann-Kendall's statistical tests on LOESS residuals on flow adjusted concentration values, and exceedance probability plots were applied on total suspended solids, nitrite + nitrate nitrogen, organic nitrogen, ortho phosphorus, and TP data at eight different monitoring stations in Richland-Chambers watershed in north central Texas.

Exploratory data analysis indicated that most of the constituents analyzed in this study showed departures from the normal distribution. Land use distribution such as the proportion of cropland area, sampling period, and existence of reservoir upstream influenced the spread in the water quality data. Trend analysis showed statistically non-significant decreasing trend for majority of the constituents. A mixed result was noticed for nitrogen and phosphorus. Availability of water quality data at some of the stations for the before and after BMP implementation facilitated plotting exceedance probability curves for pre-BMP and post-BMP periods. These plots complemented the results of statistical techniques.

Decreasing trend although non-significant, is a positive indication of the favorable effects of the implemented BMPs on water quality. This study provides information about the water quality conditions over a period of time for various constituents. Intensive implementation of the BMPs covering a larger watershed area could be required to produce significant changes in water quality due to the BMPs. Additional and more frequent time-step monitoring data is required to distinguish the trends based on seasons.

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Pushpa Tuppad, C. Santhi, and R. Srinivasan. 2009. Assessing BMP effectiveness: Trend analysis of observed water quality data. *Environmental Monitoring and Assessment*, DOI 10.1007/s10661-009-1235-8. (Published online 20 November, 2009).

PART II: Field scale BMP modeling using Agricultural Policy/Environmental eXtender (APEX) model.

INTRODUCTION

Agricultural BMPs are on-farm or in-stream activities that are designed to reduce sediment, nutrients and pesticides in drainage waters to an environmentally acceptable level while maintaining economically viable farming operations (Bottcher et al., 1995). Agricultural BMPs that reduce nonpoint source pollution are being studied more than ever in terms of design, implementation, and evaluation. The design and implementation are generally carried out by the NRCS and local SWCDs in response to farmers' interests. Information on the effectiveness of BMPs, is necessary for decision makers to evaluate the existing conservation programs and develop new programs effectively. In field studies, there are three main ways to assess the effectiveness of BMPs: (i) assessing the trends in measured data with respect to time (Edwards et al., 1997; Walker and Graczyk, 1993; Meals, 1987); (ii) direct comparison of field measured data from paired fields/watersheds (Sharpley and Smith, 1994; Sharpley et al., 1996; Edwards et al., 1997; Chow et al., 1999; Bishop et al., 2005); and (iii) modeling approach using field scale HWQ models. Although the field studies have been the primary way of evaluating the effects of BMPs, hydrologic/watershed simulation models are being used as an alternative approach due to time and cost-constraints in field studies. The predictive capability of simulation models in assessing future conditions and additional scenarios makes them to be advantageous and such capability is often needed for conservation program evaluation.

MATERIALS AND METHODS

Agricultural Policy/Environmental eXtender (APEX) model

APEX is an extension of Environmental Policy Integrated Climate (EPIC) (Williams and Sharpley, 1989), which was developed for use in whole farm/small watershed management. The model is capable of detailed field scale modeling and routing function connecting farm/field sized subareas. The EPIC/APEX models have been tested widely for their ability to simulate different agricultural management practices at both field and watershed scales (Phillips et al., 1993; King et al., 1996; Chen et al., 2000; Osei et al., 2000; Wang et al., 2006a).

Management capabilities of APEX include tillage, terraces, waterways, fertilizer and pesticide applications, manure management, buffer strips, reservoirs, crop rotation, irrigation, drainage, furrow diking, lagoons, grazing, etc. The model operates on a continuous basis using a daily time step. The smallest computational unit in APEX is a subarea which is homogeneous with respect to weather, topography, landuse, soil, and management. Slope within the subarea is assumed to be linear. Each subarea is simulated using EPIC model that simulates the upland hydrology. The major components in EPIC include weather, hydrology, erosion/sedimentation, nutrient cycling, pesticide fate and transport, plant growth, soil temperature, tillage, economics, and plant environment control. It simulates hydrologic processes such as runoff, infiltration, percolation, lateral subsurface flow, evapotranspiration, and snow-melt. Although EPIC operates on a daily time step, it offers the option of using the Green-Ampt infiltration equation to simulate rainfall excess rates at shorter time intervals (0.1 h). Also, the model offers options for simulating several other processes: five Potential EvapoTranspiration equations; seven erosion/sediment yield equations (which are variations of the Universal Soil Loss Equation (USLE)); and two peak runoff rate estimation equations. The options used in this study are given in table 6. Once the overland processes are simulated, APEX then routes water, sediment, nutrients, and pesticides across complex landscapes and channel systems to the watershed outlet. The APEX model also has groundwater and reservoir components. The routing mechanisms provide for evaluation of interactions between subareas involving surface runoff, return flow, sediment deposition and degradation, nutrient transport, and groundwater flow. Thus, flow and water quality in terms of nitrogen (soluble and organic nitrogen), phosphorus (soluble and organic phosphorus), and pesticides concentrations can be estimated for each subarea and at the watershed outlet.

Table 6: Method used to compute different components in APEX model

Component	**Method**
Runoff	NRCS*-curve number (rigid estimator)
Curve number	Variable daily CN** soil moisture index
Peak flow	Modified rational equation rigid peak estimator
Erosion	Modified USLE***
Potential evapotranspiration	Hargreaves

*NRCS: Natural Resources Conservation Service
**CN: Curve Number
***USLE: Universal Soil Loss Equation

A detailed description of the model concepts and mathematical relationships used to simulate different processes is given in Williams and Izaurralde (2006). Gassman et al. (2010) described the development and applications of the EPIC and APEX models for various studies. These studies prove that these models are suitable for simulating the impacts of climate, soil, topography, changing landuse, crop rotation, tillage, and other management practices on erosion and nutrient losses at both field and watershed scales. The APEX model has the ability to incorporate detailed field/farm level operations and effective in simulating the long-term impacts of landuse change and management practices (King et al., 1996). The APEX model is currently being used as a field-scale modeling tool to simulate various conservation practices on cultivated cropland in the Conservation Effects Assessment Project (CEAP) national assessment (Wang et al., 2006b; USDA-NRCS, 2007a).

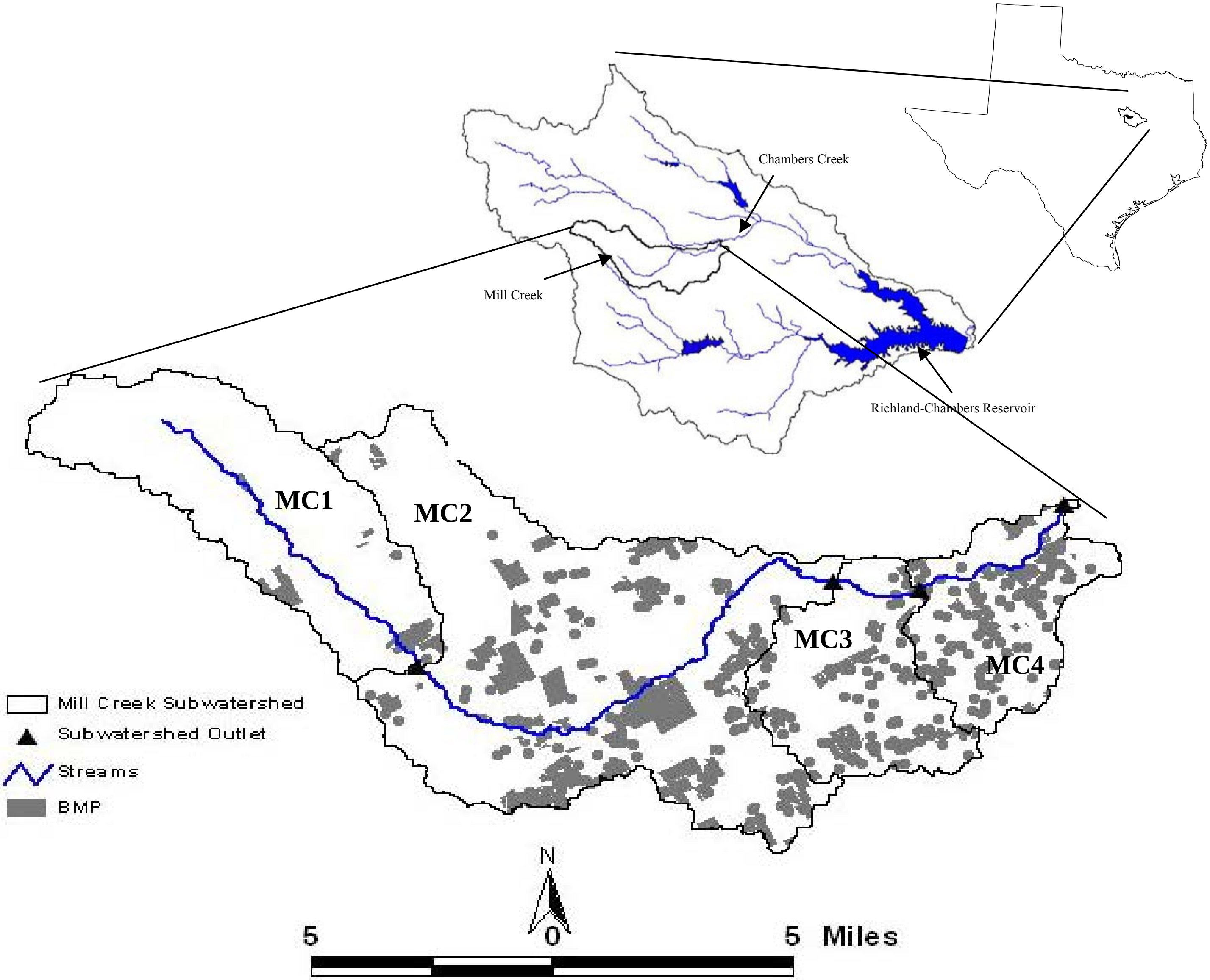

Figure 7: Location of BMPs in the Mill Creek Watershed

Study area
Mill Creek watershed, 280 km^2 in area, is a subwatershed of Richland-Chambers watershed (5,157 km^2) (Figure 7). Mill Creek is a tributary to Chambers Creek (Figure 7) and one of the major contributors of sediment and nutrient load into Chambers Creek and Richland-Chambers Reservoir. The major landuses in Mill Creek watershed are pasture (60.5%), cropland (35.1%), and others (4.4%) including range, forest, water, and urban. Corn, grain sorghum, and winter wheat are the major crops produced in the watershed. There is an intensive implementation of BMPs within Mill Creek watershed, since 1996, coordinated by TRWD in order to reduce sediment and nutrient loadings.

Model setup

The APEX model Ver. 0604 was used in this study. For simulation purposes, the Mill Creek watershed was subdivided into four subwatersheds: MC1, MC2, MC3, and MC4 (Figure 7). Each subwatershed was a site in APEX which was further divided into a number of subareas. The variations in drainage area, number of subareas, slope, soils, and portion of the subwatershed under each BMP is given in table 7. Model input data is given in table 8. Simulations were made for a period of 36 years from 1970 through 2005.

Table 7: Characteristics of subwatersheds in Mill Creek (MC) Watershed

	MC1	**MC2**	**MC3**	**MC4**
Area, ha	6,564	14,082	3,865	3,426
Number of subareas	438	510	476	522
Average subarea area (range), ha	15 (0.09 to 109)	28 (0.33 to 186)	8 (0.09 to 43.92)	7 (0.09 to 40)
Average slope (range), %	2.92 (0.44 to 7.86)	1.61 (0.22 to 4.33)	2.6 (0.15 to 6.35)	3.07 (0.06 to 10.03)
Dominant soils				
Soil type texture %clay ,%silt	Austin fine-silty 45,48	Houston black fine 30,37	Heiden fine 50,28	• Trinity very fine 70,21 • Heiden fine 50,28 • Ferris fine 53,29
Percentage of subwatershed area with BMPs	7.7	28.6	24.4	30.6

Table 8: Model input data (Note: Acronym expansion is given below this table)

Data type	**Source**
DEM	30m resolution, USGS
Landuse	NLCD-USGS
Soil	SSURGO soil database, USDA-NRCS
Weather	Daily precipitation, and minimum and maximum daily temperature data from NCDC-NWS
Flow and water quality data	TRWD
BMP	TRWD, TSSWCB
Land management	TRWD, SWCD

NCDC: National Climatic Data Center
NLCD: National Landcover Dataset
NRCS: Natural Resources Conservation Service
NWS: National Weather Service

SSURGO: Soil Survey Geographic
SWCD: Soil and Water Conservation Districts
TRWD: Tarrant Regional Water District
TSSWCB: Texas State Soil and Water Conservation Board
USDA: United States Department of Agriculture
USGS: United States Geological Survey

BMPs and their representation in pre-BMP and post-BMP conditions

A brief description of the BMPs and their representation in the APEX model is given in the sub-sections below (also see Table 9). A detailed description of the practices can be found in USDA National Handbook of Conservation Practices (USDA-NRCS, 2007b). The term 'pre-BMP' represents land management before implementing the BMPs and 'post-BMP' represents land management after implementing the BMPs. Pre-BMP simulation was the baseline to which post-BMP simulation results were compared.

Pasture planting

Pasture planting is establishing and well managing native or introduced forage species on cropland, hayland, pasture land, or any other agriculture land. Besides providing forage for livestock, carefully managed pasture lands provide good ground cover to reduce soil erosion and improve water quality. In the Mill Creek watershed, there were locations where pasture planting was carried on the land which was previously cropped or was rangeland. Therefore, pre-BMP land conditions varied accordingly. The APEX model uses Landuse Number (LUN), which designates a curve number based on soil hydrologic group, landuse type, conservation practice, and cropland management decisions on surface hydrology (Table 8). Poorly managed pastureland (pre-BMP condition) was simulated as poorly grown pasture having less ground cover. This was represented by higher curve number (CN) values and removal of 95% of above ground biomass during harvest. Post-BMP condition was simulated by using lower values and removal of 75% of above ground biomass during harvest so that adequate ground cover is maintained to resist the runoff and erosion rates. In both pre- and post-BMP conditions, hay was cut four times a year, which is the typical practice in the Mill Creek watershed area.

Nutrient management

Nutrient management involves managing the amount, source, placement, form, and timing of nutrient applications. In the Mill Creek watershed, nutrient management BMPs were implemented in combination with other BMPs such as pasture planting, conservation cropping, and prescribed grazing. The vegetation simulated on pastureland was Coastal Bermuda. Cropland was in 3–year grain sorghum–winter wheat–corn rotation. In the pre-BMP condition, nutrients were applied one-time before planting and the amounts applied were based on the recommendations by the local SWCD personnel (personal communication, December 13, 2006). The APEX model has an automatic nitrogen application feature which applies the user-specified amount of nitrogen fertilizer when the plant stress reaches a user-specified level. This mimics the amount, placement, and timing of the nutrient application which is the primary purpose of nutrient management. Thus, the post-BMP scenario was simulated with automatic nitrogen fertilizer application at varying amounts depending on the crop type, with a maximum of 300 kg/ha-year, when the plant nitrogen stress factor reached 0.8.

Brush management and pasture planting

Brush management is the removal or reduction of tree and shrub species which otherwise competes with forage species for water, space, and sunlight. Land with brush vegetation is prone to erosion due to poor ground cover. In the pre-BMP scenario, areas under brush management were simulated with mesquite and replaced by pasture or range grass in good condition in the post-BMP scenario.

Clearing and range planting

Trees, stumps, brush, and other vegetation make the land unproductive. Land with lack of adequate cover on the ground surface is a potential source of erosion. Clearing involves removing existing vegetation in order to implement a conservation plan. This BMP was simulated similar to the brush management BMP in terms of growing mesquite in the pre-BMP condition and growing a range grass in the post-BMP condition.

Range planting

Range planting is establishing adapted perennial vegetation on areas where vegetation cover on the ground is poor and/or is below the acceptable level for natural reseeding to occur. In some rangeland areas within the watershed, range grass was poor providing inadequate vegetation cover on the ground causing erosion. Therefore, pre-BMP scenario was simulated with poor growing grass and higher CN values, whereas post-BMP scenario was simulated with range grass in good condition and lower CN values.

Prescribed grazing

Overgrazing results in inadequate ground cover and exposure of soil on the surface. Prescribed grazing is managing the harvest of vegetation with grazing animals in such a way that there is adequate cover on the ground to minimize erosion. In pre-BMP scenario, overgrazed condition was simulated in terms of poor growing grass and the grazing limit set to 0.5 Mg/ha. This means that the model allowed grazing until above ground biomass reached 0.5 Mg/ha. Grass in good condition was simulated in post-BMP scenario and the grazing limit was increased to 1.0 Mg/ha.

Critical area planting

This practice consists of planting vegetation on highly erodible areas where ordinary planting methods cannot provide adequate erosion control. In the pre-BMP condition, these areas were simulated as fallow land with no vegetal cover and higher CN values whereas in the post-BMP condition, they were represented by range grass in good condition and lower CN values.

Conservation cropping

Conservation cropping practice involves less tillage. It increases the residue from the crop that remains in the field after harvest through planting. In this study, conservation cropping was simulated using appropriate CN values and maintaining residue on the surface. Crop rotations and amounts of fertilizers applied in conservation cropping practice were same as in land under conventional tillage practice except that the intensive tillage operations such as tandem disc and chisel plow before planting and after harvest were eliminated. Mostaghimi et al. (1997) simulated conservation tillage practices using CN, C factor, surface roughness condition constant, and Manning's roughness coefficient in agricultural nonpoint source pollution.

Contour farming

Contour farming consists of performing field operations including plowing, planting, cultivating, and harvesting, approximately, along the contour. Contouring intercepts runoff and reduces development of rills. Contour farming practice was represented by conservation support practice factor (PEC) and LUN.

Terrace

Terraces are broad earthen embankments or channels constructed across the slope to intercept runoff water and control erosion. Terraces decrease hill slope-length, prevent formation of gullies, and intercept and conduct runoff to a safe outlet thereby reducing sediment content in runoff water. In this study, terraces were represented by PEC and CN. To determine PEC value for the post-BMP condition, waterways or graded channel outlets were considered in conjunction with terraces. Appropriate LUN was specified for each of the pre- and post-BMP conditions. Bracmort et al. (2006) simulated the effect of parallel terraces by modifying curve number, USLE support factor, and slope-length. Secchi et al. (2007) also used USLE support factor based to represent contouring and terraces.

Pond

Pond is water impoundment made either by constructing a dam (called "embankment pond") or by excavating a pit (called "excavated pond" or "pit-type pond"). Ponds serve as a source of water for livestock, fish and wild life, fire control, and cropland and orchards. Ponds receive runoff from the upstream drainage area and aids in settling of sediment. In this study, ponds were simulated as water bodies located within subareas, receiving inflow from a fraction of the subarea. Also, ponds were assumed to have a drainage area of 5 ha. The pre-BMP condition was absence of pond in the subarea.

Grade stabilization structure

Grade stabilization structures control the grade and head-cutting in natural or artificial channels to prevent the formation or advancement of gullies. Santhi et al. (2006) simulated the areas having grade stabilization structures with poor grass cover, steeper landslope, and higher channel cover factor (Channel C-factor) in the pre-BMP scenario. In the post-BMP scenario, they were simulated with a good grass cover, milder slopes, and lower Channel C-factor. Bracmort et al. (2006) simulated grade stabilization structures by modifying channel slope and channel erodibility factor in the SWAT model. Alternatively, in the present study, grade stabilization structures were simulated as reservoirs in an attempt to represent the on-ground appearance of the structure and also give due consideration to its intended purpose and functionality. The reservoir is considered to be located in the reach and at the outlet of the subarea. Inflow to the reservoir is derived from the subarea plus all other contributing subareas upstream of it. Settling of sediment is the major influence of reservoirs in terms of erosion control. As in the case of pond, the pre-BMP condition was simply the absence of the reservoir.

Waterways/grassed waterways

Waterways safely conduct and dispose overland flow from the upstream areas. They are vegetated channels with increased surface roughness which reduces the velocity of flow. These features combined protect the soil against surface scouring. In the present study, waterways were almost always found in combination with terraces (represented by modifying PEC explained in the 'terrace' BMP description) but there were some cases where waterways were installed as stand-alone management practice. In such cases, the pre-BMP channel condition was simulated as erosive. Effects of waterways were simulated by Channel C-factor, Channel Manning's Roughness Coefficient (Manning's N), and channel dimensions (Table 9). Similar to the study by Bracmort et al. (2006), Channel C-factor of 0.2 in the pre-BMP and 0.001 in the post-BMP conditions was used. Also, in the post-BMP condition, the channel was made extremely shallow with dimensions set to: depth = 0.01 m; top width = 0.5 m; bottom width = 0.1 m; and flood plain width = 20 m so that the runoff water flows in the floodplain mimicking the flow through an actual grassed waterway. The channel dimensions in the pre-BMP condition for grassed waterways were about 0.7 m in depth, 1 m wide at the bottom, and 3-4 m wide at the top. Secchi et al. (2007) represented grassed waterways in the SWAT model by changing the P-factor (to 0.4) and Manning's N. Mostaghimi et al. (1997) adjusted Manning's N and specified zero gully sources in agricultural nonpoint source to represent grassed waterways.

Table 9: Type of BMP, and the corresponding pre- and post-BMP land management inputs and model parameters used in APEX (Note: Variable definitions are given below this table).

BMP (NRCS code)	Variable in APEX	Without BMPs (Pre-BMP)	With BMPs (Post-BMP)
Nonstructural BMPs			
Pasture Planting (512)	LUN (for pasture in pre-BMP) HI	20 0.95 (95% of above ground biomass is removed)	22 0.75 (75% of above ground biomass is removed)
Nutrient Management (590)	BFT FNP4 FMX	 One time fertilizer application	0.8 Varied depending on the crop type 300.0
Brush Management (314) Clearing (460) and either pasture planting or range planting in post-BMP	Crop type	Mesquite grown	Mesquite replaced by pasture or range grass in good condition
Range Planting (550)	 LUN	Poor growing range grass 20	Good range grass 22
Prescribed grazing (528)	Grazing limit	Poor growing range grass 0.5 Mg/ha	Good range grass 1.0 Mg/ha
Critical Area Planting (342)		Fallow land	Range grass in good condition

	LUN	1	22
Conservation cropping (328)	Tillage operations	Conventional tillage	No tandem disc and chisel plow operations before planting
Contour Farming (330)	PEC LUN	1.0 Based on crop type and no conservation practice	0.6 (for Upland Slope ≤ 2% 0.5 (for Upland Slope 3 – 5%) Based on crop type with contour practice
Structural BMPs			
Terrace (600)	PEC LUN	1.0 Based on crop type and no conservation practice	0.12 Based on crop type and contour-terraced conservation practice
Pond (378)	PCOF	0.0 (No pond)	Varied based on the area of the subarea (Note: assumed drainage area for pond = 5 ha)
Grade Stabilization Structure (GSS) (410)	Elevation, surface area, and storage at principal and emergency spillways	No reservoir	GSS added as reservoir
Waterway/Grassed Waterway (412) (shaping, vegetation, and nutrient management)	LUN RCHN RCHC RFPW	20 0.05 0.2 0.0 m	22 0.25 0.001 20.0 m Extremely shallow and small channel

BFT: Auto fertilizer trigger; when the plant nitrogen (N) stress level reaches BFT, N fertilizer will be applied automatically.
FMX: Maximum annual N fertilizer applied for a crop, kg/ha.
FNP4: Amount of fertilizer per automatically scheduled application, kg/ha.
HI: Harvest Index, defined as the fraction of the aboveground biomass removed.
LUN: Landuse Number from NRCS Landuse-Hydrologic Soil Group Table (for looking up Curve Number values).
PCOF: Fraction of the subarea that drains into the pond.
PEC: Universal Soil Loss Equation (USLE) conservation support practice factor, defined as the ratio of soil loss with a specific support practice such as terrace, contour farming to the corresponding loss with up-and-down slope cultivation.
RCHN: Channel Mannings N of the Routing Reach.
RCHC: Channel Cover factor of the Routing Reach, defined as the ratio of degradation from a channel with a specified vegetative cover to the corresponding degradation from a channel with no vegetative cover. The vegetation reduces the stream velocity, and further its erosive power, near the bed surface. The C-factor ranges from 0.0 to 1.0. A value of 0.0 indicates that the channel is completely protected from degradation by vegetal cover whereas a value of 1.0 indicates that there is no vegetative cover on the channel.
RFPW: Floodplain width, m.

Analysis of BMP effectiveness

The benefits of BMPs are reported as percent reductions in key constituents including runoff, sediment, TN, TP, both at the subarea level (overland processes) and at the subwatershed outlet (which includes overland contribution and routing of the constituent through the stream network within the subwatershed). Constituent loadings generated in the post-BMP conditions were compared with the pre-BMP loads to calculate the percent reduction. The results were compared with those reported in the literature, where available, and experts (NRCS, Temple, Texas, personal communication, August 15, 2007) when consulted where benefit/effectiveness information was not available.

The same BMP was present in more than one subarea having different soils and weather conditions and therefore a range in load reduction is presented. For a BMP, this range reflects the variability in soil type, weather, and topographic characteristics of the subareas. Subarea level reductions were estimated from only those subareas where BMPs were implemented. Overall reduction in the loadings at the subwatershed outlet including both BMP and non-BMP subareas, is also reported for all four subwatersheds.

RESULTS AND DISCUSSION

The results presented were from a long-term simulation (36 years), assuming a good condition of BMP establishment and maintenance. The benefits of the BMPs in terms of percent reduction are at the edge-of-field (or field level). Also, the benefits are quantified considering the relative performance of the BMP compared with the pre-BMP condition.

Effectiveness of BMPs at Field Level

In this study watershed, some farms/fields had 'pasture planting' as the only BMP and some other farms/fields had pasture planting in combination with nutrient management. These BMP areas were pasture for hay or pasture that is grazed or cropland in the pre-BMP period. Overall, pasture planting reduced runoff by up to 67%, sediment by up to 95%, TN by up to 86%, and TP by up to 87% (Table 10). Converting mesquite to pasture (for hay) along with nutrient management or to range grass resulted in a moderate decrease in runoff, averaging 13% and 22% (Table 10), respectively. Conservation Practice Physical Effects (CPPE) by NRCS (USDA-NRCS 2007b) reports a moderate decrease in runoff due to brush management. Brush removal followed by pasture planting reduced on average 92% of sediment, 74% of TN, and 27% of TP (Table 10) whereas brush removal followed by range planting resulted in a 96% reduction in sediment, 86% in TN, and 66% in TP. Range planting (good range grass in the post-BMP compared with poorly managed range grass in pre-BMP) reduced runoff by 26 to 72%, sediment by 94 to 99%, TN by 83 to 97%, and TP by 75 to 96% (Table 10). Predicted reduction in sediment by 97 to 98%, TN by 89 to 92%, and TP by 77 to 88% as reported by Santhi et al. (2006) were in a similar range as with those obtained in this study. Olness et al. (1980) reported average annual sediment loss of 7.3 t/ha and TN and TP losses of 4.0 kg/ha each from continuous grazing. In the present study, poor grazing resulted in overland sediment, TN, and TP losses of 3.6 t/ha, 11 kg/ha, and 9 kg/ha, respectively. Prescribed grazing reduced runoff by 65%, sediment by 99%, TN by 95%, and TP by 84% (Table 10).

Establishment of vegetation on the critically eroding areas, on average, reduced runoff by 58%, sediment by 99%, TN by 97%, and TP by 92%. Terracing and pasture planting produced moderate reductions in runoff (averaging to 32%), and substantial reductions in sediment (up to 99%), TN (up to 84%), and TP (up to 61%).

In the present study, annual average sediment loss was predicted to be in the range of 1.5 to 43 t/ha and TN in the range of 6.8 to 48 kg/ha from croplands with average slope of 0.15 and average annual precipitation of 950 mm. Similarly, terraces in combination with contour farming, conservation cropping, and nutrient management resulted in runoff reduction, that averaged 45% (Table 10). Also, this combination resulted in reductions of 96, 89, and 78% in sediment, TN, and TP, respectively.

In general, ponds did not appreciably impact runoff reduction (average of 5%). This complies with CPPE (USDA-NRCS 2007b) that reports a slight decrease in runoff due to the presence of ponds. The ponds simulated in this study were relatively small with assumed drainage areas of 5 ha and were not expected to produce much benefit in terms of pollutant load reduction. However, the presence of ponds resulted in 38% reduction in sediment, 32% in TN, and 23% in TP.

The grade stabilization structures performed well by reducing runoff by 16%, sediment by 71%, TN by 64% and TP by 51% (Table 10). These reductions followed closely the percent reductions reported in Sharpley et al. (1996). Waterways did not affect runoff generation potential but were effective in reducing sediments (by 36%), TN (by 25%), and TP (by 15%) (Table 10).

The average reduction in sediment from all BMPs at the farm level ranged from 36 to 99% (Table 10). No reduction in sediment was an outlier that resulted from a subarea with a waterway draining an area of 3 ha. A pond upstream of this subarea settled 48% of the sediment entering it. As a result, the sediment load entering the waterway was small without leaving any scope for further settling. Simulation results in this study showed that there was a higher percent reduction in sediment compared with reductions in runoff, TN, and TP as most of the BMPs are primarily designed to reduce the erosion potential and sediment bound nutrient losses.

Table 10: Percent reduction in predicted overland runoff, and sediment and nutrient loads between pre-BMP and post-BMP conditions.

	Surface runoff			Sediment yield			TN			TP		
BMP type	**avg**	**Min**	**Max**	**avg**	**Min**	**Max**	**avg**	**Min**	**Max**	**avg**	**Min**	**Max**
Pasture planting & nutr. mgmt (pasture-hay in pre-BMP)	45	42	65	79	76	91	67	64	79	63	53	81
Pasture planting & nutr. mgmt (pasture-graze in pre-BMP)	31	28	40	73	60	85	60	45	74	69	27	76
Pasture planting & nutr. mgmt (cropland in pre-BMP)	40	38	42	94	93	95	81	70	86	47	3	71
Pasture planting (pasture-hay in pre-BMP)	52	42	64	66	58	87	69	56	78	54	44	74
Pasture planting (pasture-graze in pre-BMP)	35	26	67	67	51	89	49	28	84	72	66	87
Pasture planting (cropland in pre-BMP)	39	38	40	93	93	93	67	62	76	27	13	46
Brush mgmt, pasture planting, & nutr. mgmt	13	12	13	92	92	92	74	73	75	27	19	35
Clearing & range planting (mesquite in pre-BMP)	22	15	69	96	93	99	86	78	96	66	51	92
Range planting	41	26	72	96	94	99	89	83	97	85	75	96
Presc. grazing & nutr. mgmt (pasture-grazing in pre-BMP)	64	42	79	97	93	100	93	83	98	84	75	92
Presc. grazing & nutr. mgmt (cropland in pre-BMP)	65	60	76	99	98	100	95	92	99	63	42	87
Critical area planting	58	54	81	99	99	100	97	96	99	92	90	99
Cont. farming, cons. cropping, & nut. mgmt	24	23	25	73	73	77	60	56	66	49	36	57
Terr., pasture planting & nutr. mgmt (cropland in pre-BMP)	30	30	30	99	99	99	84	82	86	59	54	63
Terr., pasture planting, & nutr. mgmt (pasture in pre-BMP)	32	31	33	96	96	97	69	65	70	61	55	65
Terr. (cropland in pre-BMP)	39	37	47	93	93	94	82	77	87	72	60	79
Terr., cont. farming, cons. cropping, & nutr. mgmt	45	44	45	96	96	96	89	87	89	78	73	82
Pond	5	0	16	38	5	81	32	4	80	23	3	52
Grade Stabilization Structure	16	1	55	71	21	95	64	45	84	51	27	77
Waterway	0	0	0	36	0	85	25	0	69	15	0	56

Cont.-contour; Cons.-conservation; Mgmt-management; Nutr.-nutrient; Presc.-prescribed; Terr.-terrace

Effects of BMPs at subwatershed level

The reductions at the subwatershed outlets were less compared to the significant reductions predicted at the field scale. Depending on the areas of BMP implementation, soils, and landuse characteristics (Table 7), the percent reduction in runoff, and sediment and nutrient loads varied among the subwatersheds. Runoff reduced in the range from 2.9 to 6.5%. Sediment reduction at the subwatershed outlet ranged from 6.3 to 14.8%, TN from 11.0 to 15.1%, and TP from 6.3 to 8.6%. The reduction in sediment at the watershed outlet (Figure 8) was proportional to the area treated with BMPs. This general trend was not followed by other constituents such as runoff, TN, and TP because most of the BMPs implemented were for control of erosion. Some BMPs (example, pasture planting with nutrient management) have additional benefit of nutrient management. MC1 had the lowest proportion of the subwatershed area with BMPs (7.7%; Table 7) and the dominant BMP in MC1 was prescribed grazing with nutrient management, resulting in higher percent reduction in total nitrogen loading. MC2, MC3, and MC4 had comparable proportions of subwatershed area treated with BMPs (Table 7). Higher percent reduction in sediment and nutrients in MC4 is due to larger area treated with BMPs, especially critical area planting. All the BMPs simulated in this study except grade stabilization structures, grassed waterways, and ponds intend to reduce overland pollution generation.

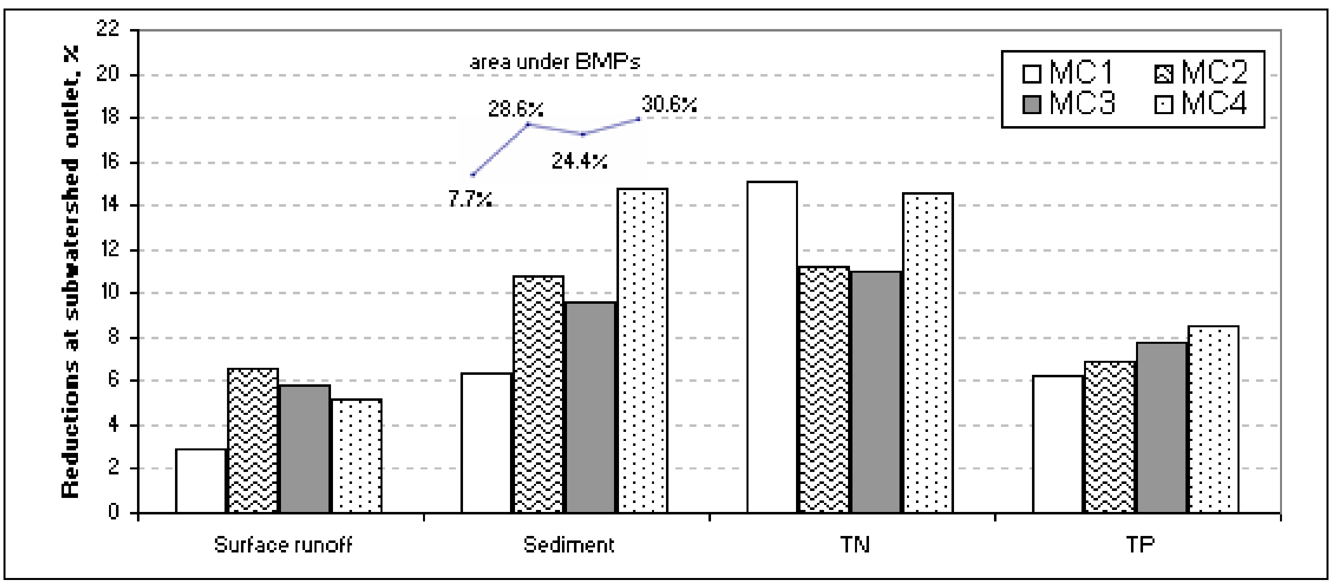

Figure 8: Percentage reduction in flow, sediment and nutrient loadings at the outlets of the four Mill Creek subwatersheds

CONCLUSIONS

Federal and state agencies are investing substantial amount in implementing several conservation programs across the United States. Information on quantitative benefits of water quality management programs is necessary for future planning and resource allocation. Long-term monitoring data is not available for most watersheds due to the level of expense involved in collecting such data. Also, there is not adequate documentation or literature available showing the quantitative benefits of conservation practices/BMPs at the watershed level. Given these facts, a modeling approach is very helpful.

A modeling study was conducted to demonstrate a method to assess the effectiveness of BMPs both at field and subwatershed levels. The APEX model was used to simulate various structural and non-structural BMPs implemented in a 280-km^2 Mill Creek watershed, a subwatershed of Richland-Chambers watershed in north-central Texas. Various BMPs simulated include pasture planting, nutrient management, brush management, clearing and range planting, prescribed grazing, critical area planting, conservation cropping, contour farming, terrace, ponds, grade stabilization structures, and waterways. The long-term impact of BMPs on water quality in Mill Creek were estimated by percent reduction in surface runoff, sediment, TN, and TP loadings between pre-BMP (without BMP) and post-BMP (with BMP) conditions. Annual average field level reductions obtained by these BMPs (considering only BMP subareas) were 35% in runoff, 83% in sediment, 72% in TN, and 58% in TP. At the subwatershed outlets, the reductions ranged from 2.9 to 6.5% in runoff, 6.3 to 14.8% in sediment, 11 to 15.1% in TN, and 6.3 to 8.6% in TP. Increasing the areas with BMP implementation would further reduce the overland pollutant loads and in-turn load at the watershed outlet. More research is needed to study the impacts of additional in-stream BMPs that have potential to reduce channel erosion and/or trap sediment and sediment bound nutrients.

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PART III: Watershed scale BMP modeling using Soil and Water Assessment Tool (SWAT) model

INTRODUCTION

Federal and state agencies are investing substantial amount in implementing several conservation programs across the United States. Though these conservation programs are widely recognized to preserve/enhance water quality and conserve natural resources, more study is necessary to quantify their environmental benefits at different spatial scales and geographic locations. It is important to estimate the pollution reduction efficiency of these BMPs in order to help policy makers make decision on future resource allocations. Published literature values exist; however, site characteristics can alter their worth. A comprehensive watershed modeling tool can more effectively capture site-specific characteristics (i.e. climate, topography, and soil) and multiple scenarios limiting labor, time, and financial expenses associated with intensive field studies, but no clear guidelines exist on representing various BMPs in the simulation models. Moreover, non-availability of long-term and continuous monitoring data limits BMP field validation efforts. The overall objective of this study is to apply the SWAT model to simulate various BMPs and assess their long-term impacts on sediment and nutrient loads at field (or Hydrologic Response Unit (HRU)) and watershed levels.

MATERIALS AND METHODS

The Soil and Water Assessment Tool (SWAT) Model

The SWAT model is a nonproprietary hydrologic/water quality tool developed by the United States Department of Agriculture-Agriculture Research Service (Arnold et al., 1998; Neitsch et al., 2002). The SWAT model is also available within the USEPA's Better Assessment Science for Integrated Point and Nonpoint Sources as one of the models that they support and recommend for state and federal agencies to use to address point and nonpoint source pollution control. The SWAT model is a distributed parameter, continuous scale model that operates on a daily time-step. It has the capability to simulate a variety of land management practices and has been used as a tool to assess water resource and water quality issues across a wide range of spatial and temporal scales. The SWAT model divides the watershed into a number of subwatersheds based on topography and user defined threshold drainage area. Each subwatershed is further divided into HRUs, which are a unique combination of soil, land use, and land management. The HRU is the smallest landscape component of SWAT used for computing the hydrologic processes. The model first determines the overland loadings of flow, sediment, and nutrients and then routes these loading through the stream network. Flow, sediment, and nutrient processes within the model are largely determined by modeled runoff. SWAT has the option of using a modification of USDA - Soil Conservation Service's (USDA-SCS) CN method (USDA-SCS, 1972) or the Green-Ampt (Green and Ampt, 1911) infiltration method to estimate surface runoff. In the CN method, surface runoff is estimated as a function of daily CN adjusted for the moisture content of the soil on that day. The CN method is widely used due to simplicity, predictability, and its responsiveness to soil type, land use and land condition, and antecedent soil moisture. Some of the disadvantages are that the method has no explicit provision for spatial scale effects and is sensitive to low CNs and low rainfall depths (Ponce and Hawkins, 1996). Also, this method only considers total rainfall volume and not rainfall intensity and duration. However, break point rainfall input and streamflow routing at sub-daily time step used by Green-Ampt infiltration method not necessarily result in significant improvement in the model prediction for large basins (King et al., 1999). Further, Van Liew et al. (2003) reported that the Philip infiltration equation used in HSPF model may provide accurate simulation of hydrologic processes when site-specific data are available.

The SWAT model uses the Modified Universal Soil Loss Equation (MUSLE) (Williams, 1975) and modified Bagnold's equation (Bagnold, 1977) to estimate erosion and deposition. The QUAL2E model (Brown and Barnwell, 1987) has been incorporated into SWAT to process in-stream nutrient dynamics. A detailed description of the components and mathematical equations representing various processes can be found in Neitsch et al. (2005). The SWAT model has been extensively applied for issues ranging from hydrology, climate change, pollutant load assessment, and BMP evaluation at various spatial and temporal scales.

The present study used SWAT2005 version and ArcGIS (ArcSWAT) interface tool (Olivera et al., 2006) designed to use ArcGIS 9.x GIS platform to generate model inputs and execute SWAT2005.

Model Setup

The SWAT model was applied to the Richland-Chambers watershed. The watershed's major landuses are pasture (51%) followed by cropland (20%) and forest (14%), range (6%) and others including water, and urban. Corn, grain sorghum, winter wheat, and cotton are the major crops produced in the watershed. Input dataset used in the model setup are listed in table 11. Daily rainfall and minimum and maximum temperature was collected from 11 National Weather service COOP rainfall stations in and around the watershed for the period from 1975 to 2006. Missing rainfall/temperature data were replaced by data from the nearest stations. Solar radiation, wind speed, and relative humidity data were generated by the built-in weather generated in the SWAT model. Using a DEM of 30 m resolution (Figure 9), Soil Survey Geographic soils (Figure 10), National Land Cover Dataset 2001 landuse/landcover merged with the BMP areas (Figure 11 and Figure 1); and the Richland-Chambers watershed was delineated into 156 subwatersheds (Figure 12) and further into 3687 HRUs, which are a unique combination of soil, landuse, slope, and land management. Grazing was simulated for 75% of the pastureland and the rest was simulated as hay with 3 cuttings per year. Winterwheat (32%) was the dominant crop followed by corn (30%), sorghum (22%), and cotton (16%). Typical management inputs related to type and dates of tillage, and type, rates and dates of fertilizer were used. Also, 307 PL-566 reservoirs (inclusive of Bardwell, Waxahachie, and Navarro Mills Lakes) (Figure 13) were incorporated into the simulation. The pertinent reservoir data (i.e., surface area and storage at principal and emergency spillways) was lumped within a subwatershed because there were more than one PL-566 reservoir in a subwatershed. These PL-566 reservoirs were simulated as existing in the pre-BMP condition because of their existence during the period considered for model calibration. Except Bardwell, Waxahachie, and Navarro Mills lakes, all PL-566 reservoirs were modeled as ponds in the SWAT model. Reservoir data including the locations and dimensions were obtained from the US Army Corps of Engineers National Inventory of Dams dataset (USACE, 1982).

Table 11: The SWAT model input data type, scale, and source for Richland-Chambers Watershed

Type	**Scale/#**	**Source**
Topography/DEM	1:24,000 (30m resolution)	USGS
Landuse/Landcover	1:24,000	USGS NLCD 2001
Soils	1:24,000	SSURGO
PL-566	307 no.	USDA-NRCS
Weather (Precipitation and Temperature)	10 precipitation stations 8 temperature stations	NWS-NCDC
Land Management	---	County extension agents; Expert opinion

DEM: Digital Elevation Model
NWS-NCDC: National Weather Service-National Climatic Data Center
SSURGO: Soil survey Geographic
USGS NLCD: United States Geological Survey National Landcover Dataset
USDA-NRCS: United States Department of Agriculture-Natural Resources Conservation Service

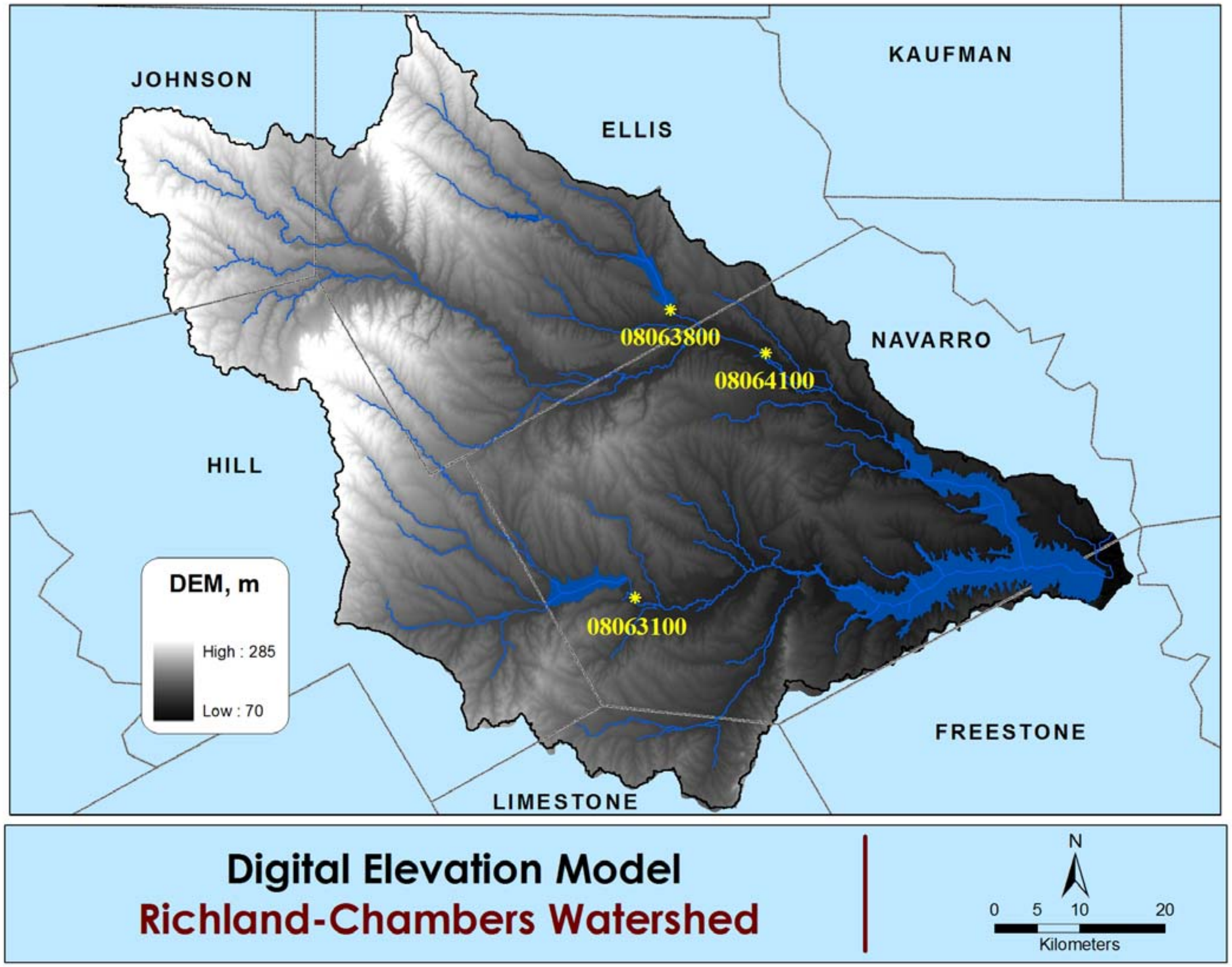


Figure 9: Digital Elevation Model (30 m resolution) of Richland-Chambers Watershed.

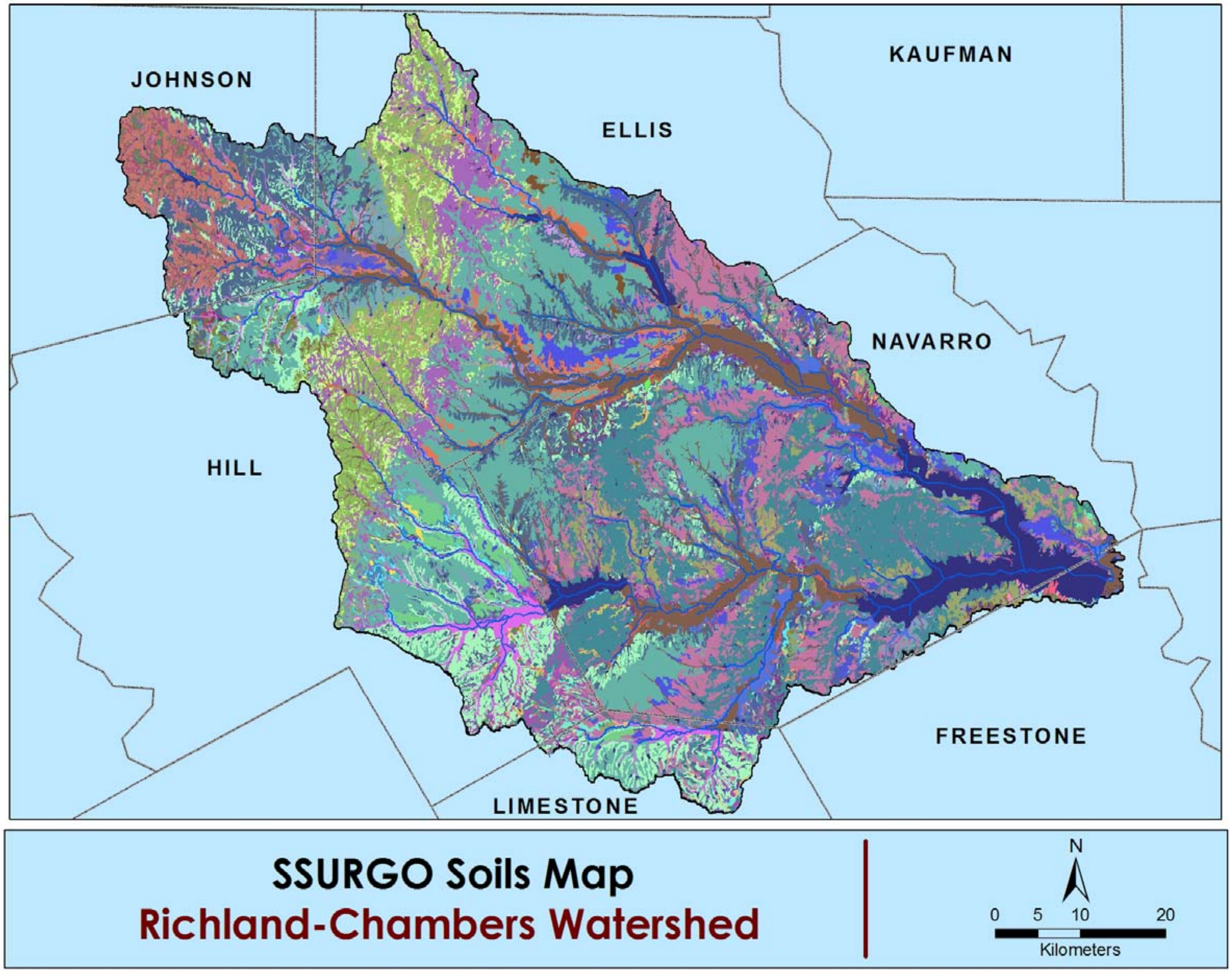


Figure 10: SSURGO Soil map of Richland-Chambers Watershed.

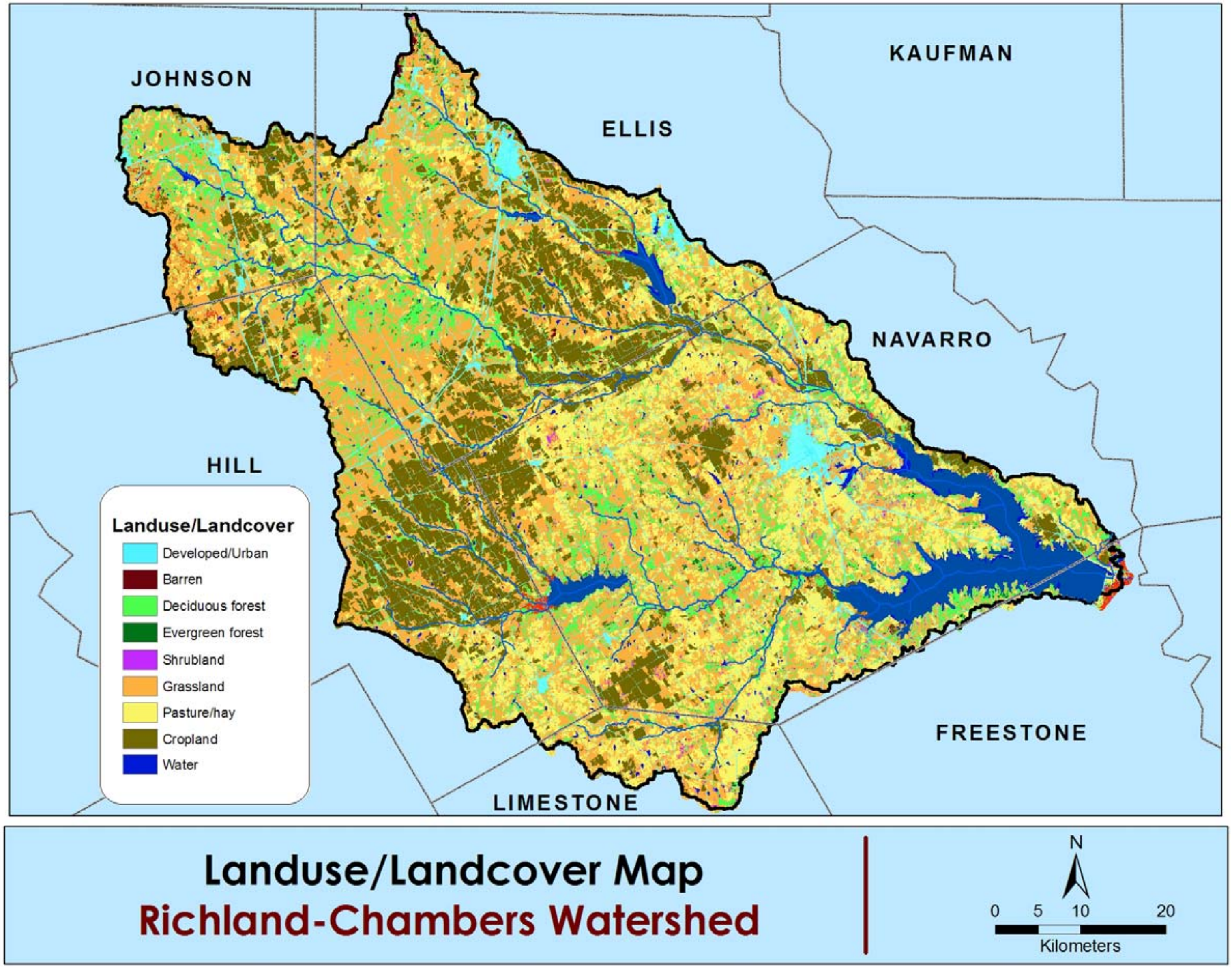


Figure 11: Landuse/Landcover map of Richland-Chambers Watershed.

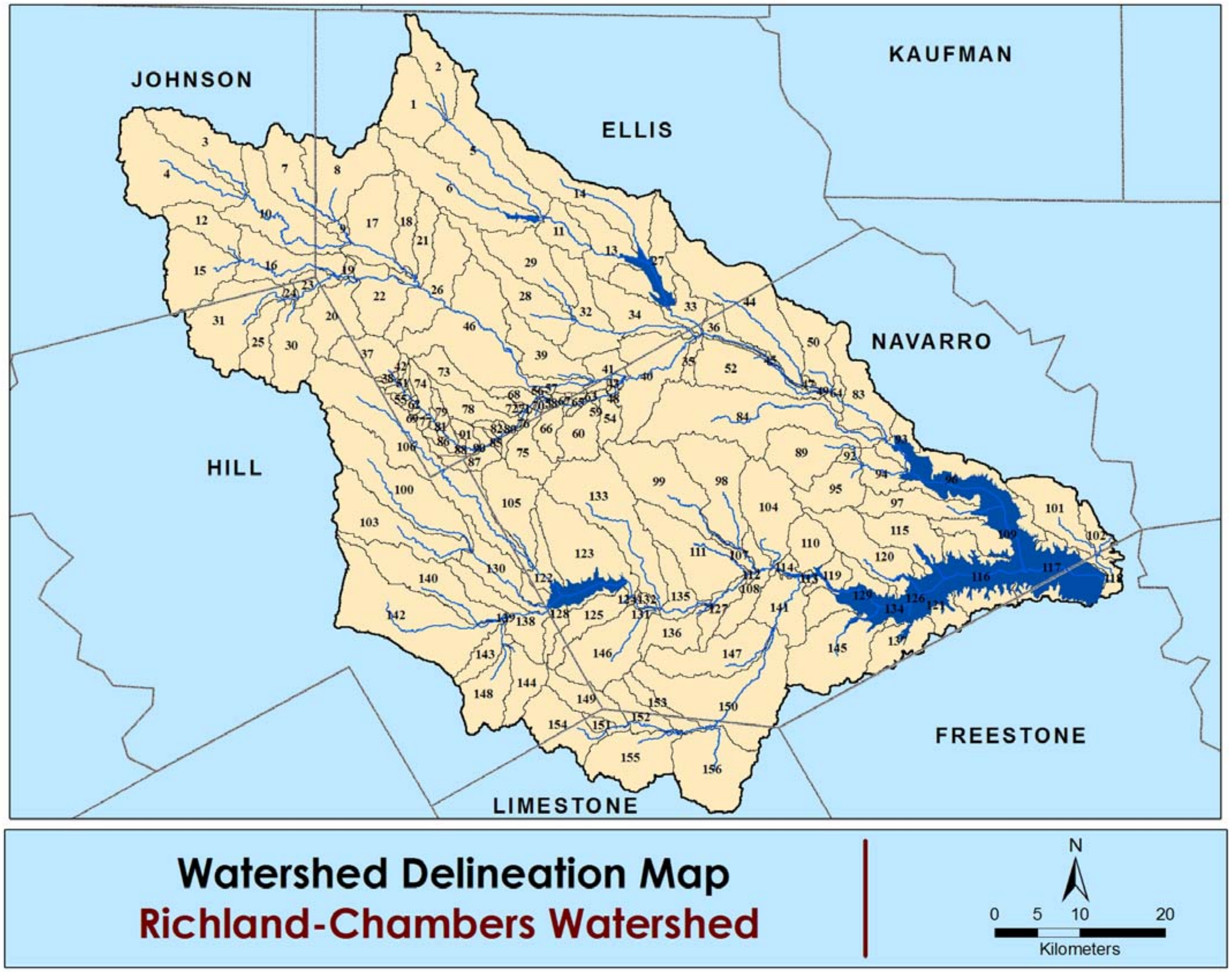


Figure 12: Subwatershed delineation of Richland-Chambers Watershed for SWAT modeling

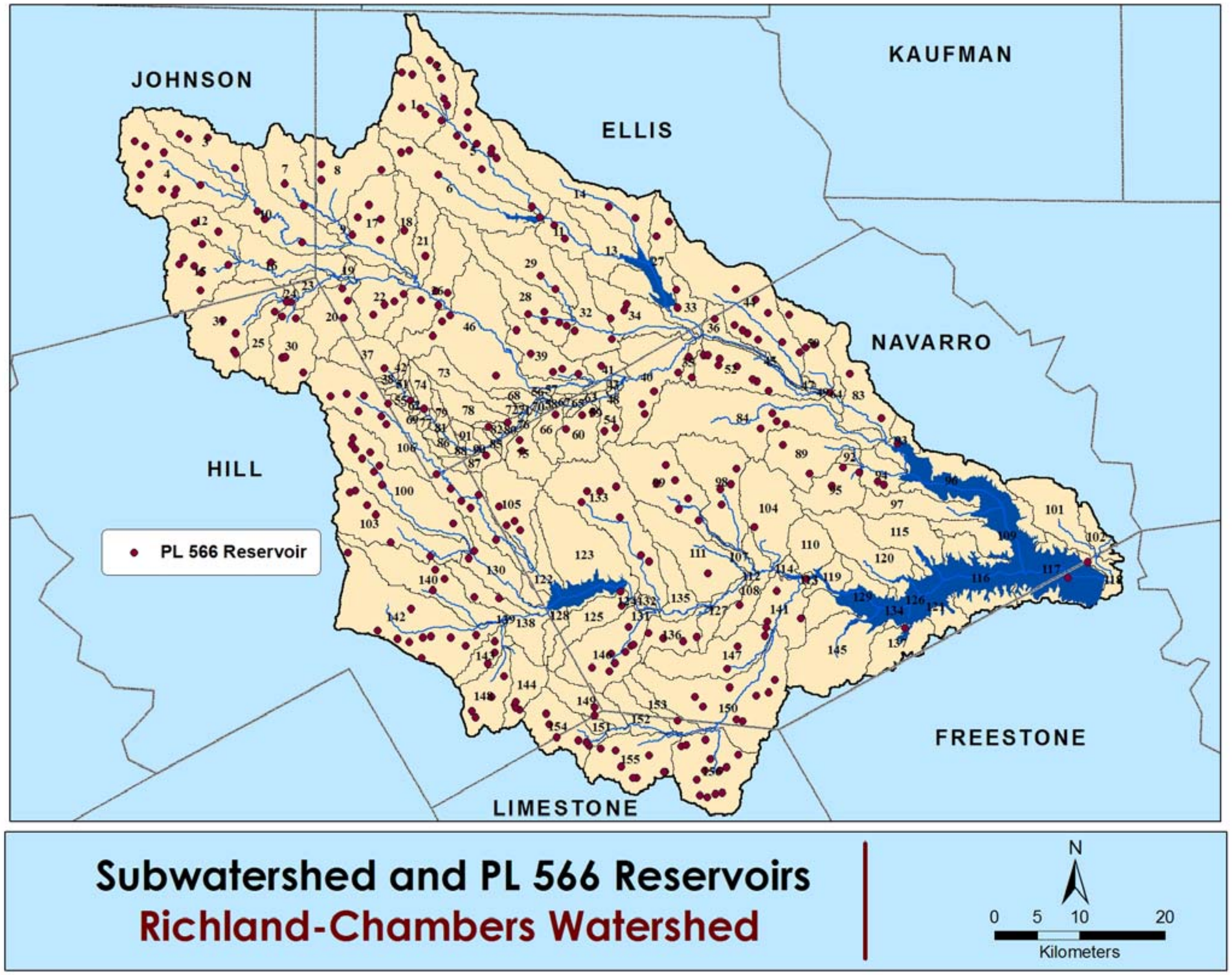


Figure 13: PL-566 reservoirs in Richland-Chambers Watershed.

Calibration and validation

Flow and water quality data from USGS gaging stations and the monitoring stations managed by TRWD (Figure 1) were used to calibrate the SWAT model for flow, sediment, and nutrients. All three USGS gaging stations have long-term continuous records of observed streamflow data. Continuous records of monitoring data for sediment and nutrients are not available for this watershed. However, grab sample data are available for the calibration period (usually 2-5 samples per year, with a few years missing in some cases) at the USGS station 08604100 and all three TRWD monitoring stations. Conservation practices began being implemented in the watershed in 1996. The model calibration and validation approach has been modified to reflect this change in landuse and land management. The model is calibrated for the pre-BMP (up to 1996) and post-BMP (1996 through 2006). The calibration is done at annual and monthly time step for flow at three USGS gaging stations which have long term daily streamflow records from 1982 through 1995, with the first two years as a model warm-up period. During calibration, care was also given to match the proportions of surface flow and baseflow contribution to streamflow. Baseflow contribution to streamflow was analyzed using baseflow filter program (Arnold and Allen, 1999; Arnold et al., 1995, Nathan and McMahon, 1990). A rigorous calibration of sediment and nutrients could not be performed due to limited sampling data. However, certain model parameters were adjusted giving careful consideration to the key upland and channel processes influencing the model simulated pollutant loads.

Mean, standard deviation, coefficient of determination (R^2), and Nash-Sutcliffe modeling efficiency (NSE) (Nash and Sutcliffe, 1970) were used to evaluate model predicted streamflow during calibration and validation. A value greater than 0.75 for NSE can be considered very good; between 0.65 and 0.75 can be considered good while its value between 0.5 and 0.65 is considered satisfactory (Moriasi et al., 2007). Mean simulated flow, and sediment and nutrient loadings for the days that the grab sample data was available were compared with mean observed data. The type, a brief description, range, and the actual value of the variable used for calibration along with the component(s) that the variable influences are listed in table 12.

For validation, estimates on the inflow to the Bardwell Lake and Navarro Mills Lake obtained from Corps of Engineers hydrologic data website (USACE, 2007), and Richland-Chambers Reservoir, obtained from TRWD were used as observed data against which the model simulated streamflow values were compared.

Table 12: Model parameter range and their actual values used for SWAT model calibration

Variable	Model component	Description	Range	Actual value used in this study
CN2	Flow	Initial SCS runoff curve number for moisture condition II	-5 – +5	-4
ESCO	Flow	Soil evaporation compensation factor	0.01 – 1.00	0.55
EPCO	Flow	Plant uptake compensation factor	0.01 – 1.00	1.0
GWQMN	Flow	Threshold depth of water in the shallow aquifer required for return flow to occur	0.0 – 300.0	250
GW_REVAP	Flow	Groundwater revap coefficient	0.02 – 0.40	0.02
C-factor	Sediment	Land surface cover factor	0.003 to 0.45	Corn: 0.2 Cotton: 0.2 Sorghum: 0.2 Wheat: 0.03 Range: 0.007 Pasture: 0.007
SPEXP	Sediment	Exponent parameter for estimating maximum amount of sediment that can be reentrained during channel sediment routing	1.0 – 2.0	1.0
SPCON	Sediment	Linear parameter for estimating maximum amount of sediment that can be reentrained during channel sediment routing	0.0001 – 0.01	0.01
CH_COV	Sediment	Channel cover factor	0.0 – 1.0	0.8
CH_EROD	Sediment	Channel erodibility factor	0.0 – 1.0	0.056 – 0.075
CH_N(2)	Sediment	Channel Manning's roughness coefficient	0.014	0.02
CDN	Mineral nitrogen	Denitrification exponential rate coefficient	0.0 – 3.0	0.3

CMN	Nitrogen and phosphosrus	Rate factor for humus mineralization of active organic nutrients (N and P)	0.0001 – 0.0003	0.0003
NPERCO	Mineral nitrogen	Nitrate percolation coefficient	0.01 – 1.0	0.9
PPERCO	Mineral phosphorus	Phosphorus percolation coefficient	10.0 – 17.5	10
PHOSKD	Mineral phosphorus	Phosphorus soil partitioning coefficient	100 - 400	350
RSDCO	Sediment and nutrients	Residue decomposition coefficient	0.01 – 0.05	0.05
BC2	Nitrogen in reach	Rate constant for biological oxidation of NO2 to NO3 in the reach at 20 ^oC (day^{-1})	0.2 – 2.0	2.0
BC3	Nitrogen in reach	Rate constant for hydrolysis of organic N to NH4 in the reach at 20º C (day^{-1})	0.2 – 0.4	0.3
BC4	Phosphorus in reach	Rate constant for mineralization of organic P to dissolved P in the reach at 20 ^oC (day^{-1})	0.01 – 0.70	0.01
RS4	Nitrogen in reach	Rate coefficient for organic N settling in the reach at 20ºC (day^{-1})	0.001 – 0.1	0.001
RS5	Phosphorus in reach	Organic phosphorus settling rate in the reach at 20 ^oC (day^{-1})	0.001 – 0.1	0.1
AI1	Nitrogen in reach	Fraction of algal biomass that is nitrogen	0.07 – 0.09	0.09
AI2	Phosphorus in reach	Fraction of algal biomass that is phosphorus	0.01 – 0.02	0.01
MUMAX	Nitrogen and phosphorus in reach	Maximum specific algal growth rate (day^{-1})	1.0 – 3.0	1.0

BMP simulation and post-BMP model performance

The model was initially calibrated in pre-BMP conditions. The BMPs simulated include terraces, contour farming, conservation cropping, cropland conversion to pasture, prescribed grazing, range management, brush management, and critical area planting. Certain model parameters were appropriately modified in value (Table 13) to represent the influence of the BMPs on the hydrologic processes. Considering the HWQ processes simulated by SWAT and the watershed subdivision pertaining to this study, these parameters and their values selected were based on published literature and expert opinion. All of these BMPs except cropland conversion to pasture are described in the 'BMPs and their representation in pre-BMP and post-BMP conditions' section in Part II of this report. As the name suggests, agricultural land that was in corn-cotton rotation was converted to pasture with prescribed grazing in the post-BMP condition (Table 13). It was not practical to spatially represent grade stabilization structures, grassed waterways, and farm ponds in the SWAT model because of the spatial scale and HRU being virtual in the SWAT model. These BMPs represent a small section of the reach which was practically unreasonable to represent and simulate them in the model considering the lack of field details of existing practices and subwatershed delineation of this study. For example, the grade stabilization structures were simulated as to affect channel erodibility and channel slope by Bracmort et al. (2006) over two small watersheds of size 6.23 km^2 and 7.3 km^2 within Black Creek watershed in northeast Indiana. These watersheds were small and the subwatershed delineation considered in their study could reasonably represent the characteristics of the grade stabilization structures. Similar is the case with grassed waterways. Almost all subbasins in the Richland-Chambers study had one or more PL-566 reservoirs that were represented as ponds in the model. The addition of farm ponds to already existing PL-566 reservoirs were believed to make insignificant changes in load reduction at the subwatershed/watershed scale and therefore were not considered in the SWAT modeling part of the present study. However, these BMPs were well represented and their effectiveness was assessed using the APEX model described in Part II. As in the pre-BMP calibration and validation, the SWAT model performance was evaluated during the post-BMP analysis for long-term flow from 1996 through 2006 at three USGS gaging stations. Median, 25^{th}, and 75^{th} percentile of simulated sediment and nutrient values at the USGS 08064100, Richland Creek and Chambers Creek stations were compared with observed grab sample data.

Table 13: Model parameters used to represent pre-BMP and post-BMP conditions in SWAT.

BMP	Variable name	Pre-BMP (from calibration)	Post-BMP	Reference
Terrace + Contour	CN2	Varies	CN2 reduced by 6 from the calibration values	Neitsch et al., 2005
	P-factor	1.0	0.12, if slope = 1 to 2% 0.10, if slope = 3 to 8%	Arabi et al., 2008
	SLSUBBSN	Assigned by SWAT	----[a]	
Terrace + Contour + Conservation tillage+ Nutrient management	EFFMIX	0.70 – 0.75	0.25	Neitsch et al., 2005
	CN2	varies	CN2 reduced by 7 from the calibration values	
	P-factor	1.0	0.12, if slope = 1 to 2% 0.10, if slope = 3 to 8%	
	SLSUBBSN	Assigned by SWAT	----[a]	
Contour + Conservation tillage+ Nutrient management	EFFMIX	0.70 – 0.75	0.25	Neitsch et al., 2005
	CN2	varies	CN2 reduced by 7 from the calibration values	
	P-factor	1.0	0.6, if slope = 1 to 2% 0.5, if slope = 3 to 8%	
Ag to pasture with prescribed grazing		Cotton-corn rotation	Pasture with grazing	Neitsch et al., 2005
	CN2	Varies	CN2 reduced by 8 from the calibration values	
	BIO_MIN	500	3000	

Improved pasture with prescribed grazing + Nutrient management	CN2 BIO_MIN	Varies 500	CN2 reduced by 10 from the calibration values 3000 Auto fertilization	Neitsch et al., 2005
Prescribed grazing + Nutrient management	CN2 BIO_MIN	Varies 500	CN2 reduced by 6 from the calibration values 3000 Auto fertilization	Neitsch et al., 2005
Range with prescribed grazing	CN2 BIO_MIN	Varies 500	CN2 reduced by 6 from the calibration values 3000	Neitsch et al., 2005
Brush management	Land management CN2 BIO_MIN	Mesquite Varies 500	Pasture CN2 reduced by 10 from the calibration values 3000	Neitsch et al., 2005
Brush management + Nutrient management	Land management CN2 BIO_MIN	Mesquite Varies 500	Pasture CN2 reduced by 10 from the calibration values 3000 Autofertilization	Neitsch et al., 2005

Critical area planting + Nutrient management	Land management CN2	Barren Varies	Pasture CN2 reduced by 20 from the calibration values Autofertilization

BIO_MIN: Minimum biomass required to allow grazing
CN2: Initial SCS runoff curve number for moisture condition II
EFFMIX: Mixing efficiency of tillage operation
P-factor: Conservation support practice factor
SLSUBBSN: Slope length
[a]: Estimated for each terrace based on SWAT assigned overland slope of the HRU where it is installed
SLSUBBSN = (x * S + y) * 100/S, where S is the average slope of the HRU, x = 0.15, and y = 0.9 (ASAE Standards, 2003)

BMP Evaluation

The calibrated model of the pre-BMP setup was run for 32 years (1975 – 2006, including first two years of warm-up for parameter initialization) to establish the baseline condition. The post-BMP model setup was run for the same 32 years period and the outputs were compared with the outputs from the baseline model setup. The effects of BMP implementation on water quality are presented as percent reductions in average annual sediment, TN, and TP loadings at the HRU level and the watershed outlet. The HRU level percent reductions represent overland load reductions due to BMP implementation. Load reductions at the watershed outlet include cumulative load reductions considering overland transport and routing through the stream network. The percent reduction was calculated as:

$$reduction,\% = \frac{100(preBMP - postBMP)}{preBMP} \quad \text{Eq. (1)}$$

RESULTS AND DISCUSSION

Model Calibration and Validation

Calibration results for measured and simulated annual and monthly flow data for the three USGS gaging stations is presented in table 14. The absolute percent difference between measured and simulated flows at annual and monthly time steps was up to 4%. The model performance was considered very good with both R^2 and NSE being ≥0.90 at USGS gaging stations 08064100 and 08063100 and was satisfactory at the USGS gaging station 08063800, based on the rating of Moriasi et al. (2007).

Table 14: Summary of model performance statistics for flow at the USGS gaging stations during calibration in the pre-BMP period (1984-1995)

Station	Time-step	Mean		Std. Dev		R^2	NSE
		Measured	Simulated	Measured	Simulated		
08064100							
	Annual	14.66	14.3	5.87	5.95	0.94	0.93
	Monthly	14.69	14.33	19.85	16.66	0.91	0.90
08063100							
	Annual	5.73	5.79	2.96	3.22	0.99	0.98
	Monthly	5.74	5.83	7.97	8.14	0.98	0.98
08063800							
	Annual	3.39	3.54	1.70	1.81	0.63	0.55
	Monthly	3.40	3.54	5.21	4.07	0.67	0.44

Due to the non-availability of water quality data at the USGS stations 08063100 and 08063800, only data from station 08064100 was used to calibrate the model for sediment and nutrients. Additionally, the TRWD monitoring stations on Richland Creek and Chambers Creek have limited numbers of grab sample data on sediment and nutrients and were also used to compare the SWAT model predicted values. At the USGS station 08064100, the model simulations of sediment, organic nitrogen, and mineral nitrogen were closer to the observed values (within 4%) whereas simulated means of mineral and TP were higher because of large over prediction by the model on a few days (Table 15). The model over predicted almost all constituents at the TRWD monitoring stations on Richland and Chambers Creeks (Figure 14). Due to the limited sampling data, matching the daily simulated values with the observed values considering only those days of observation was tedious. Additional monitoring data would be very helpful to adequately calibrate and validate the model predicted loadings.

Table 15: Summary of model performance statistics for water quality at the USGS gaging station #08064100 during calibration in the pre-BMP period (1984-1995)

Component (unit)	**# of samples**	**Mean**		**Std. dev.**	
		Measured	Predicted	Measured	Predicted
Sediment (t)	37	1541.50	1487.00	3249.40	1865.38
Organic N (kg)	91	1762.30	1735.00	5354.30	14276.00
Mineral N (kg)	41	3367.00	3256.00	7488.00	3.38
Mineral P (kg)	41	50.00	64.31	104.70	135.45
Total P (kg)	91	443.00	800.00	2041.00	4482.00

The model performance statistics were calculated comparing the SWAT simulated inflow and measured/estimated inflow to Lake Bardwell, Navarro Mills Lake and Richland-Chambers Reservoir during validation in the pre-BMP period is summarized in table 16. The model simulated cumulative inflow to Richland-Chambers was less than estimated (by TRWD) value by 1.3% (Figure 15). The simulated sediment load into the Richland-Chamber Reservoir was less than the estimated value by 14%.

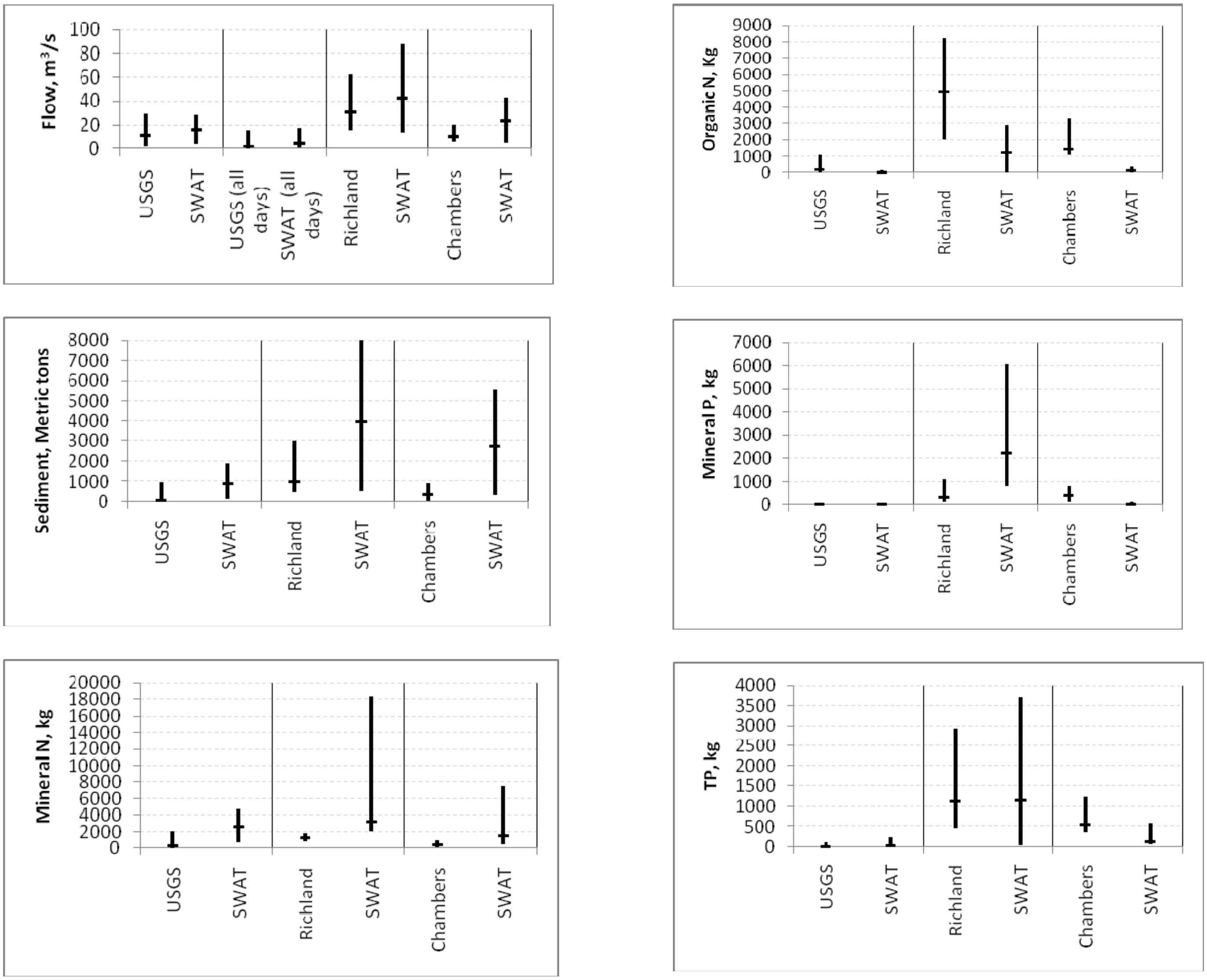


Figure 14: Measured and simulated streamflow, sediment, mineral nitrogen (mineral N), organic nitrogen (organic N), mineral phosphorus (mineral P), and total phosphorus (TP) (median, 25th percentile, and 75th percentile) at USGS 08064100, Richland Creek, and Chambers Creek monitoring stations during pre-BMP calibration (1984-1995).

Table 16: Summary of SWAT model performance statistics of simulated versus measured inflow to the reservoirs during validation in the pre-BMP period (1984-1995)

Location	Time-step	Mean		SD		R^2	NSE
		Measured	Simulated	Measured	Simulated		
Richland-Chambers Reservior (1987-1995)							
	Annual	40.82	39.42	13.30	15.14	0.80	0.73
	Monthly	41.73	39.53	43.56	42.22	0.87	0.85
Bardwell Reservoir (1991-1995)							
	Annual	5.00	4.98	0.55	1.00	0.98	0.94
	Monthly	4.91	4.91	5.52	4.54	0.76	0.76
Navarro Mills Reservoir (1984-1995)							
	Annual	6.74	5.10	2.52	2.05	0.78	0.59
	Monthly	6.79	5.25	9.21	5.56	0.74	0.65

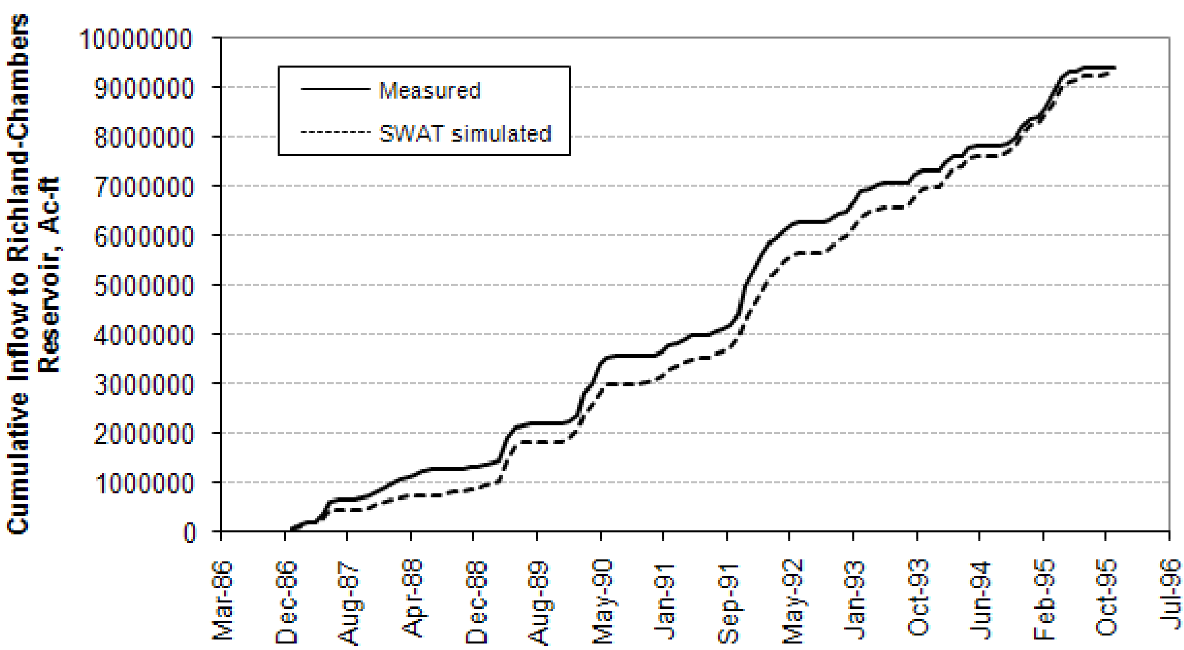


Figure 16: Monthly cumulative measured versus SWAT simulated flow into the Richland-Chambers Reservoir during the pre-BMP validation (1984-1995).

Post-BMP model performance analysis

The absolute percent difference between measured and simulated flows at annual and monthly time steps were up to 11%. The model performance was considered very good with both R^2 and NSE being ≥0.81 at USGS gaging stations 08064100 and 08063100 and was satisfactory at the USGS gaging station 08063800 (Table 17). The model performance statistics calculated comparing the SWAT simulated inflow and measured/estimated inflow to Bardwell, Navarro Mills and Richland-Chambers is summarized in table 18. The model simulated cumulative inflow to Richland-Chambers was less than estimated (by TRWD) value by 3.6% (Figure 16).

Contrary to the modeled results during the pre-BMP calibration at USGS station 08064100, during the post BMP period, the model simulated mineral and TP mean values were closer to the observed values whereas simulated means of sediment and mineral nitrogen were higher and simulated mean of organic nitrogen was lower than the observed value. Considering the model performance at Richland and Chambers Creek stations, it under predicted almost all constituents except sediment and mineral nitrogen at the Chambers Creek station (Figure 17).

Table 17: Summary of model performance statistics for flow at the USGS gaging stations during post-BMP period (1996-2006)

Station	Time-step	Mean		SD		R^2	NSE
		Measured	Simulated	Measured	Simulated		
08064100							
	Annual	10.30	11.51	8.32	7.03	0.84	0.81
	Monthly	10.35	11.56	17.18	14.88	0.85	0.84
08063100							
	Annual	3.95	3.63	3.44	3.12	0.99	0.97
	Monthly	3.97	3.68	7.87	7.33	0.99	0.98
08063800							
	Annual	2.54	2.81	1.93	1.42	0.67	0.64
	Monthly	2.54	2.82	4.71	3.31	0.64	0.40

Table 18: Summary of SWAT model performance statistics of simulated versus measured inflow to the reservoirs during post-BMP period (1995-2006)

Location	Time-step	Mean		SD		R^2	NSE
		Measured	Simulated	Measured	Simulated		
Richland-Chambers Reservoir (1996-2006)							
	Annual	27.02	27.36	19.71	17.19	0.93	0.92
	Monthly	27.17	27.48	41.35	36.82	0.92	0.92
Bardwell Reservoir (1996-2005)							
	Annual	3.51	2.36	2.17	1.26	0.96	0.48
	Monthly	3.57	2.41	4.89	2.96	0.88	0.71
Navarro Mills Reservoir (1996-2005)							
	Annual	4.71	4.33	3.39	2.76	0.97	0.92
	Monthly	4.73	4.24	7.44	5.54	0.83	0.80

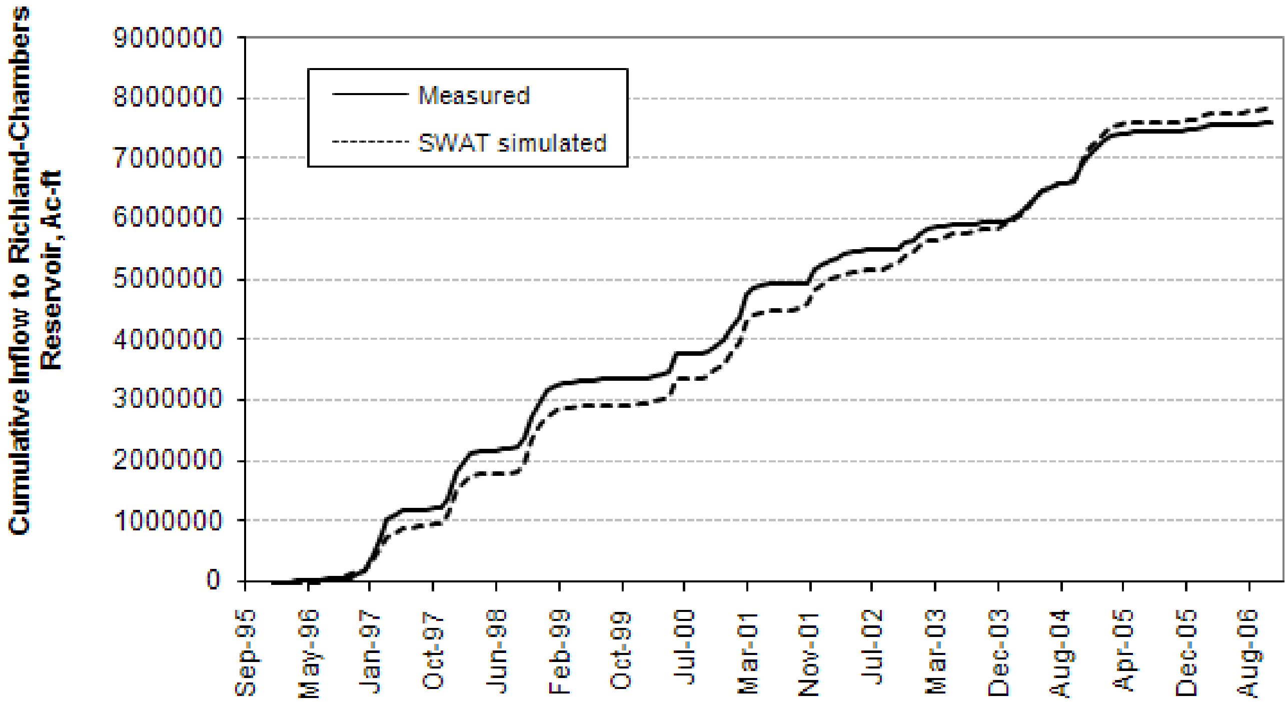


Figure 17: Monthly cumulative measured versus SWAT simulated flow into the Richland-Chambers Reservoir (1996-2006).

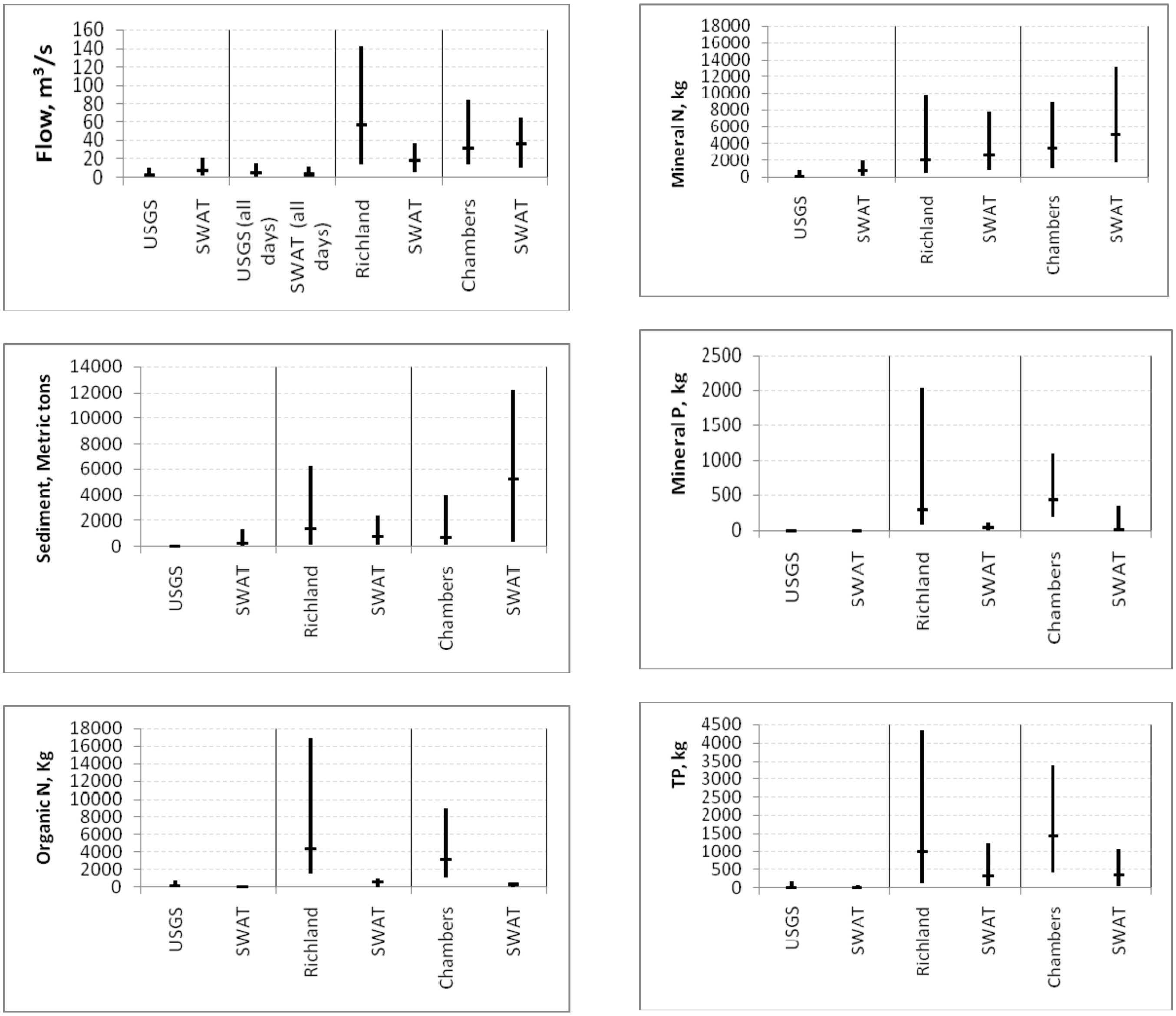
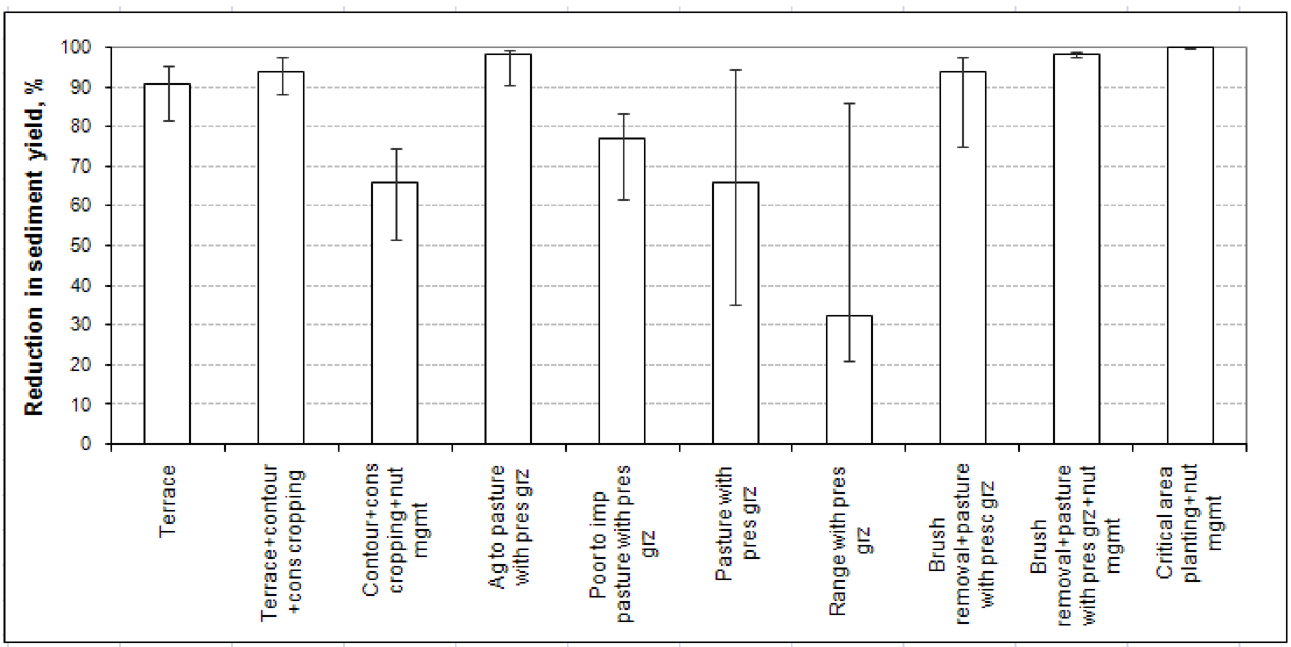


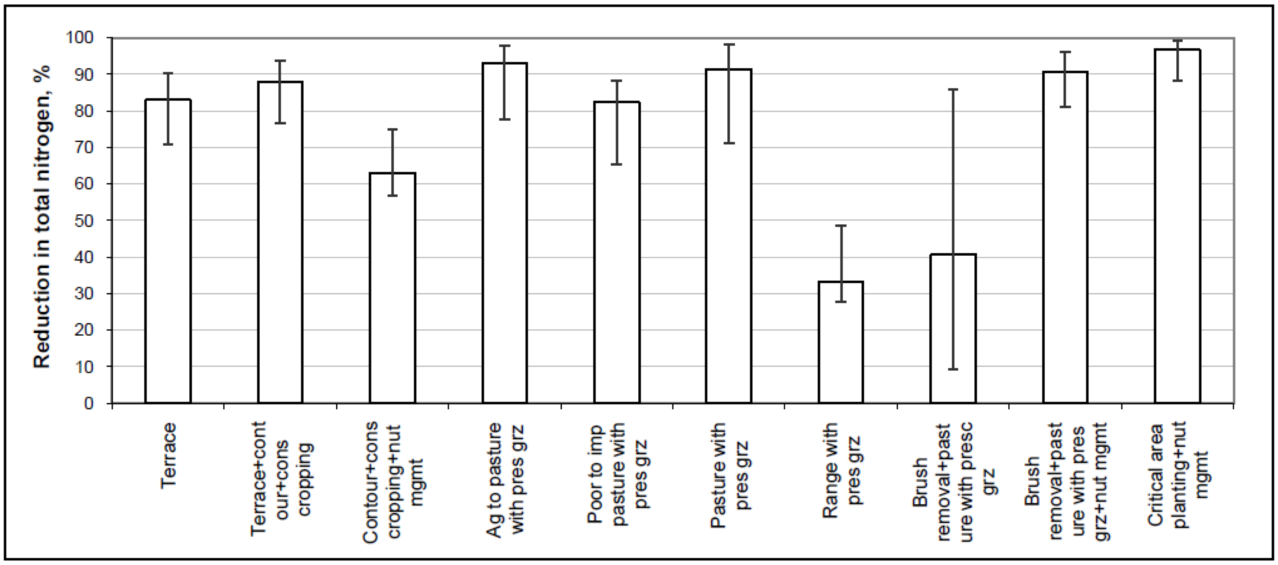
Figure 18: Measured and simulated streamflow, sediment, mineral nitrogen (mineral N), organic nitrogen (organic N), mineral phosphorus (mineral P), and total phosphorus (TP) (median, 25th percentile, and 75th percentile) at USGS 08064100, Richland Creek, and Chambers Creek monitoring stations during post-BMP (1996-2006).

Each of the BMPs simulated were implemented in more than one HRU. Considering all the HRUs on which one type of BMP was implemented we get a range in pollutant reduction because of the variability in soils, slope, and weather. The distribution (mean, minimum, and maximum) in pollutant (sediment, TN, and TP) reduction due to each type of BMP is illustrated in figures 18a, b, and c. Among all the BMPs simulated, critical area planting produced the greatest reduction in sediment (99.8%) and TN (96.7%). Cropland conversion to pasture and brush removal followed by pasture planting with prescribed grazing and nutrient management were also highly effective in reducing sediment yield, TN, and TP at the HRU level. Without the field data on production practices for nutrient management, it was simulated by using the automatic fertilization option in SWAT wherein amount of each application and maximum amount that could be applied in a given year. A significant effectiveness of nutrient management can be noticed between brush removal practice (followed by pasture planting with prescribed grazing) with and without nutrient management (Figure 18). With nutrient management, reduction in TN increased from 41% to 91% and reduction in TP increased from 20% to 61%. Range management with prescribed grazing produced the modest, nevertheless significant, reductions in sediment (32%), TN (33%), and TP (30%).

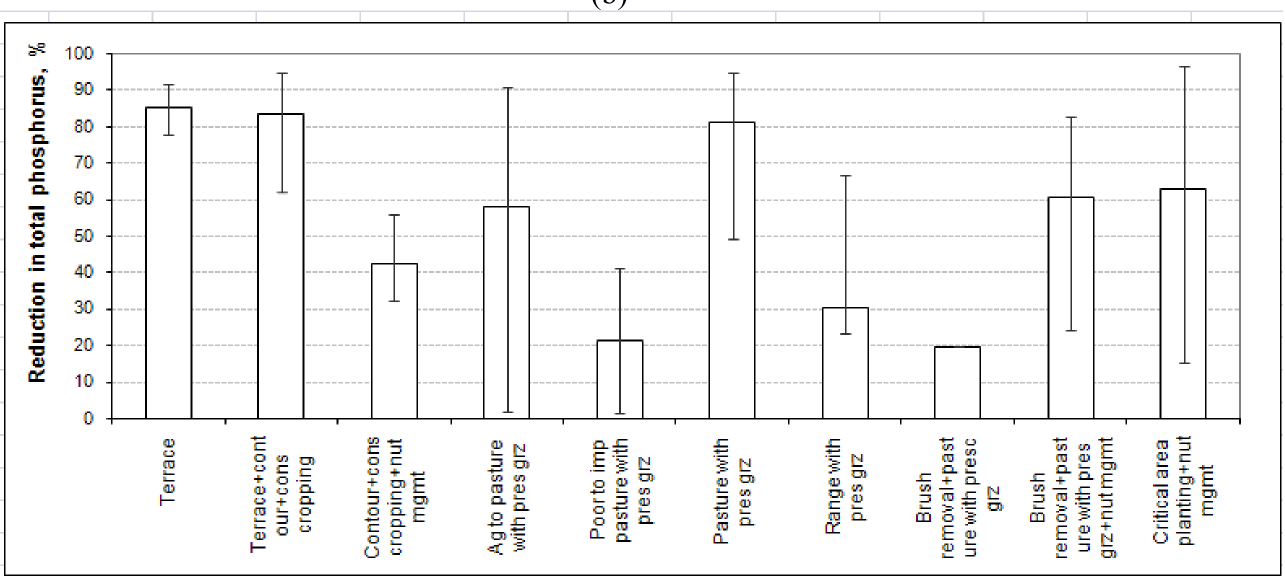
Collectively, these BMPs resulted in 1%, 2%, and 3% reduction in sediment, TN, and TP, respectively at the watershed level.



(a)



(b)



(c)

Figure 19: HRU average load (bars) and range (minimum-maximum represented by the line through the bars) in pre- and post-BMP conditions, considering only BMP HRUs: (a) Sediment, (b) Total nitrogen, and (c) Total phosphorus.

CONCLUSIONS

The SWAT model was used to simulate and assess the HWQ impacts of several BMPs in Richland-Chambers watershed. The BMPs simulated included terraces, conservation cropping, pasture planting, nutrient management, prescribed grazing, brush management, and critical area planting. In general, the BMPs achieved significant reductions at the HRU level. Average annual reduction in sediment ranged from 32% to 99.8%, TN ranged from 33% to 97%, and TP ranged from 20% to 85%. At the watershed outlet, the reductions in sediment, TN, and TP achieved by the BMPs were 1%, 2%, and 3% respectively. The lower reductions due to BMPs at the watershed level are expected and reasonable due to the fact that the area of BMP implementation is only about 6% of the watershed area.

The modeling approach to assess the BMP effectiveness demonstrated in this project will provide scientific information to make recommendations for future BMP implementation. Additional monitoring data on flow and water quality would be of great use to calibrate and validate the model predicted pollutant loadings. Identifying and optimizing the location of BMPs for future implementation and cost-economic analysis is recommended to obtain maximum bank-for-the-buck.

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PUBLICATIONS

Part I and Part II in this report have been published in peer-reviewed journals and Part III is published in a conference proceedings. The citations are given below.

- Pushpa Tuppad, C. Santhi, and R. Srinivasan. 2009. Assessing BMP effectiveness: Trend analysis of observed water quality data. *Environmental Monitoring and Assessment*, DOI 10.1007/s10661-009-1235-8. (Published online 20 November, 2009).

- Pushpa Tuppad, C. Santhi, J. R. Williams, R. Srinivasan, X. Wang, and P. H. Gowda. 2009. Simulation of conservation practices using APEX model. *Applied Engineering in Agriculture* (In Press).

- Pushpa Tuppad, Santhi Chinnasamy, and Raghavan Srinivasan. Modeling environmental benefits of conservation practices in Richland-Chambers watershed, TX. (Oral). *In Proceedings of 2009 5th International SWAT Conference*, August 3-7, 2009, Boulder, Colorado, USA. Available at http://twri.tamu.edu/reports/2009/tr356.pdf

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