Modeling of Agricultural BMP Scenarios in the Paw Paw River Watershed using the Soil and Water Assessment Tool (SWAT)

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1. Introduction

In 2005, the St Joseph River Watershed Management Plan (DeGraves, 2005) listed the Paw Paw River Watershed as a critical area for preservation and protection because of its biodiversity. The Paw Paw River Watershed was modeled as part of the St Joseph River WMP but the model lacked details because of the large size of the St Joseph River Watershed. Data used did not specifically relate to the Paw Paw River Watershed. The efforts reported here model conditions specific to the Paw Paw River Watershed using recent and locally available data. This report also quantifies the impact of selected agricultural best management practices on water quality as required by the United States Environmental Protection Agency (US EPA).

The US EPA recently issued new requirements for watershed management plans funded through Section 319 grants. These requirements call for additional quantification of pollutant loads in order to focus management efforts and implementation practices where they will provide the greatest pollutant load reductions. The US EPA supports the use of water quality models to satisfy the load quantification requirements in the development of a watershed management plan (US EPA, 2005). In part, the US EPA developed "BASINS" (Better Assessment Science Integrating point and Nonpoint Sources), a multipurpose analytical tool that integrates environmental databases and water quality models in a geographic information systems (GIS) framework. The Soil and Water Assessment Tool (SWAT), one of the models included in BASINS 3.1, was selected for this study due to its ability to simulate agricultural best management practices. The model was used to assess sediment and nutrient loads for 36 subwatersheds within the Paw Paw River Watershed, and to predict load reductions under selected agricultural best management practices (BMP) scenarios.

SWAT is a continuous time, watershed-scale model developed by the USDA Agricultural Research Service. SWAT was developed to predict the impact of land management practices on water, sediment and agricultural chemical yields in large complex watersheds with varying soils, land use and management conditions over long periods of time (Neitsch et al., 2002a). In the last ten years, SWAT has been used extensively in the United States for TMDL development and watershed management planning. It is also widely accepted as an effective water quality modeling tool.

2. SWAT Model Preparation

The SWAT model simulates a number of climate, hydrological, erosion, plant and pollutant processes and requires, at a minimum, topography, land use and soils data. However, additional data, such as local management practices and point source loadings, will increase the accuracy of modeling predictions. The best available local and national data were input into the model for use in the Paw Paw River Watershed. These inputs are described as follows.

2.1. Data inputs

a) Base GIS layers

BASINS 3.1 provides a powerful data download interface that will mosaic, re-project and clip data layers to the selected watershed boundary. The following layers were downloaded through the BASINS interface:

- USGS National Elevation Dataset (NED): this layer gives topographic information on a 30-m resolution.
- USGS National Hydrography Dataset (NHD), which provides the stream network for the Paw Paw River Watershed.

These two GIS layers were processed using BASINS to delineate subwatersheds for the Paw Paw River Watershed. Subwatersheds are the main units used in SWAT to summarize load results and determine target BMP areas. Jha et al. (2004) have demonstrated that, to adequately predict nutrient and sediment loads, threshold subwatershed areas should be on average about 2 to 5% of the total watershed area. In total, 36 subwatersheds were therefore delineated (Figure 1) for the Paw Paw River Watershed application.

The most recent land use layer available was the 2001 Lower Peninsula IFMAP layer[1]. This dataset, provided by the Michigan Department of Natural Resources, has a 30-m resolution and classifies land use into 35 categories derived from analysis of Landsat TM imagery. This layer was re-classified according to SWAT's broader land use categories.

The State Soil Geographic (STATSGO) database, included in BASINS, was overlaid with the land use layer to create Hydrologic Response Units (HRUs). HRUs, the smallest modeling unit used in SWAT, correspond to a unique combination of soil and land use. Modeling accuracy increases when subwatersheds are modeled with multiple HRUs (Haverkamp et al., 2002). A threshold value set at 13% (i.e., any land use or soil area representing less than 13% of a subwatershed surface area is not modeled) resulted in at least two HRUs per subwatershed. In total, 136 HRUs were created in the watershed (Appendix A).

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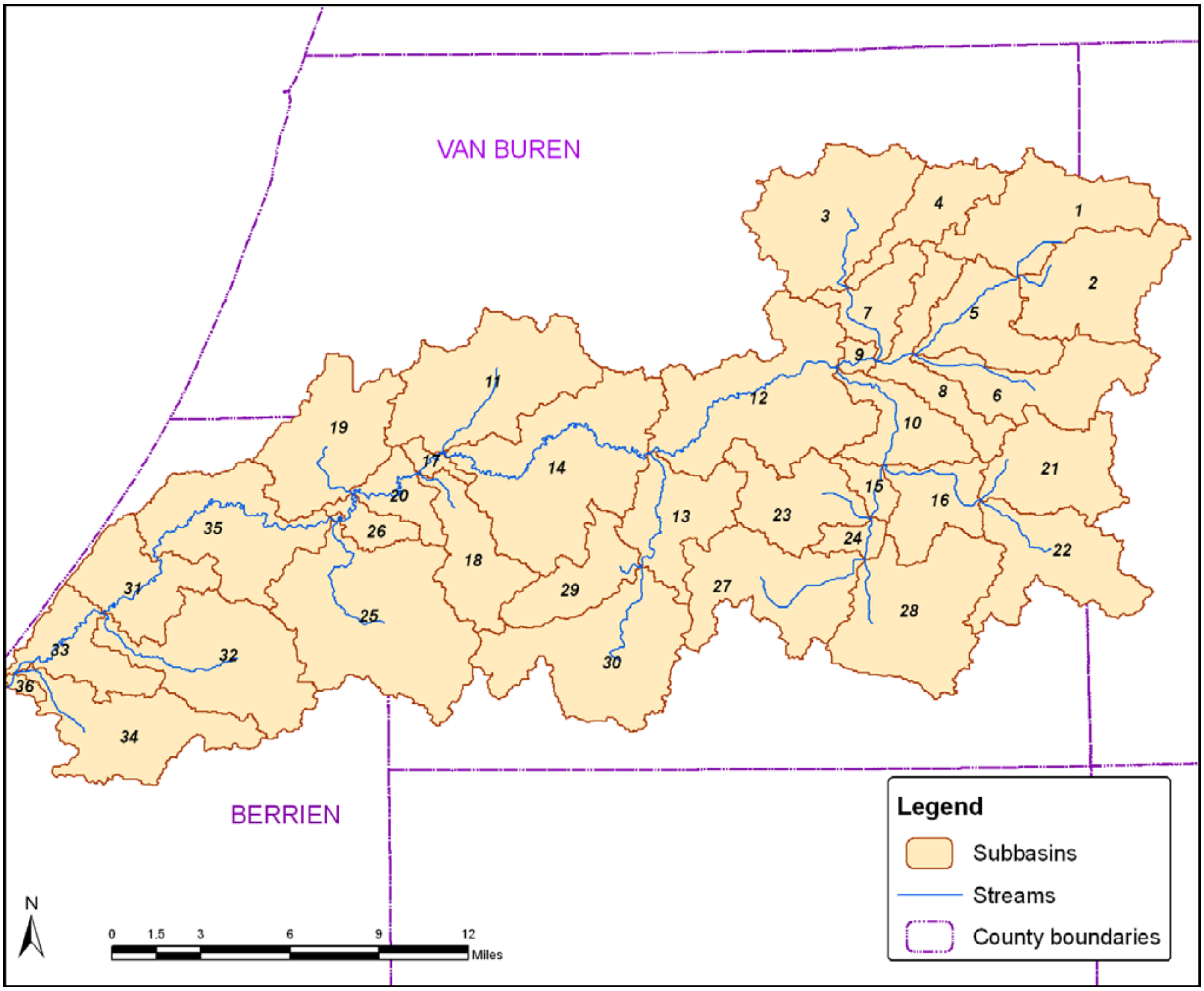
[1] Available from the Michigan Geographic Data Library (http://www.mcgi.state.mi.us/mgdl/)

Figure 1: Subwatersheds as delineated by BASINS.



b) *Additional Data Input*

Local climate data are required for accurate model simulation. While SWAT has the ability to generate climatic data through its Weather Generator model, it is preferable to input daily temperature and precipitation values from local weather stations. Temperature and precipitation data from three gages (Berrien Springs, Bloomingdale and South Haven) for a 19-year period of record (1986 to 2004) were added to SWAT. Solar radiation, wind speed and relative humidity were simulated. It should be noted here that no weather station was located directly within the Paw Paw River Watershed (see Figure 2). This fact may have affected to some extent modeling results.

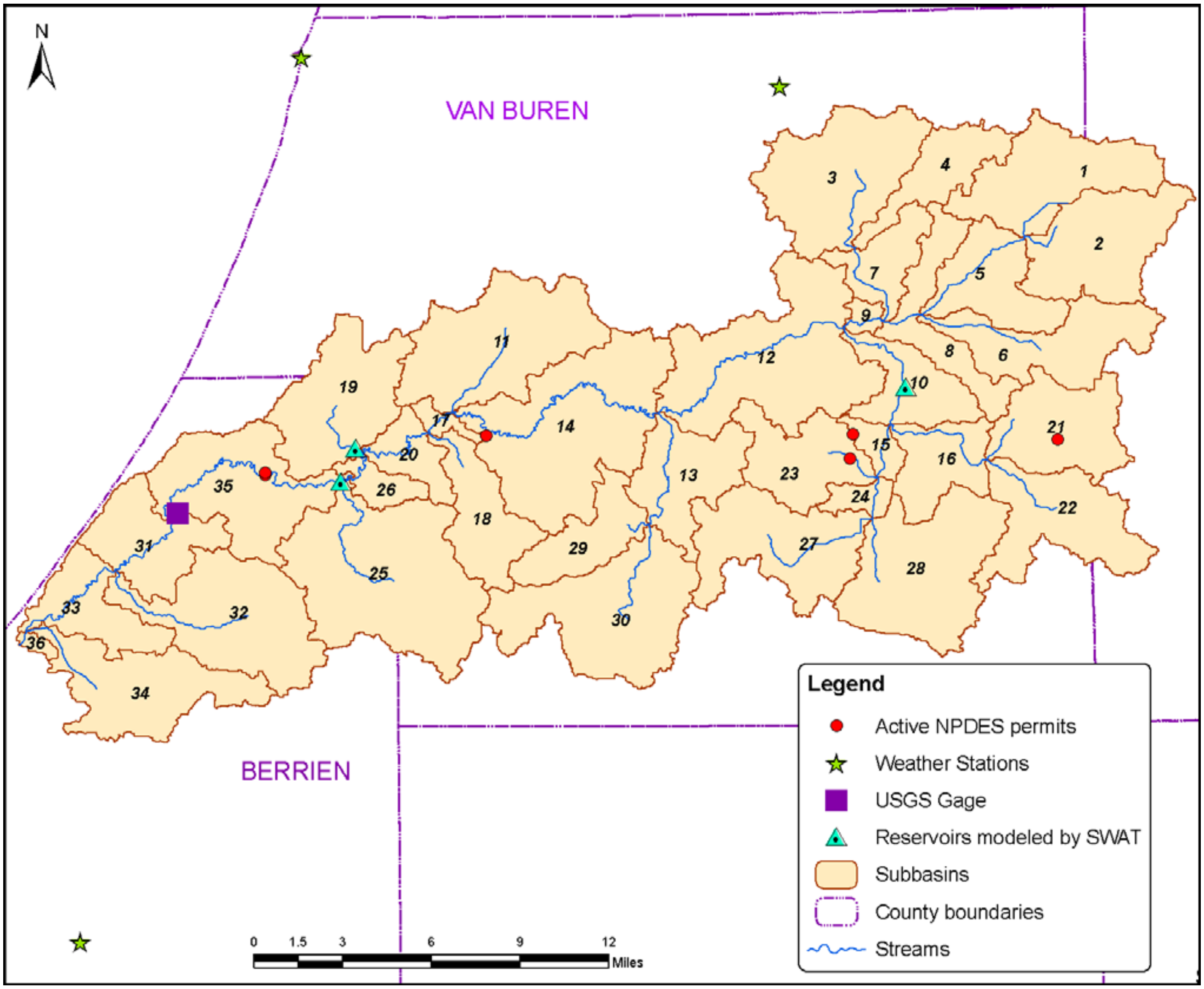
Point source discharge data were obtained from the US EPA Envirofact website (http://www.epa.gov/enviro/index.html). Only five point sources were found to have active NPDES permits in the watershed: Coca Cola Paw Paw/Minute Maid (MI0056367), Paw Paw WWTP (MI0021741), MDNR Wolf Lake Hatchery (MI0035734), Hartford WWTP

(MI0023094), and Paw Paw Lake Area WWTP (MI0023779). These point sources were used in the model.

A dam dataset available in the previous BASINS version, and used in the St Joseph River WMP, was used in this model application with updates provided by the SWMPC. Impoundments located on the main stream network are defined as reservoirs by SWAT, while impoundments located elsewhere in a subwatershed are defined as ponds. Therefore, reservoirs were modeled in three subwatersheds and ponds were modeled in 14 subwatersheds.

SWAT allows detailed inputs of agricultural practices which are key to an appropriate simulation of baseline conditions and BMP scenarios. Interviews with Van Buren's MSU Extension Agents for crops and for orchards provided local information on crop rotation, crop location, fertilizer applications, and management practices being implemented in the watershed. These data were incorporated as much as possible into appropriate subwatersheds based on information received.

Figure 2: Weather stations, point sources, USGS gage and reservoirs in the Paw Paw River Watershed.



2.2. SWAT Model Calibration

a) *Flow calibration and validation*

Standard calibration procedures were followed as detailed in the SWAT 2000 manual (Neitsch et al., 2002b). First, simulated flow at the outlet of subwatershed #35 was calibrated using recorded flow data from USGS gage station # 04050001 (Paw Paw near Riverside): the only gage station in the watershed with data available for the simulation period. This gage reflects the drainage of 88% of the total watershed area.

Surface runoff was modeled using the daily curve number (CN) method while potential evapotranspiration was modeled using the Priestley-Taylor method. These methods were used in the SWAT modeling of the St Joseph River (DeGraves, 2005) and are considered appropriate for the Paw Paw River Watershed. An automated baseflow filter program (Arnold and Allen, 1999) was used to determine the value of the groundwater baseflow parameter (ALPHA_BF).

The model calibration was performed over a six-year period (1991-1996), while allowing the first year (1990) for model equilibration. Table 2 lists the model parameters that were adjusted during calibration. The model's simulated flow data are shown in comparison to USGS flow records in Figure 3. Overall, the mean simulated monthly flow data were within 8% of the mean observed flow for the period. The calibration was considered adequate with the Nash-Sutcliffe efficiency coefficient (measure of the goodness-of-fit between observed and simulated values) close to 0.7 (Table 1).

Table 1: Flow calibration statistics.

	Average flow rate (m3/sec)	**R^2**	**RMSE**	**E_{NS} ***
Calibration period (1991-1996)				
Simulated (observed)	15.12 (14.02)	0.76	2.40	0.68
Validation period (1997-2004, excluding period 06/1999 to 12/2001)				
Simulated (observed)	12.86 (12.17)	0.74	2.92	0.63

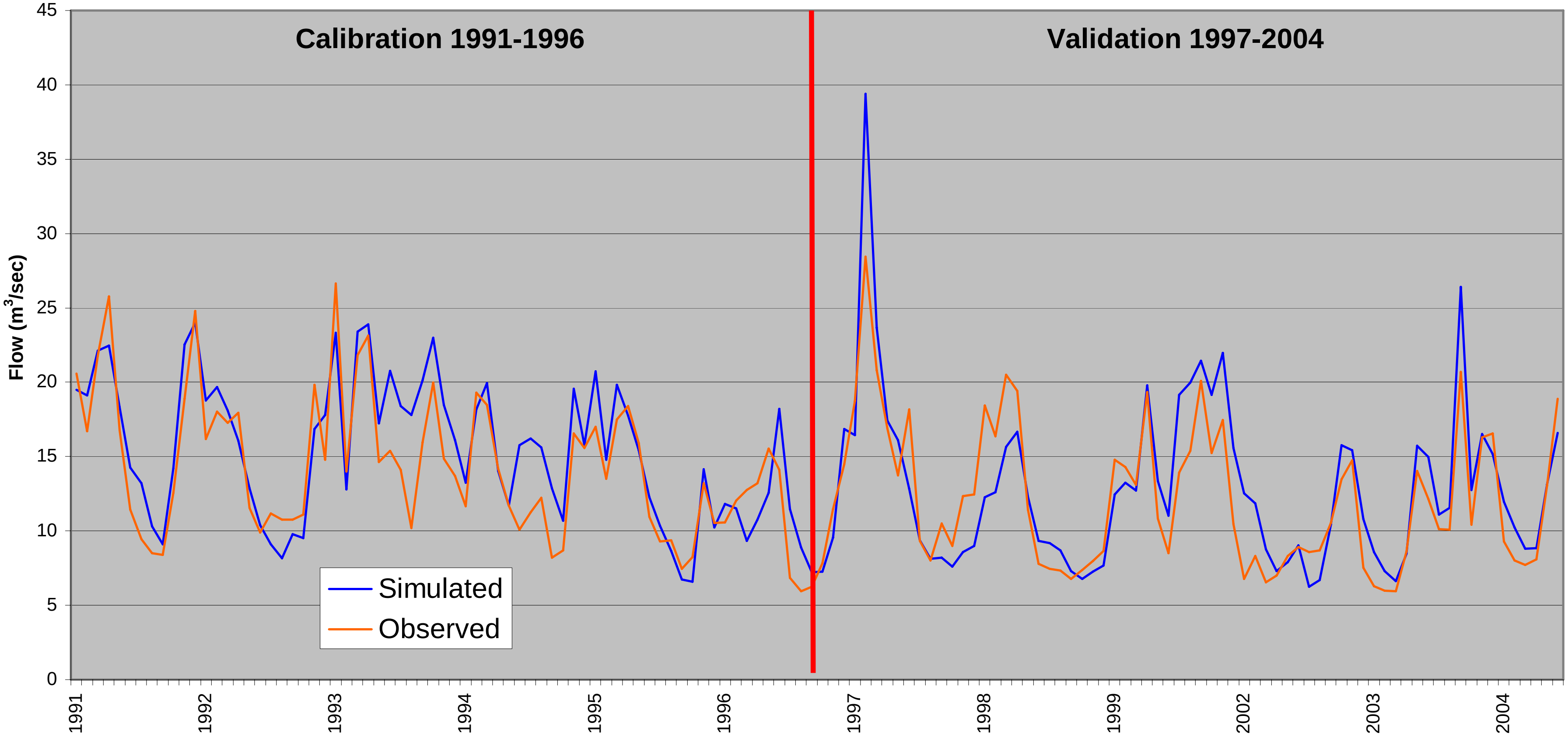
* Nash Sutcliffe efficiency coefficient: values ≥ 0.50 are generally accepted as adequate (Santhi et al., 2001)

Model validation was conducted using flow data from the same USGS gage used in the calibration phase. Validation was performed for the period from 1997 to 2004, with results from July 1999 to June 2001 removed due to missing precipitation and temperature data from South Haven Weather Station. Validation results (Table 1) were similar to calibration results, with mean monthly simulated flow within 6% of mean observed monthly flow.

Table 2: SWAT parameters changed for flow and nutrient calibration.

Parameters changed	Description	Variation allowed (default value)	Actual value used/change used
Streamflow calibration			
CN2	Curve number	+/- 8	-8
ESCO	Soil evaporation compensation factor	0.00 to 1.00 (0.95)	0.5
CANMX	Maximum canopy storage	0.000 to 100.000	2.5 (Wu et al., 2006)
SMTMP	Snowmelt base temperature	-5.0 to 5.0 (0.5)	0.8
SMFMN	Melt factor for snow on Dec. 21	0.00 to 10.00 (4.5)	0.90
SMFMX	Melt factor for snow on June 21	0.00 to 10.00 (4.5)	2.75
SURLAG	Surface runoff lag coefficient	1.0 to 24.0 (4.0)	1.0
GW_DELAY	Groundwater delay time	0 to 500 (31)	10 to 235 depending on soil types
ALPHA_BF	Baseflow alpha factor	+/- 25% (0.0114)	0.0108
REVAPMN	Threshold depth of water for "revap"	0 to 500 (0)	150
SOL_AWC	Soil available water capacity	+/- 0.04 (varies)	-0.03
BLAI	Maximum potential leaf area index		Forest Corn
Sediment calibration			
USLE_P	USLE Equation support practice factor	0 to 1 (1)	1
SLOPE	Average slope steepness	+/- 25% (varies)	+15%
SLSUBBSN	Average slope length	+/- 25% (varies)	+15%
APM	Peak rate adjustment factor for sediment routing in the subbasin (tributary channels)	0.5-2.0 (1.0)	1.2
SPCON	Linear parameter for calculating the maximum amount of sediment that can be reentrained during channel sediment routing	0.001-0.01 (0.001)	0.01
SPEXP	Exponent parameter for calculating sediment reentrained in channel sediment routing	1.0-1.5 (1.0)	1.5
Nutrient calibration			
PPERCO	Phosphorus percolation coefficient	10.0 to 17.5 (10)	12
BIOMIX	Biological mixing efficiency	0 to 1 (0.2)	0.4
PHOSKD	Phosphorus soil partitioning coefficient	100 to 200 (175)	175
SOL_LABP	Initial organic P concentration in soil layer	0-100	50 (Row crops) 25 (Orchards)
SOL_ORGP	Initial organic P concentration in soil layer	0-4000	125 (Row crops) 60 (Orchards)

Figure 3: Comparison of SWAT simulated monthly flow and observed flow data (USGS #04050001) for the calibration and validation period (period from 06/1999 to 12/2001 excluded).



b) Nutrient Calibration

Calibration of sediment and total phosphorus loads was attempted based on a limited number of grab samples taken by the Michigan Department of Environmental Quality in the summers of 1991 and 2001. However, this effort corresponded more to a coarse model adjustment than a rigorous calibration for the following reasons: 1) it was not appropriate to compare grab sample values with SWAT daily average concentrations, and 2) sample locations often did not match SWAT output location (i.e., at the outlet of a subwatershed). Values were only compared based on their order of magnitude (Table 3). Such comparisons suggest that the SWAT model provides results that are reasonable for generalized model simulation of agricultural BMP scenarios.

Table 3: Comparison of observed and simulated total phosphorus concentrations.

Sample location (approximate) based on SWAT subwatersheds	Sample Date	Simulated (SWAT)	Observed (MDEQ)
Total Phosphorus (mg/L)			
Sub 33 (outlet)	4/2/1991	0.034	0.047
	5/14/1991	0.011	0.069
	6/11/1991	0.289	0.080
	7/9/1991	0.037	0.072
	8/6/1991	0.004	0.038
	9/4/1991	0.005	0.047
	10/2/1991	0.065	0.036
	11/5/1991	0.030	0.042
Sub 14 (inlet)	7/18/2001	0.016	0.040
Sub 14 (middle)	7/18/2001	0.016	0.038
Sub 20 (middle)	7/18/2001	0.016	0.032

3. Best management practices scenarios

3.1. Baseline Results

SWAT was run on an annual basis from 1997 to 2004 (excluding the year 2000 from the results because of missing precipitation data). Average annual loadings were calculated for sediment, total phosphorus and total nitrogen. Results are presented in Figures 4 to 6. These values were used as the baseline loading conditions to which the simulated loads from agricultural BMP scenarios were compared (see Section 3.2)

Figure 4: Sediment loading (ton/ac/yr) per subwatershed.

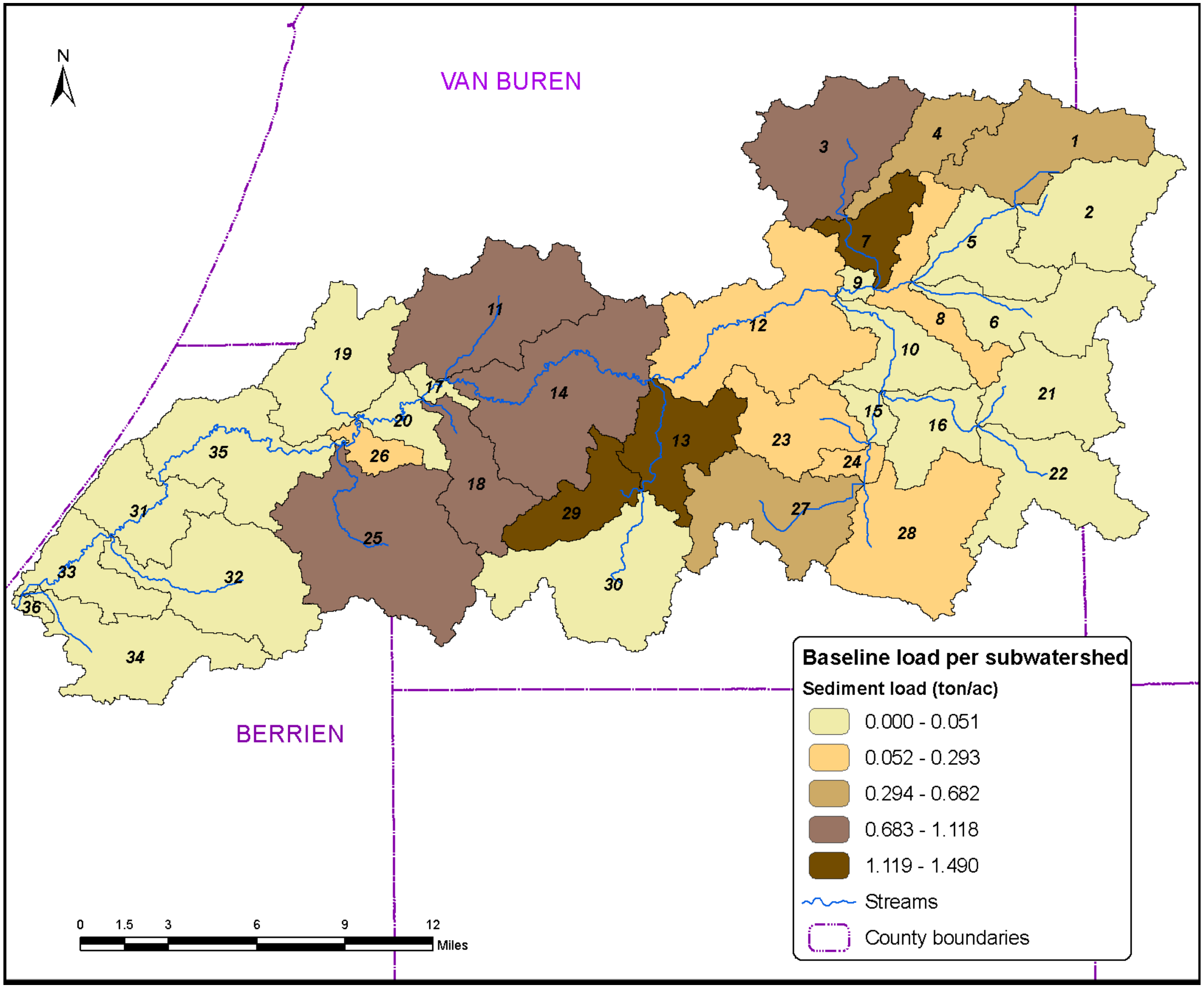


Figure 5: Total phosphorus loading (lbs/ac/yr) per subwatershed.

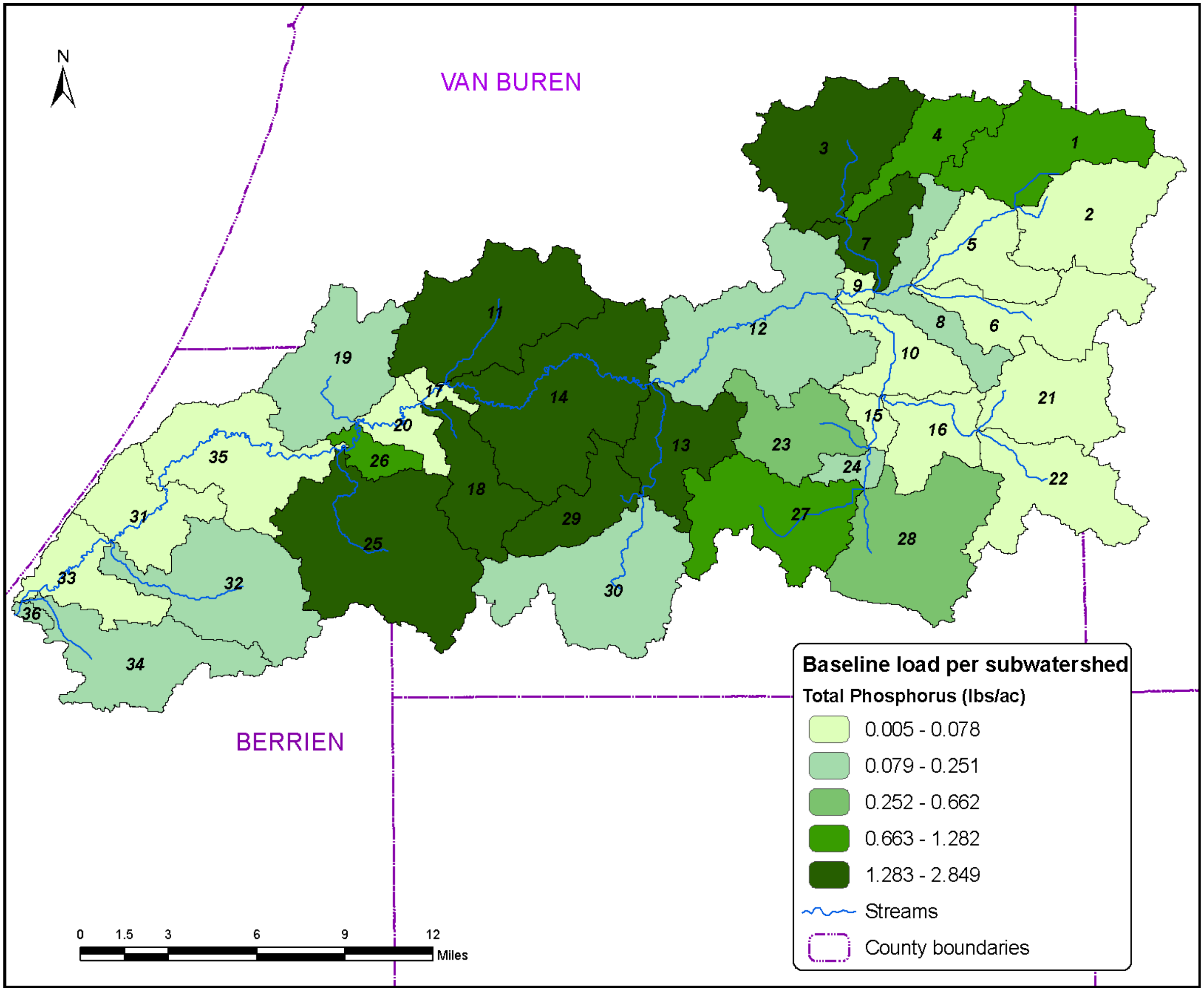
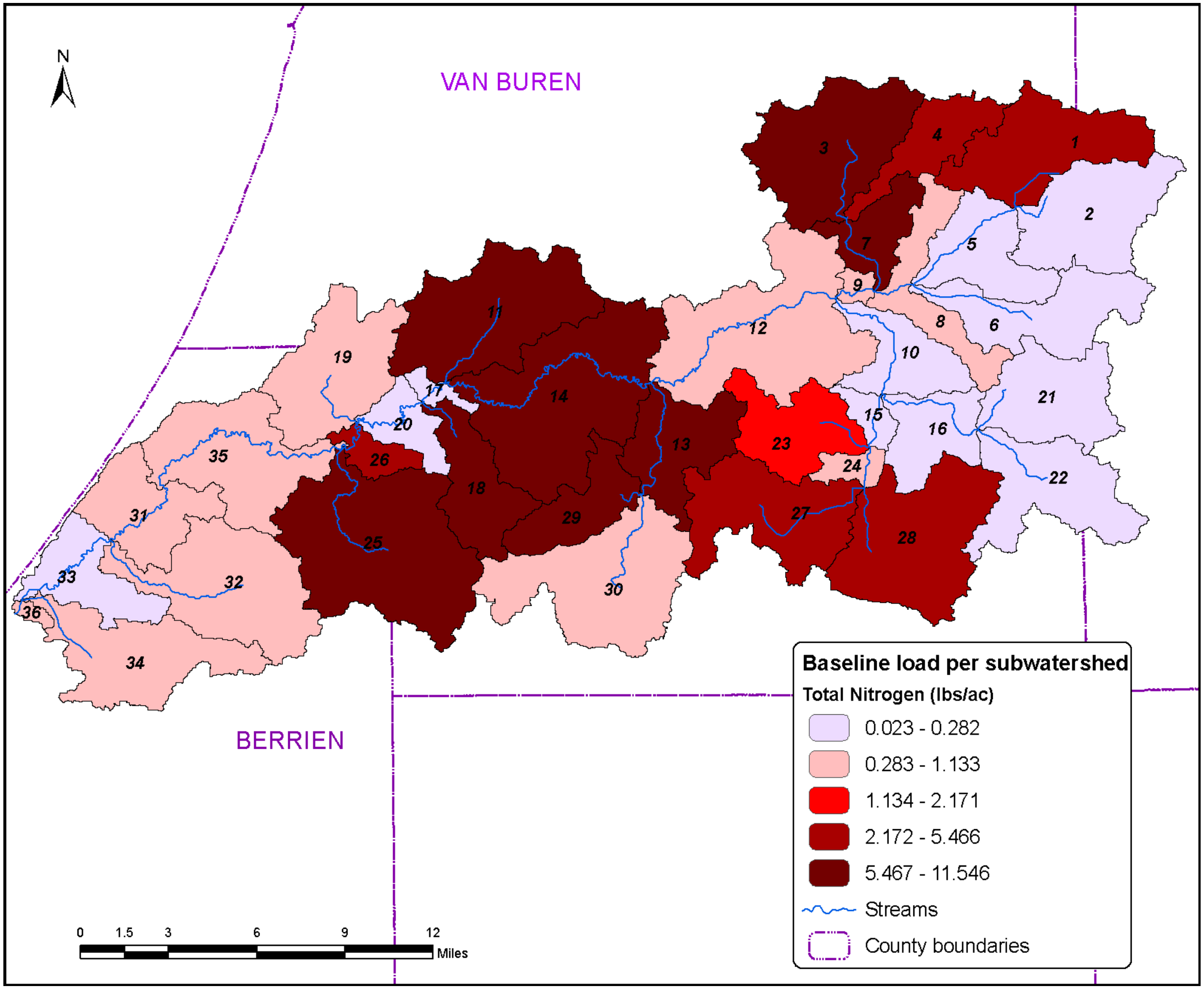


Figure 6: Total nitrogen loading (lbs/ac/yr) per subwatershed.



Model results indicate that the highest loading subwatersheds have a large proportion of silty clay loam soils, with a slow infiltration rate and higher runoff potential (hydrologic soil group C - Figure 7). These subwatersheds also have a higher proportion of agricultural land use, in particular row crops (Figure 8).

Figure 7: Proportion of hydrologic soil groups (A-C) in highest loading subwatersheds compared to the watershed average.

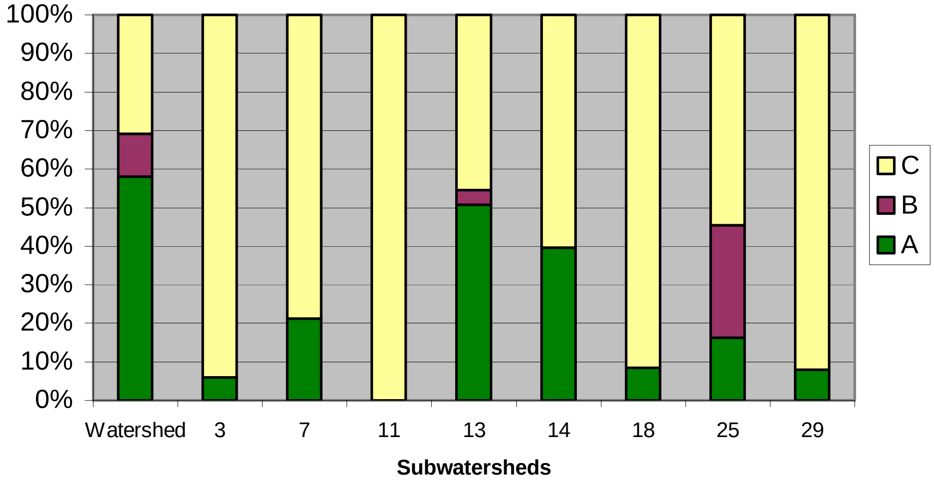
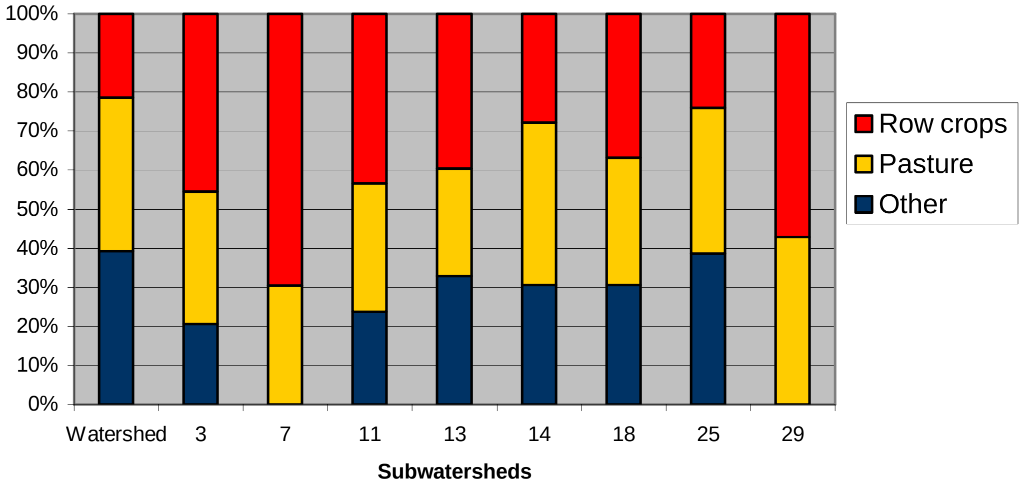


Figure 8: Proportion of land use in highest loading subwatersheds compared to the watershed average.



3.2. Agricultural BMP Scenarios

This study examined load reductions resulting from a combination of agricultural BMPs and hypothetical BMP implementation rates. The model scenarios were only performed in the subwatersheds with the highest baseline loading, and in subwatersheds with over 30% of their area in agricultural land use. In total, 14 subwatersheds were selected in this regard (see Figure 9).

Five BMPs were selected based on recommendations from the Southwest Michigan Planning Commission and the Nature Conservancy (Table 4). These BMPs were implemented in the selected subwatersheds at three different rates that represent the percentage of the selected land area receiving the BMP. For the no-till scenario, the BMP was implemented on the remaining land area not already modeled as no-till[2]. The two most efficient BMPs were also combined to form the fifth scenario. Overall, 15 scenarios were run in SWAT (Table 4).

Table 4: BMP implementation scenarios simulated in SWAT.

BMP	**Application rate**		
	25%	50%	75%
No-till	✓	✓	✓
Filter strip	✓	✓	✓
Cover crop	✓	✓	✓
Nutrient Management	✓	✓	✓
Combination of the 2 most efficient BMPs	✓	✓	✓

Results were interpreted as load reductions at the mouth of the watershed because, due to in-stream settling, re-suspension and/or algal uptake/release, load reductions achieved at the subwatershed level can be diminished at downstream observation points. In addition, results were analyzed using the duration curve approach to provide an indication of BMP efficiency under different hydrologic conditions (Cleland, 2002; US EPA, 2007).

BMP scenarios were modeled in SWAT using the following methods:

- Conservation tillage of corn or corn silage rotation was simulated in SWAT with reduced C factors in the Modified Universal Soil Loss Equation and the removal of tillage practices in the agricultural management input files.
- Nutrient management (fertilizer application rate reduction) was simulated with a 25% reduction of fertilizer and manure application rates.
- Installation of filter strips was simulated by adding 9.14 m (30ft) edge-of-field filter strips in the HRU input file of selected subwatersheds.
- Cover crop was simulated by planting a rye winter crop following corn harvest in the agricultural management input files.

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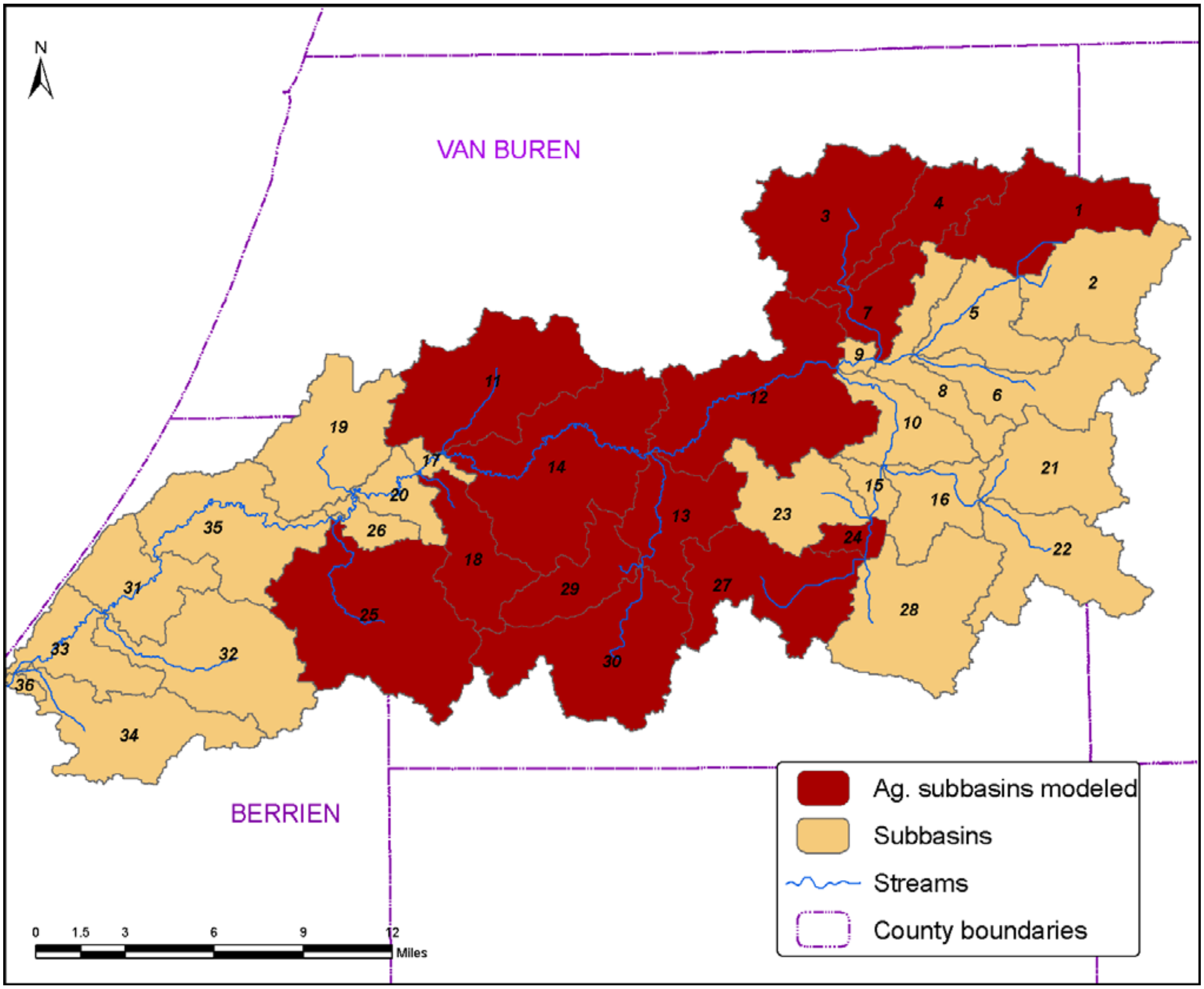
[2] Approximately 20% of the agricultural land in the watershed is managed using no-till practices (MSU Extension interviews) and was modeled as such in the baseline.

Figure 9: Agricultural subbasins modeled in BMP scenarios.



3.3. BMP Scenario Results

a) Load reductions

BMP scenarios were run for the same 6-year period as the baseline. The average annual loads for sediment, TP and TN were calculated under each scenario and compared with values obtained from the baseline condition. The difference in average annual load between a BMP scenario and the baseline was used to indicate the load reduction achieved by BMP implementation.

Results in Table 5 show that filter strips and no-till consistently provide the highest load reductions. No-till is particularly effective for sediment, especially at the 75% implementation level. In addition, no-till shows greater efficiency than filter strips when the implementation rate goes from 25% to 50%, and even more so when the rate goes from 50% to 75%. This can have a significant cost implication considering that filter strip are more expensive to install than implementing no-till. Compared to other BMPs, filter strips provide significant sediment and pollutant load reductions at the 25% level.

TP and TN load reductions from cover crops are similar to TP and TN load reductions from no-till, except when the implementation rate goes from 50% to 75% level. At the 75% implementation level, no-till is almost twice as effective as cover crops.

The least effective BMP is reduced fertilizer application rate while the combination scenario (including no-till and filter strips) provides the highest overall load reductions, particularly at the 75% level.

As detailed in Section 3.1, the subwatersheds modeled in the BMP scenarios tend to have a high proportion of clay loam soils that do not drain well, and have the potential to produce significant runoff. Therefore, it is logical that filter strips and no-till provide significant load reductions. Filter strips trap fine soil particles from surface runoff and utilize excess nutrients. No-till reduces soil erosion by promoting infiltration.

Table 5: Load reduction (%) at the mouth of the Paw Paw River Watershed under BMP scenarios.

	Implementation rate (% of selected agricultural area)		
	25%	***50%***	***75%***
Sediment			
No-till[a]	13	33.1	49.8
Filterstrip[b]	19.8	34.6	42.9
Cover crop[c]	7.8	18.5	23.9
Fertilizer reduction[d]	0	0.9	1.1
Combo[e]	22.5	39.5	65.3
Total Phosphorus			
No-till	11.1	25.1	41.7
Filterstrip	23.1	35.8	44.4
Cover crop	10.5	21.1	26.3
Fertilizer reduction	0.6	1.4	1.7
Combo	23.7	40.3	62.1
Total Nitrogen			
No-till	11	24.9	41.1
Filterstrip	21.7	34.4	43.2
Cover crop	10.1	21.4	27.2
Fertilizer reduction	0.7	1.5	1.9
Combo	22.9	39.2	60.8

[a] No-till for corn
[b] 30-ft edge-of-field filter strip
[c] Rye cover crop during winter
[d] Fertilizer application rate reduction of 25%
[e] Combination of filter strips and no-till

b) *Duration Curve Analysis*

Scenario results were also analyzed using the duration curve approach. The duration curve approach is often used as a tool in TMDL development (Cleland, 2002; Cleland, 2003; US EPA, 2007). This approach provides a visualization of pollutant loads/concentrations and of BMP efficiency under different flow regimes. The analysis is based on the development of a flow duration curve which is created using the cumulative frequency of flow data over a long period of time. Five duration intervals are commonly defined based on the percentage of time a specific flow is met or exceeded. The 0% value corresponds to the highest flows (flood conditions) that are seldom exceeded while 100% corresponds to the lowest flows on record (drought conditions) which are always exceeded.

The flow duration curve for the watershed (Figure 10) was produced using SWAT simulated average daily flows for a 10-year period (1993-2004, excluding the two years of missing weather data). This curve was used as the foundation for the load and concentration duration analysis. Due to budget constraints, only results from the three combination scenarios (combination scenario at the 25%, 50% and 75% implementation rate) were analyzed. Load and concentration duration curves (Figure 11A-C, Figure 12A-C) were created using loads and concentration values associated with the simulated flow values for the 10-year SWAT run. Boxplots for baseline and combination scenario results were graphed for each duration interval to provide a visual analysis of the impact of BMPs under the various flow conditions.

Figure 10: Flow duration curve for simulated flows at the mouth of the Paw Paw River Watershed.

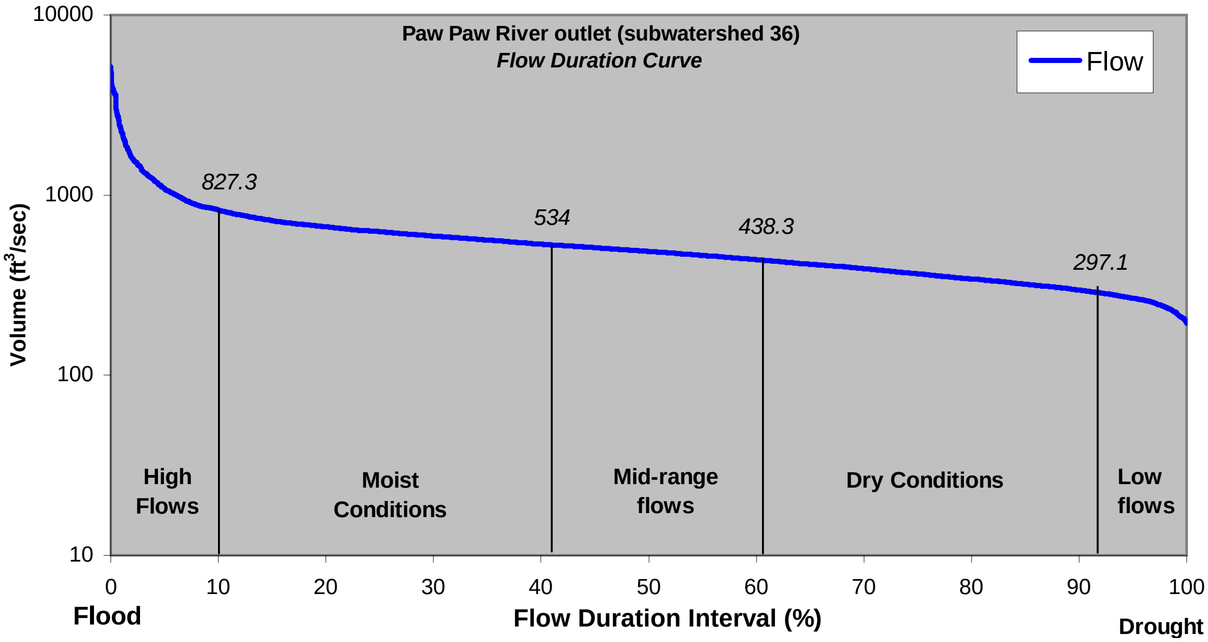


Figure 11A: Load duration curve for baseline and combination scenarios for sediment load (lbs) at the mouth of the watershed.

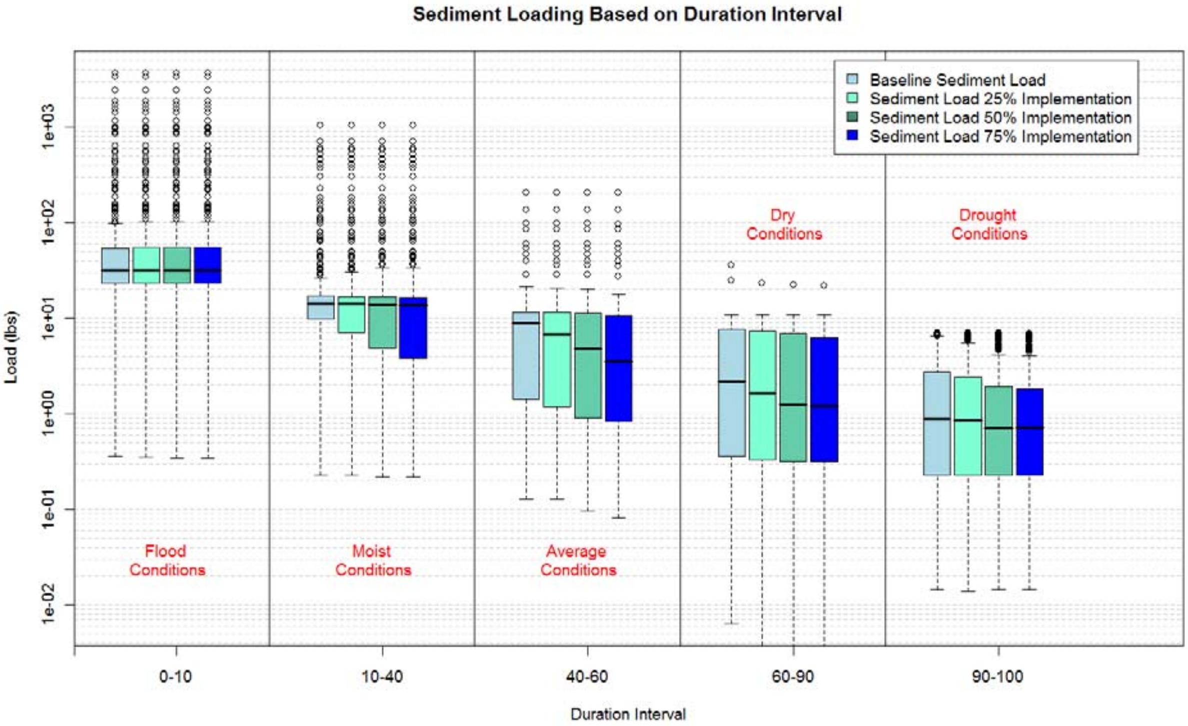


Figure 11B: Load duration curves for baseline and combination scenarios TP load (lbs) at the mouth of the watershed.

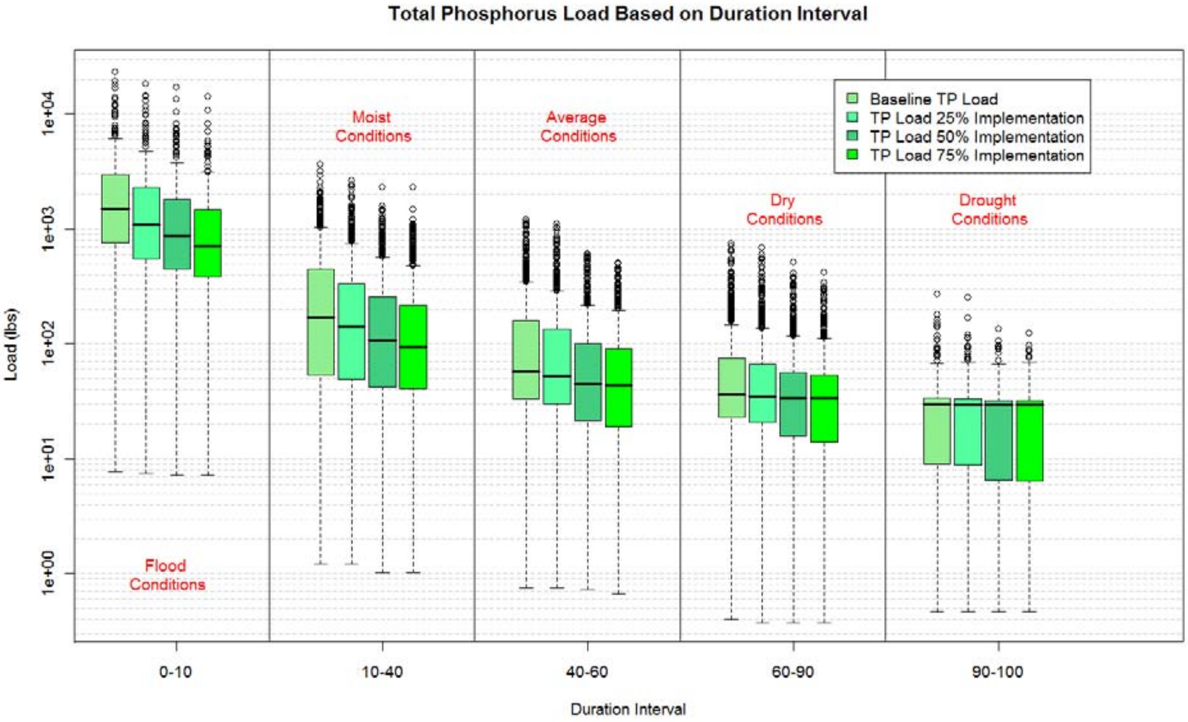


Figure 11C: Load duration curves for baseline and combination scenarios for TN load (lbs) at the mouth of the watershed.

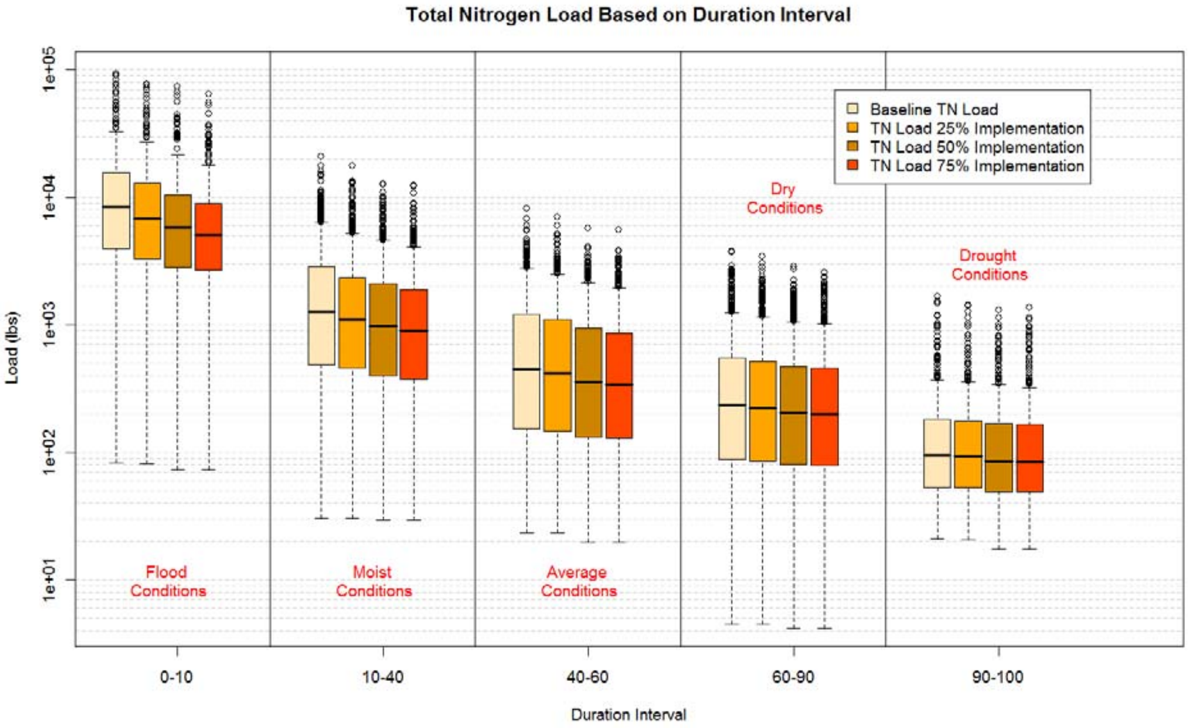


Figure 12A: Concentration duration curves for baseline and combination scenarios for sediment concentration (mg/L) at the mouth of the watershed.

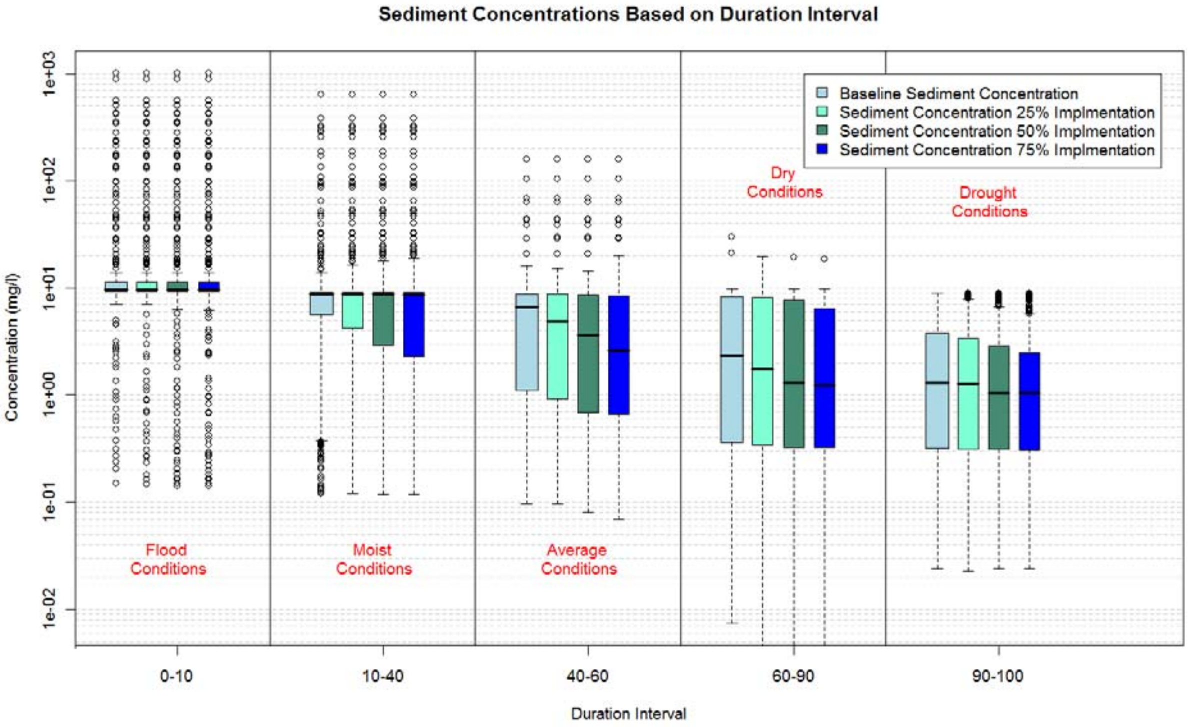


Figure 12B: Concentration duration curves for baseline and combination scenarios for TP concentration (mg/L) at the mouth of the watershed.

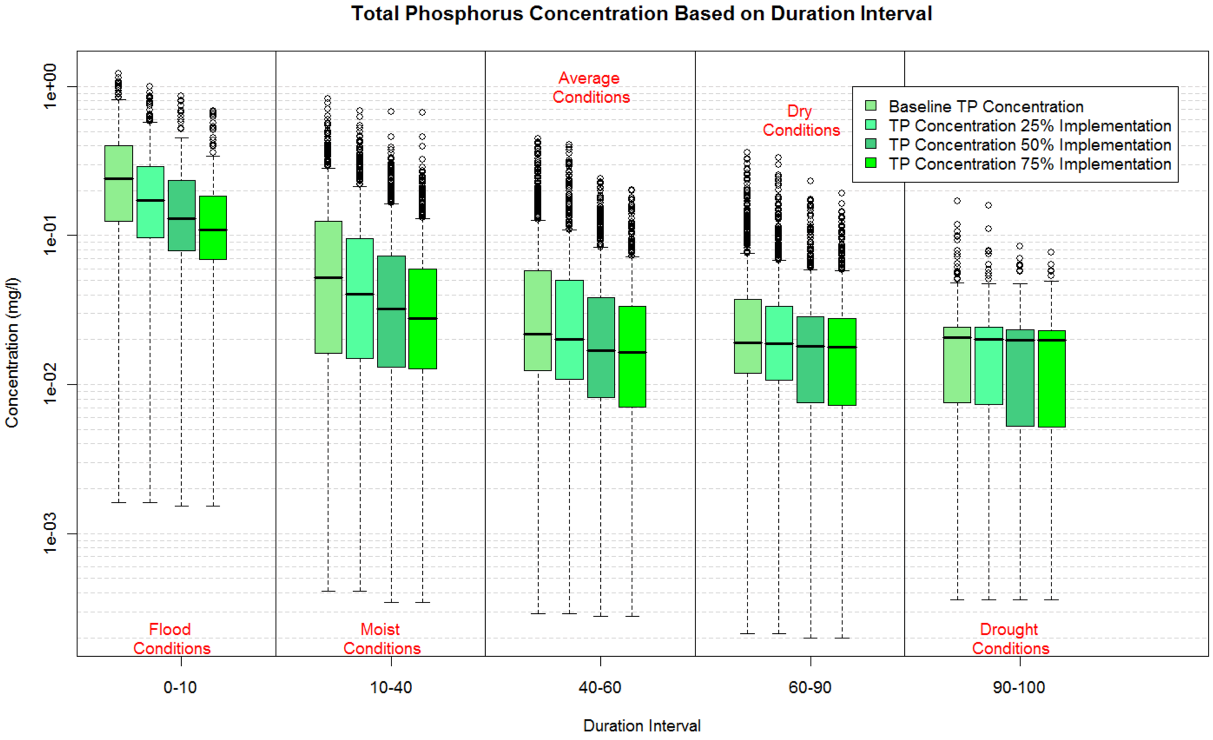
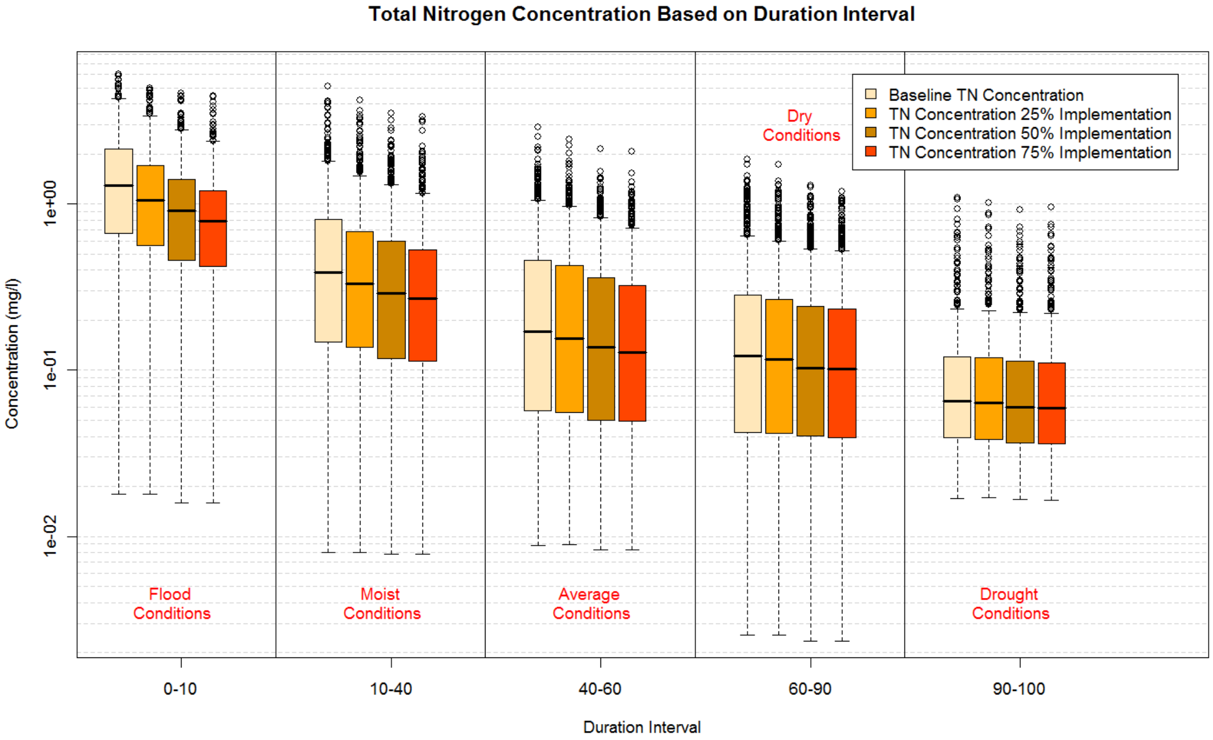


Figure 12C: Concentration duration curves for baseline and combination scenarios for TN concentration (mg/L) at the mouth of the watershed.



When considering the impact on sediment, the combination BMPs (filter strip and no-till) perform best under average (mid-range) and dry conditions, with the median load and concentration values consistently decreasing with the increase in BMP implementation acreage (Figure 11A and 12A). They also help reduce the duration of impact under moist conditions (10-40%) with a significant slope for the lower quartile, but they do not have a significant effect on average loads. Filter strips and no-till do not provide any benefits under high flows conditions while they moderately reduce higher loads and concentrations under low flow conditions. Overall, BMPs will provide an improvement on median sediment loads and concentrations 60% of the time, mainly during average to lower flow conditions.

BMPs work differently for TP control under the different flow regimes than for sediment. They perform better under high and average flow conditions (high, moist and mid-range duration intervals) with an observable decrease for most statistical comparisons (Figures 11B and 12B). BMP effectiveness starts to level off during dry conditions. In dry conditions, BMP implementation does not have a significant impact on median load and concentration values for TP but does help moderate the highest load and concentration values. Such BMPs also reduce the duration of impact (especially between the 25 and 50% implementation rate). Filter strip and no-till BMPs have limited impact in low flow conditions, although the lower quartile loads and concentrations decrease when the implementation rate goes from 25 to 50%. Under dry and low flow conditions, increasing the implementation rate from 50% to 75% does not provide any additional benefits. Overall, filter strips and no-till will have a measurable impact on reducing phosphorus loads and concentrations across a wide range of flow conditions, with their best performance during high flows.

The impact of BMPs on TN loads and concentrations is very similar to the results for TP. BMPs are more effective under high flows conditions but their influence starts to level off under average flow conditions (Figures 11C and 12C). Like TP, under average to low flow conditions, increasing implementation acreage from 50% to 75% does not provide any significant benefits.

For nutrients in general, filter strip and no-till BMPs are more efficient under higher flows conditions; they will provide significant benefits 60% of the time and some smaller reductions up to 90% of the time.

c) *Agricultural BMP Cost*

Watershed specific costs for conducting various agricultural management practices in the Paw Paw River watershed were limited. It was therefore decided that, for the purpose of this study, literature values would be used. Direct payments to farmers to induce no-till vary widely among different localities and individual farmers. Many farmers in the upper Midwest have adopted no-till or other forms of conservation tillage even without incentive payments. In addition, farm-level economic cost-benefit analyses often indicate a net profit with the adoption of conservation tillage or no-till (e.g., University of Illinois Extension, 2006). A study on the cost of nutrient and sediment reduction in the Chesapeake Bay watershed (US EPA, 2003a) cited a net farm cost of $2.72/acre/year for applying conservation tillage. Kurkalova et al. (2003) used a modeling approach based on the contingent valuations literature that directly computed subsidies needed for adoption of conservation tillage in Iowa. They incorporated an adoption premium related to uncertainty in addition to changes in expected profit because the adoption premium may exceed the profit gain. Consequently, the farmer would require a subsidy to adopt the practice. They concluded that it would require an annual subsidy of $2.85 per acre for a corn-soybean rotation (1992 dollars).

Among the literature reviewed for this study, the Kurkalova et al. (2003) estimate represented the most rigorous evaluation of subsidies for inducing conservation tillage (including no-till) in the upper Midwest. Therefore, the average of the annual subsidies for corn and soybean from their study was used for this analysis. Applying a Producer Price Index increase of 13.4% from 1992 to 2006, this number was translated into $3.23 per acre in 2006 dollars.

Costs for implementing nutrient management on cropland correspond to equipment and labor for soil testing, hiring a consultant to design the plan, and the costs of any additional passes over the field to fertilize. Assuming a 3-year useful life for a plan once it is developed, and including the costs of soil testing, implementation, (and in some cases, cost savings and yield increases), net cost estimates range from -$30/acre/yr (i.e., a net cost savings) to $14/acre/yr in 2001 dollars (US EPA, 2003a). In this study, a cost of $2.79/acre/yr in 2006 dollars was used as cited by US EPA in its National Management Measures for the Control of Non-point Pollution from Agriculture (US EPA, 2003b).

Costs for installing edge-of-field grass filter strips consist of a one-time establishment expense and an annual rental for the land used for filter strips. Devlin et al. (2003) suggested an establishment cost of $100 per acre. Rental cost for the land in the Paw Paw River watershed was obtained from a survey conducted by Wittenberg and Harsh (2006) for Michigan agricultural lands. For the watershed, the average rent of $102.7 per acre per year for tiled, non-tiled, and irrigated lands in the survey district including Van Buren, Berrien and Kalamazoo counties was used.

Costs for cover crops consist of field preparation, seeding, planting and harvesting or killing the crop. Cover crop costs range from $4 to $40 per acre depending on the crop being seeded (Lemunyon, no date; Mannering et al., 2000). A publication from Michigan State University Extension Service (Mutch and Martin, 1988) put the cost of ryegrass seeds at $7.50/ac/yr. The US EPA (2003b) cites a total cost of $10/acre/yr. This value, adjusted to $10.55 in 2006 dollars, was used in this study. This value may be low considering recent fluctuations and availability of rye grass seed.

d) <u>BMP Cost-Analysis</u>

Following the convention of typical cost-benefit analysis, net present worth values were calculated for these agricultural management practices based on the acreage of practice adoption, a 15-year BMP implementation time (assuming farmers committed to the BMPs for the same time period as Conservation Reserve Enhancement Programs in Michigan), and a five percent interest rate. Cost-effectiveness of these practices on a per pound basis was then calculated by dividing the net present worth by the total load reduction achieved over the 15-year period to arrive at average annual costs per ton of sediment or per pound of nutrient reduced.

Table 6 shows the total annual cost for implementing each BMP in the watershed while Table 7 presents the BMP cost per mass load reduction. No-till and reduced fertilizer applications have similar total costs but no-till is by far the least expensive and most cost-effective BMP to implement under any of the scenarios. It is worth noting that no-till cost-effectiveness increases (decreasing $/lb values) as the implementation rate increases (in particular for TP and TN). This suggests that large scale implementation of no-till would be particularly beneficial.

Filter strips and cover crops are the most expensive BMPs because of their installation and maintenance costs. However, when considering the cost per pound reduced, filter strips are more cost-efficient than cover crops. Contrary to no-till, filter strip cost-effectiveness decreases as implementation rate increases, suggesting that small scale implementation is best for filter strips. Despite this trend, filter strips remain the second most cost-effective BMP.

While cover crops provide similar nutrient load reductions to no-till at the 25% and 50% level, they are about four times more costly to implement than no-till. It is worth noting that cover crops are most cost-effective at the 50% implementation rate. Reducing fertilizer application rates is not cost-efficient compared to any of the other practices.

The combination scenarios, which include the two most efficient and cost-effective BMPs, logically rate as the third implementation option. Their combined cost-effectiveness is highest at the 25% implementation rate.

Table 6: Total average annual cost (in $) of BMP implementation in the Paw Paw River Watershed.

	Application rate (% of total land)		
	25%	*50%*	*75%*
No-till[a]	24,000	48,000	72,000
Filter strip[b]	115,000	230,000	346,000
Cover crop[c]	98,000	197,000	295,000
Fertilizer[d]	26,000	52,000	78,000
Combo[e]	139, 000	278,000	418,000

[a] No-till for corn
[b] 30-ft edge-of-field filter strip
[c] Rye cover crop during winter
[d] Fertilizer application rate reduction of 25%
[e] Combination of filter strips and no-till

Table 7: Cost of average annual load reductions as manifested at the mouth of the Paw Paw River Watershed.

	Application rate (% of total land)		
	25%	*50%*	*75%*
Sediment (in $/ton)			
No-till[a]	2.29	1.79	1.79
Filter strip[b]	7.12	8.15	9.90
Cover crop[c]	16.53	13.04	15.20
Fertilizer[d]	NA	70.27	5.82
Combo[e]	7.56	8.61	7.84
Total P (in $/lb)			
No-till[a]	1.24	1.11	1.00
Filter strip[b]	2.84	3.67	4.45
Cover crop[c]	5.35	5.33	6.40
Fertilizer[d]	23.44	20.71	25.82
Combo[e]	3.34	3.93	3.84
Total N (in $/lb)			
No-till[a]	0.39	0.35	0.31
Filter strip[b]	0.75	0.94	1.12
Cover crop[c]	1.38	1.30	1.53
Fertilizer[d]	5.37	4.76	5.82
Combo[e]	0.89	1.05	1.01

[a] No-till for corn
[b] 30-ft edge-of-field filter strip
[c] Rye cover crop during winter
[d] Fertilizer application rate reduction of 25%
[e] Combination of filter strips and no-till

4. Model Limitations and Potential Improvements

Due to the lack of local data, there are some key limitations with this modeling study. Though the watershed is very well suited to be modeled by SWAT because of the predominance of agricultural land use, a lack of water quality, local climate information and more specific information on agricultural practices/costs limit the utility of the model to more generalized uses. Results and experience gained from the current study, however, can be a valuable source of information for any future modeling refinements.

Long-term climate data were not available within the Paw Paw River Watershed. Precipitation and temperature data representative of conditions within the watershed boundaries would most likely improve modeling results. However, data from multiple stations close to the watershed ensure that climate variation within the region was taken into account. In addition, the lack of long-term sediment and TP sampling data did not allow for robust model calibration and validation. The development of a monitoring program would provide a representative overview of water quality in the Paw Paw River as well as allow for modeling improvements.

This study summarizes the impact of agricultural BMPs on pollutant and sediment loads at the mouth of the watershed. However, BMP load reductions could also be quantified for specific subwatersheds to identify the potential for local water quality improvement provided local monitoring data were available to support robust calibration.

While SWAT calculates the deposition and re-entraining of sediment carried by surface runoff in the routing channels, it should be noted that the current version of the SWAT model does not have a fully functioning module that simulates streambank erosion and channel degradation processes (Neitsch et al, 2002a). Recent volunteer field surveys conducted throughout the watershed by SWMPC may provide additional information to the relative contribution of streambank erosion to sediment loading.

Lastly, it should also be noted that, due to the agricultural focus of SWAT, urban areas in the watershed are not adequately simulated by this model. This is an acceptable short-coming however, considering that this modeling study focused on quantifying the effectiveness of agricultural BMPs. This does not suggest that pollutant loadings from urban areas are not important. Urban loadings, although small compared to agricultural sources in the Paw Paw River watershed, are particularly damaging to local receiving streams due to concentrated flow and high content of phosphorus and other pollutants. In addition, the development of urban areas in the watershed may thwart further efforts to improve water quality. The reader is referred to the separate urban BMP modeling report of the Paw Paw River Watershed Management Plan for more information.

5. Conclusions

This study developed a coarsely calibrated SWAT model for the Paw Paw River watershed given the limited availability of monitoring data. The model was used to simulate baseline loading conditions for TP, TN, and sediments and analyzed the impact of five agricultural best management practices on water quality.

Among the four individual agricultural BMPs simulated, no-till emerged as the most cost-efficient BMP at all implementation rates due to its low per acre implementation cost ($3.23/ac/yr). Large scale implementation for this BMP would bring significant water quality benefits. Filter strips may represent the most expensive BMP to install but they provide the largest sediment and nutrient load reductions, and are second to no-till when considering cost-effectiveness. A small scale implementation of filter strips would represent the best option given increasing cost with diminishing returns at higher application rates. This result suggests that preservation of existing stream buffers should be a high priority for the watershed. The combined BMP scenario (no-till and filter strips) provided the largest load reductions in all scenarios. However, it was shown that effectiveness gains will be diminished when more than one BMP is implemented on top of one another. Finally, it must be noted that filter strip and no-till BMPs (as modeled in the combination scenario) will not consistently improve water quality under all streamflow conditions as they do not have an impact on sediment loads under high flows, and they have minimal benefit on TP and TN loads under low flow conditions.

In summary, despite the coarse nature of model setup due to limited monitoring data available for model calibration, this SWAT modeling study yielded valuable quantitative information on the relative effectiveness of agricultural BMPs in reducing pollutant loads and improving water quality, and the costs associated with these improvements.

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APPENDIX A

Hydrologic Response Units (HRUs) Defined by SWAT

Subbasin	HRU number	HRU description (land use/soil ID)	Area (acres)	% of the watershed area	% of the subwatershed area
1	1	Wetlands-Forested/MI083	1,935.41	0.67	19.39
	2	Wetlands-Forested/MI011	486.84	0.17	4.88
	3	Forest-Deciduous/MI083	743.07	0.26	7.44
	4	Forest-Deciduous/MI045	725.64	0.25	7.27
	5	Forest-Deciduous/MI011	1,164.29	0.41	11.66
	6	Agricultural Land-Row Crops/MI083	1,091.59	0.38	10.94
	7	Agricultural Land-Row Crops/MI045	1,532.15	0.53	15.35
	8	Agricultural Land-Row Crops/MI011	2,302.71	0.80	23.07
2	9	Pasture/MI011	2,905.46	1.01	29.81
	10	Forest-Deciduous/MI045	1,597.90	0.56	16.39
	11	Forest-Deciduous/MI011	5,244.24	1.83	53.80
3	12	Pasture/MI048	3,368.81	1.17	27.90
	13	Pasture/MI011	718.81	0.25	5.95
	14	Forest-Deciduous/MI048	2,486.72	0.87	20.60
	15	Agricultural Land-Row Crops/MI048	5,498.26	1.92	45.54
4	16	Pasture/MI011	1,400.80	0.49	28.30
	17	Forest-Deciduous/MI011	1,381.89	0.48	27.91
	18	Agricultural Land-Row Crops/MI048	560.41	0.20	11.32
	19	Agricultural Land-Row Crops/MI011	1,607.40	0.56	32.47
5	20	Pasture/MI083	416.71	0.15	6.31
	21	Pasture/MI011	1,504.37	0.52	22.79
	22	Wetlands-Forested/MI083	1,991.83	0.69	30.17
	23	Forest-Deciduous/MI083	1,673.64	0.58	25.35
	24	Forest-Deciduous/MI011	1,015.62	0.35	15.38
6	25	Pasture/MI011	4,303.64	1.50	51.47
	26	Forest-Deciduous/MI011	4,058.58	1.41	48.53
7	27	Pasture/MI048	853.87	0.30	20.60
	28	Pasture/MI011	411.10	0.14	9.92
	29	Agricultural Land-Row Crops/MI048	2,414.02	0.84	58.23
	30	Agricultural Land-Row Crops/MI011	466.84	0.16	11.26
8	31	Pasture/MI011	2,829.15	0.99	48.64
	32	Forest-Deciduous/MI011	1,327.65	0.46	22.82
	33	Agricultural Land-Row Crops/MI011	1,660.06	0.58	28.54
9	34	Pasture/MI048	222.58	0.08	28.57
	35	Pasture/MI011	45.97	0.02	5.90
	36	Wetlands-Forested/MI048	160.31	0.06	20.58
	37	Wetlands-Forested/MI011	83.50	0.03	10.72
	38	Forest-Deciduous/MI048	170.50	0.06	21.88
	39	Forest-Deciduous/MI011	96.30	0.03	12.36
10	40	Pasture/MI011	3,425.39	1.19	61.78
	41	Forest-Deciduous/MI011	2,119.40	0.74	38.22
11	42	Pasture/MI048	4,434.47	1.55	32.94
	43	Forest-Deciduous/MI048	3,192.82	1.11	23.72
	44	Agricultural Land-Row Crops/MI048	5,833.24	2.03	43.34

Subbasin	HRU number	HRU description (land use/soil ID)	Area (acres)	% of the watershed area	% of the subwatershed area
12	45	Pasture/MI048	3,690.62	1.29	21.44
	46	Pasture/MI083	917.36	0.32	5.33
	47	Pasture/MI011	2,335.04	0.81	13.57
	48	Forest-Deciduous/MI048	2,061.23	0.72	11.98
	49	Forest-Deciduous/MI083	1,467.03	0.51	8.52
	50	Forest-Deciduous/MI011	1,542.04	0.54	8.96
	51	Agricultural Land-Row Crops/MI048	2,723.56	0.95	15.82
	52	Agricultural Land-Row Crops/MI083	745.43	0.26	4.33
	53	Agricultural Land-Row Crops/MI011	1,729.30	0.60	10.05
13	54	Pasture/MI048	790.28	0.28	11.00
	55	Pasture/MI045	275.81	0.10	3.84
	56	Pasture/MI011	900.68	0.31	12.54
	57	Forest-Deciduous/MI048	1,219.07	0.42	16.97
	58	Forest-Deciduous/MI011	1,172.14	0.41	16.31
	59	Agricultural Land-Row Crops/MI048	1,251.51	0.44	17.42
	60	Agricultural Land-Row Crops/MI011	1,575.21	0.55	21.92
14	61	Pasture/MI048	4,532.05	1.58	25.10
	62	Pasture/MI011	2,960.72	1.03	16.40
	63	Forest-Deciduous/MI048	2,729.64	0.95	15.12
	64	Forest-Deciduous/MI011	2,794.41	0.97	15.48
	65	Agricultural Land-Row Crops/MI048	3,645.82	1.27	20.19
	66	Agricultural Land-Row Crops/MI011	1,392.00	0.49	7.71
15	67	Pasture/MI011	722.92	0.25	46.13
	68	Pasture/MI022	166.66	0.06	10.64
	69	Forest-Deciduous/MI011	394.12	0.14	25.15
	70	Forest-Deciduous/MI022	283.31	0.10	18.08
16	71	Pasture/MI083	364.64	0.13	6.88
	72	Pasture/MI011	1,885.95	0.66	35.61
	73	Forest-Deciduous/MI083	594.35	0.21	11.22
	74	Forest-Deciduous/MI011	2,451.27	0.85	46.28
17	75	Pasture/MI011	522.92	0.18	54.31
	76	Pasture/MI057	91.74	0.03	9.53
	77	Wetlands-Forested/MI011	243.48	0.08	25.29
	78	Wetlands-Forested/MI057	104.64	0.04	10.87
18	79	Pasture/MI048	1,508.04	0.53	24.07
	80	Pasture/MI011	531.65	0.19	8.48
	81	Agricultural Land-Row Crops/MI048	2,310.97	0.81	36.88
	82	Orchard/MI048	1,915.76	0.67	30.57
19	83	Pasture/MI048	809.91	0.28	8.02
	84	Pasture/MI033	1,084.10	0.38	10.73
	85	Pasture/MI031	1,710.25	0.60	16.93
	86	Pasture/MI057	1,722.92	0.60	17.05
	87	Forest-Deciduous/MI048	805.32	0.28	7.97
	88	Forest-Deciduous/MI033	1,723.73	0.60	17.06
	89	Forest-Deciduous/MI031	2,246.31	0.78	22.24

Subbasin	HRU number	HRU description (land use/soil ID)	Area (acres)	% of the watershed area	% of the subwatershed area
20	90	Pasture/MI048	345.89	0.12	11.06
	91	Pasture/MI011	691.39	0.24	22.11
	92	Wetlands-Forested/MI048	213.31	0.07	6.82
	93	Wetlands-Forested/MI011	867.01	0.30	27.72
	94	Orchard/MI048	297.40	0.10	9.51
	95	Orchard/MI011	712.34	0.25	22.78
21	96	Pasture/MI011	4,345.88	1.51	54.38
	97	Forest-Deciduous/MI011	3,645.66	1.27	45.62
22	98	Pasture/MI045	1,983.82	0.69	21.49
	99	Pasture/MI011	1,796.40	0.63	19.46
	100	Forest-Deciduous/MI045	1,816.91	0.63	19.68
	101	Forest-Deciduous/MI011	3,633.44	1.27	39.36
23	102	Pasture/MI045	427.12	0.15	6.33
	103	Pasture/MI011	1,514.62	0.53	22.44
	104	Forest-Deciduous/MI045	339.01	0.12	5.02
	105	Forest-Deciduous/MI011	1,142.87	0.40	16.93
	106	Agricultural Land-Row Crops/MI045	757.88	0.26	11.23
	107	Agricultural Land-Row Crops/MI011	1,062.53	0.37	15.74
	108	Orchard/MI045	199.26	0.07	2.95
	109	Orchard/MI011	1,307.78	0.46	19.37
24	110	Pasture/MI011	419.73	0.15	29.01
	111	Pasture/MI022	67.59	0.02	4.67
	112	Wetlands-Forested/MI011	76.53	0.03	5.29
	113	Wetlands-Forested/MI022	406.85	0.14	28.12
	114	Agricultural Land-Row Crops/MI011	372.70	0.13	25.76
	115	Agricultural Land-Row Crops/MI022	103.31	0.04	7.14
25	116	Pasture/MI011	1,039.19	0.36	5.58
	117	Pasture/MI031	4,623.93	1.61	24.81
	118	Pasture/MI057	1,277.38	0.45	6.85
	119	Agricultural Land-Row Crops/MI048	759.17	0.26	4.07
	120	Agricultural Land-Row Crops/MI031	3,727.74	1.30	20.00
	121	Orchard/MI011	1,995.75	0.70	10.71
	122	Orchard/MI031	1,071.79	0.37	5.75
	123	Orchard/MI057	4,142.21	1.44	22.23
26	124	Pasture/MI011	329.69	0.11	16.74
	125	Pasture/MI031	546.78	0.19	27.77
	126	Forest-Deciduous/MI011	174.64	0.06	8.87
	127	Forest-Deciduous/MI031	375.51	0.13	19.07
	128	Agricultural Land-Row Crops/MI031	542.55	0.19	27.55
27	129	Pasture/MI045	3,060.58	1.07	29.20
	130	Pasture/MI011	2,587.11	0.90	24.68
	131	Agricultural Land-Row Crops/MI045	2,954.40	1.03	28.18
	132	Agricultural Land-Row Crops/MI011	1,880.89	0.66	17.94

Subbasin	HRU number	HRU description (land use/soil ID)	Area (acres)	% of the watershed area	% of the subwatershed area
28	133	Pasture/MI083	1,278.92	0.45	9.74
	134	Pasture/MI011	4,443.06	1.55	33.84
	135	Forest-Deciduous/MI083	1,029.52	0.36	7.84
	136	Forest-Deciduous/MI011	2,771.75	0.97	21.11
	137	Agricultural Land-Row Crops/MI083	746.74	0.26	5.69
	138	Agricultural Land-Row Crops/MI045	591.35	0.21	4.50
	139	Agricultural Land-Row Crops/MI011	1,045.06	0.36	7.96
	140	Agricultural Land-Row Crops/MI022	1,223.80	0.43	9.32
29	141	Pasture/MI048	2,299.77	0.80	42.86
	142	Agricultural Land-Row Crops/MI048	2,638.85	0.92	49.18
	143	Agricultural Land-Row Crops/MI011	426.88	0.15	7.96
30	144	Pasture/MI011	9,558.72	3.33	69.07
	145	Agricultural Land-Row Crops/MI011	4,281.16	1.49	30.93
31	146	Pasture/MI011	2,205.09	0.77	31.34
	147	Pasture/MI031	564.27	0.20	8.02
	148	Forest-Deciduous/MI011	1,298.66	0.45	18.46
	149	Forest-Deciduous/MI031	931.46	0.32	13.24
	150	Orchard/MI011	1,708.86	0.60	24.29
	151	Orchard/MI031	326.75	0.11	4.64
32	152	Pasture/MI011	2,539.49	0.88	20.28
	153	Pasture/MI031	947.58	0.33	7.57
	154	Forest-Deciduous/MI011	1,551.05	0.54	12.39
	155	Forest-Deciduous/MI031	1,063.28	0.37	8.49
	156	Orchard/MI011	5,391.87	1.88	43.07
	157	Orchard/MI057	1,025.82	0.36	8.19
33	158	Range-Grasses/MI011	1,258.77	0.44	22.28
	159	Range-Grasses/MI082	830.70	0.29	14.71
	160	Forest-Deciduous/MI011	1,177.65	0.41	20.85
	161	Forest-Deciduous/MI082	479.46	0.17	8.49
	162	Forest-Deciduous/MI021	318.37	0.11	5.64
	163	Transportation-->UTRN/MI011	382.35	0.13	6.77
	164	Transportation-->UTRN/MI057	292.62	0.10	5.18
	165	Transportation-->UTRN/MI082	909.06	0.32	16.09
34	166	Pasture/MI011	3,079.87	1.07	31.07
	167	Pasture/MI021	1,209.18	0.42	12.20
	168	Pasture/MI052	1,304.15	0.45	13.16
	169	Orchard/MI011	3,532.28	1.23	35.64
	170	Orchard/MI031	786.02	0.27	7.93
35	171	Pasture/MI011	2,800.52	0.98	24.72
	172	Pasture/MI031	1,315.53	0.46	11.61
	173	Forest-Deciduous/MI011	1,514.49	0.53	13.37
	174	Forest-Deciduous/MI031	1,314.76	0.46	11.60
	175	Orchard/MI011	2,357.36	0.82	20.81
	176	Orchard/MI031	661.39	0.23	5.84
	177	Orchard/MI057	1,366.30	0.48	12.06

Subbasin	HRU number	HRU description (land use/soil ID)	Area (acres)	% of the watershed area	% of the subwatershed area
36	178	Residential-High Density/MI057	185.19	0.06	39.85
	179	Transportation/MI057	191.53	0.07	41.21
	180	Residential-Med/Low Density/MI057	88.03	0.03	18.94