

Modeling and Simulating Nutrient Management Practices for the Mobile River Watershed

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Abstract. In this research, an existing hydrological model of the Mobile River watershed is expanded to include water quality modeling of Nitrate (NO₃) and Total Ammonia (TAM). The Hydrological Simulation Program Fortran is used for modeling the hydrological and the water quality processes. The resulting water quality model is used to implement nutrient management practices scenarios and, via simulation, explore the effects of those management scenarios at the most downstream river (Mobile River). Results show that the implementation of reported Best Management Practices (BMPs) at sub-watershed level (filter strips, stream bank stabilization and fencing) do not work as efficiently as when applied to the entire Mobile River watershed. Removal efficiencies reported for those BMPs at the sub-watershed scale ranged between 10.6 % and 54.0 %. When Filter Strips were applied to agricultural lands throughout the watershed, reductions of NO₃ concentrations ranged from 1.48 % to 12.24 % and TAM concentrations were reduced between 0.84 % and 6.97 %. Applying Stream Bank Stabilization and Fencing to the whole watershed produced removals of NO₃ of up to 14.06 %, and maximum TAM reductions of 8.01 %. The reasons for the discrepancy may be due to the site-specificity of the BMP techniques. This may preclude extrapolating those BMPs to sites where the characteristics are different (topography, soils, stream regime, etc.) reducing the effect of the applied BMPs. Watershed-wide aspects such as sub-basin-to-sub-basin or stream-to-stream interactions, may also reduce the effect of the management practices.

Keywords: Mobile River watershed · Water-quality modeling · HSPF · Nitrate · Total Ammonia · BMP

1 Introduction

Several coastal estuaries in the US Gulf Coast have experienced seasonal hypoxia events in recent years. While the origin of this problem may be related in part to an increase of urban development along the Gulf Coast, the dissolved oxygen depletion occurs mainly due to nutrient contributions from upland watersheds where the main economic activity is agriculture. Nutrients washed-off by rain events from the agricultural fields end up into streams that carry the nutrient-rich water to coastal water bodies. Aquatic vegetation

growth is enhanced by the availability of nutrients and the dissolved oxygen budget is unbalanced leading to eutrophication and subsequent hypoxia.

Mobile Bay, Alabama, recipient of the sixth-largest freshwater discharge in North America [1] experiences regular hypoxic events during the summer [2]. One of the upland watersheds that drains into Mobile Bay (via secondary streams to Mobile River) has been identified [3] as one of the sources of nutrient input due to its intensive agricultural activity: the Tombigbee River watershed. The increase of agricultural lands could potentially worsen the current situation. It has been estimated [4] that in some portions of the Tombigbee watershed the following land-use/land-cover changes have occurred in a span of 17 years: 34 % increase of agricultural lands, 263 % increase of lands used for grazing or hunting animals (rangeland), and a 16 % decrease of natural forest lands. It is reasonable to infer that nutrient inputs from this watershed may have an impact on the downstream rivers and water bodies. In fact, a recent study [5] has estimated (at a small geographical scale) several management scenarios that may be used for reducing the effects of nutrient and sediment contamination to some of the Tombigbee streams. The Best Management Practices postulated by Kleinschmidt [5] included the following.

- For cropland: filter strips, reduced tillage, stream bank stabilization and fencing, and terraces
- For pasture land: stream bank stabilization and fencing, and terraces

Estimating the effects of nutrient wash-off from agricultural fields to streams and water bodies is not an easy task. Since the sources of those nutrients are distributed in space (non-point sources), complex physical and biochemical processes occur during the transport of those contaminants through soil and water. Watershed models are able to quantify those processes occurring either under natural conditions or due to anthropogenic activities. These models use mechanistic and empirical algorithms to calculate the hydrological processes within a watershed and also the migration of pollutants from point and non-point sources to water bodies. Previous research has shown the use of these types of models for quantification of processes in agricultural watersheds [6]. For the Mobile River watershed, there exists an initial hydrological model [7] that covers all major streams in the watershed, including the Tombigbee River watershed. A water quality model for the entire watershed, however, is yet to be developed.

In this research, the existing hydrological model of the Mobile River watershed [7] is further hydrologically calibrated and validated, and built-up to include water quality modeling of nutrients. The Hydrological Simulation Program Fortran (HSPF, [8]) is used for modeling both: the hydrological and the water quality processes. The Better Assessment Science Integrating Point & Nonpoint Sources (BASINS [9]) GIS system is used to perform most of the geospatial operations. Once the nutrient modeling portion was developed, the water quality model is used to implement the nutrient management practices scenarios [5], and via simulation, explore the effects of those management scenarios at the most downstream river (Mobile River).

2 Methods

2.1 Study Area

The Mobile River is the main contributor of freshwater to Mobile Bay. In its approximately 72 km of length it carries waters coming from the confluence of the Tombigbee and Alabama rivers. The Mobile River has an average annual stream flow of 1840 m³/s. The Mobile River watershed (Fig. 1) covers approximately 115,000 km², extending into

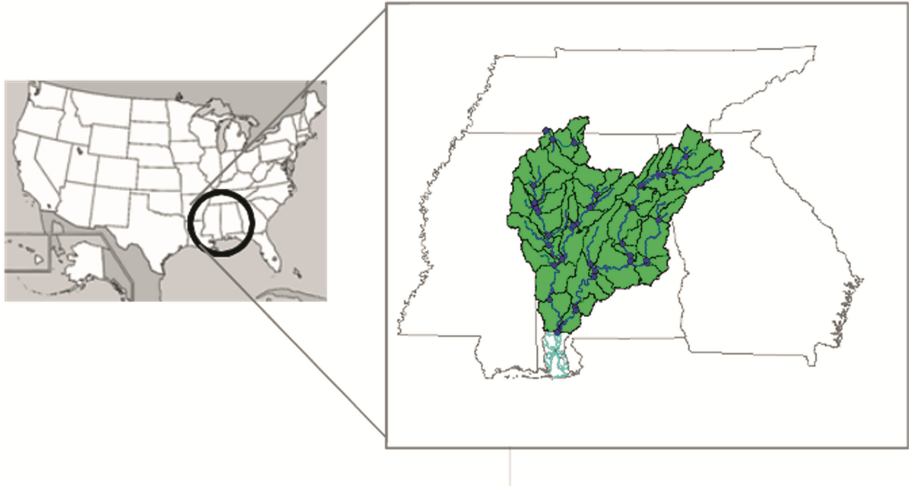


Fig. 1. Mobile River watershed. The drainage basin (fourth-largest in the United States) drains streams located in Alabama, Mississippi, Georgia, and Tennessee.

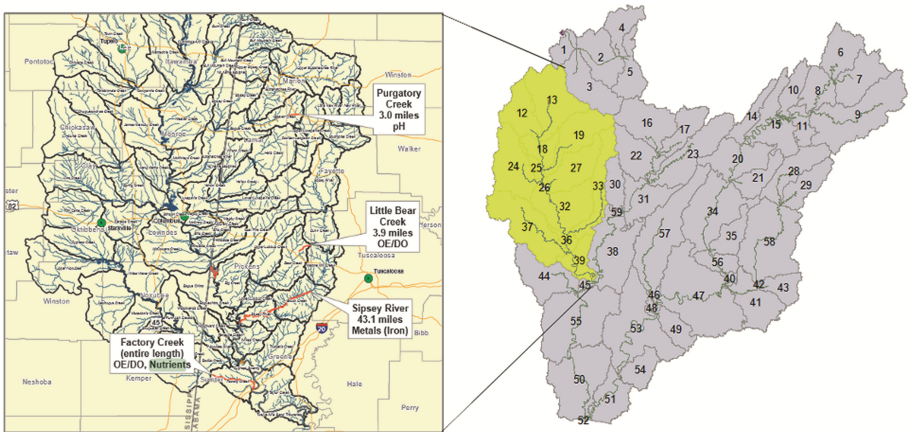


Fig. 2. Tombigbee watershed. The extent of the Tombigbee watershed included in the Tombigbee River Basin Management Plan [5] is shown in relation to the total extent of the Mobile River watershed.

four southeastern states: Alabama, Mississippi, Georgia, and Tennessee. This drainage basin is the fourth-largest in the United States. The river and its contributors have historically provided the principal navigational access for Alabama.

The Tombigbee River watershed is located in northwest Alabama and northeast Mississippi. It drains waters from a watershed (Fig. 2) that cover an area of approximately 35,650 km² between both states. Fifty six percent of the watershed is in Mississippi and the rest (44 %) lies in Alabama.

2.2 Hydrological Code

Hydrological and water quality modeling of the Mobile River watershed is performed using the Hydrological Simulation Program Fortran (HSPF). The HSPF is freely-available code designed for modeling and simulation of non-point source watershed hydrology and water quality. Time-series of meteorological/water-quality data, land use and topographical data are used to estimate stream flow hydrographs and pollutio-graphs. The model simulates interception, soil moisture, surface runoff, interflow, base flow, snowpack depth and water content, snowmelt, evapo-transpiration, and ground-water recharge. Simulation results are provided as time-series of runoff, sediment load, and nutrient and pesticide concentrations, along with time-series of water quantity and quality, at any point in a watershed. Additional software (WDMUtil and GenScn) is used for data pre-processing and post-processing, and for statistical and graphical analysis of input and output data [10]. The BASINS 4.1 GIS system [9] was used for downloading basic data and delineating the watershed included in this study. The creation of the initial HSPF models was done using the WinHSPF interface included in BASINS 4.1.

2.3 Topographical, Landuse, and Meteorological Datasets

The topographical characterization of the study area was performed using National Elevation Data (NED) (30 m horizontal, 1 m vertical), and USGS DEM (300 m horizontal 1 m vertical) topographical datasets. The NED dataset provides a seamless mosaic elevation data having as primary initial data source the 7.5 min elevation data for the conterminous United States [11]. NED has a consistent projection (geographic), resolution (1 arc second, approximately 30 m), and metric elevation units [12].

The USGS GIRAS is a set of maps of land use and land cover for the conterminous U.S. delineated with a minimum mapping unit of 4 hectares and a maximum of 16 hectares (equivalent to 400 m spatial resolution), generated using the Geographic Information Retrieval and Analysis System (GIRAS) software. Today, they are widely known as the USGS GIRAS land use data sets [10].

2.4 Water Quality Simulations

The Tombigbee River Basin Management Plan [5] established (through watershed modeling) a series of Best Management Practices for several sub-watersheds of the Tombigbee watershed (Fig. 2).

The study applied nine BMPs for each watershed that was modeled, including five different levels of BMP implementation in the subwatershed being modeled: 0 % (no BMP), 25 %, 50 %, 75 %, and 100 %. These percentages represent the proportion of the total acreage of a particular land use (cropland, pasture land) in the sub-watershed in which the BMP would be implemented [5]. The BMPs modeled by the study were: filter strips, reduced tillage, stream bank stabilization and fencing, and terraces. The best BMPs resulting from that exploration (in terms of removal of nutrients) are summarized in Table 1.

Table 1. Average nutrient removal efficiency for Filter Strips, and Streambank Stabilization and Fencing (identified in [5]).

Acreage covered by the BMP	% Nutrient Removal Filter Strip	% Nutrient Removal Stream bank Stabilization and Fencing
25 %	10.6 %	16.0 %
50 %	29.0 %	36.2 %
75 %	43.4 %	54.0 %
100 %	62.8 %	75.0 %

Table 1 shows that BMP Bank Stabilization and Fencing seem to provide good removal efficiency. The average nutrient removals shown in the table were calculated from results for all BMPs implemented in [5]. It is important to remark that those BMPs were implemented at a localized level (i.e., per sub-watershed). Hence, the results were also obtained at a sub-watershed scale.

In this research, we wanted to test the efficiency of two types of BMPs in the reduction of Nitrate (NO_3) and Total Ammonia (TAM) if these management practices were implemented throughout the entire Mobile River watershed. In order to undertake this computational exploration, a selection of sub-watersheds was first performed to reduce computer processing time.

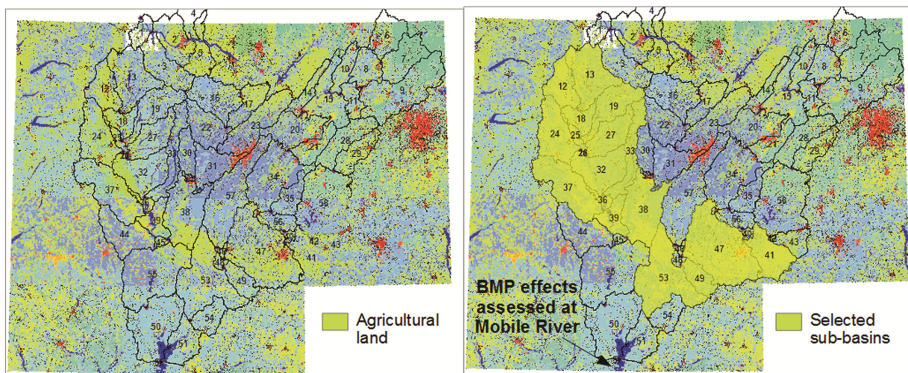


Fig. 3. Distribution of agricultural lands in the Mobile River watershed (left). Sub-basins selected for nutrient simulation are also shown (right). BMP effects were measured at the Mobile River (watershed outlet). (Color figure online)

Figure 3 shows agricultural lands in the Mobile River watershed area (left). It is evident that most of the agricultural activity in the area is concentrated in an agricultural belt that originates in northeastern Mississippi, crosses mid-southern Alabama, and ends in southwestern Georgia. Therefore, the sub-watersheds to which these agricultural lands belong were selected for implementing the BMPs and their corresponding removal efficiency (summarized in Table 1). Three levels of implementation (in terms of percent of agricultural acreage) were simulated: 25 %, 50 %, and 75 %. Those percentages of BMP were selected for ease in comparison with the results reported in [5]. The application of 100 % BMP was not included in this research because it is unrealistic to expect to achieve that level of BMP implementation in such a large area.

3 Results

3.1 Filter Strip BMP

In this section, simulated concentrations for NO₃ and TAM are shown after a Filter Strip BMP was applied to agricultural lands shown in Fig. 3.

Figure 4 shows summarized simulated results for NO₃ concentrations at the Mobile River after implementation of a Filter Strip BMP to agricultural lands. Since the effect of the BMP implementations was not well visualized at daily temporal resolution, the daily results were averaged at monthly and yearly scales. Simulations were generated for the period from January 1st, 1970 to December 31st 1995.

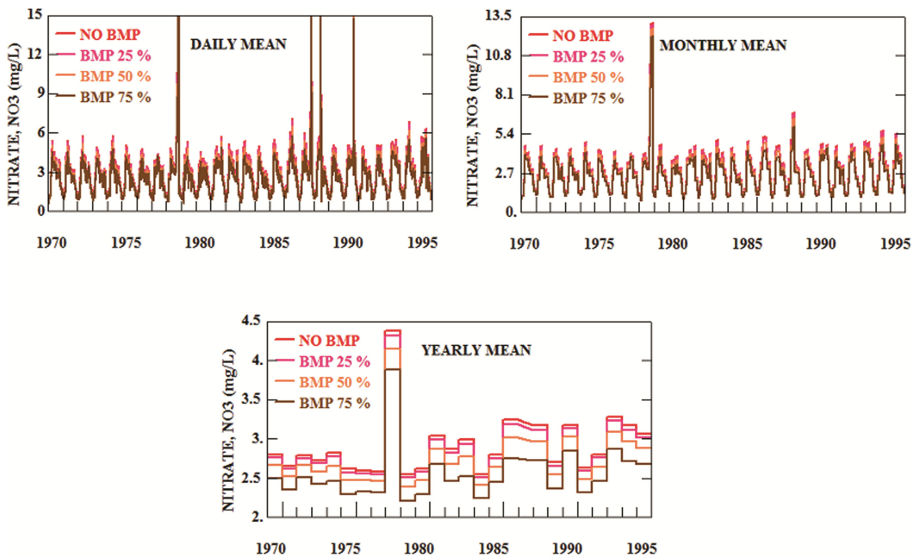


Fig. 4. Simulated Nitrate concentrations at the Mobile River watershed after implementation of a Filter Strip BMP to agricultural lands. (Color figure online)

The model correctly simulates the common seasonal trend for NO_3 concentrations in agricultural lands. Concentration values range between 1 and 6 mg/L, with peaks during summer and minimums in winter. The model simulates four events in which concentrations are higher than 13 mg/L. These uncommon peaks are correlated with four periods of very low flows that occurred in 1978, 1987, 1988, and 1990.

Figure 5 shows simulated results for TAM concentrations occurring at the watershed outlet for four scenarios for the time period 1970/01/01 to 1995/12/31. Since TAM concentrations at a daily level did not show noticeable changes after the implementation of BMPs, Fig. 5 only shows average concentrations at monthly and yearly temporal scales where effects are more significant. TAM concentrations simulated by the model range between 0.005 and 0.04 mg/L. The model correctly simulates higher TAM concentrations for the crop growing season (March–July). Simulation results show that TAM concentrations through the year are around 0.016 mg/L with the exception of the concentrations during low flow events already identified in the NO_3 simulation.

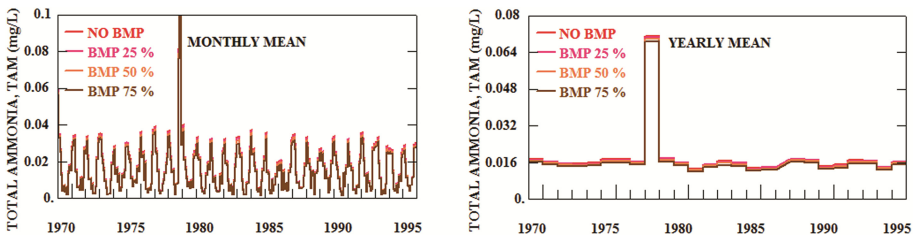


Fig. 5. Simulated TAM concentrations in the Mobile River watershed after implementation of a Filter Strip BMP to agricultural lands. Due to the slight effect of this BMP in TAM concentrations at daily level, only monthly and annual averages are shown. (Color figure online)

In order to assess the effects of the implementation the Filter Strip BMP to agricultural lands, the NO_3 and TAM concentrations produced by the model for each of the Filter Strip BMP percentages (25 %, 50 % and 75 %) were averaged and removal efficiencies were calculated with respect to the scenario where no BMP was implemented. Table 2 summarizes the results.

Table 2. Average nutrient concentration reductions after implementation of a Filter Strip BMP to agricultural lands.

Filter Strip	NO_3 mg/L	TAM mg/L	% NO_3 Reduction	% TAM Reduction
NO BMP	2.86	0.0240	0.00	0.00
BMP 25 %	2.82	0.0238	1.48	0.84
BMP 50 %	2.70	0.0230	5.56	3.16
BMP 75 %	2.52	0.0214	12.24	6.97

The results summarized in Table 2 show that the removal efficiency of the BMP implemented at 25 %, 50 % and 75 %, does not correlate with the results achieved at sub-watershed scale (reported by [5]). Reported removal efficiencies for the BMP Streambank Stabilization range from 16 % to 54 % (see Table 1). The simulation results

from our model indicate that the maximum removal efficiency achieved for the Mobile River, if Filter Strips were to apply to areas with the most intensive agricultural activity, is 12 % for NO₃ and 6 % for TAM (at a 75 % BMP level).

3.2 Stream Bank Stabilization and Fencing BMP

Figure 6 shows summarized simulated results for NO₃ concentrations at the Mobile River watershed after implementation of a Stream Bank Stabilization and Fencing BMP to agricultural lands. The effect of the BMP implementations is somewhat visualized at daily temporal resolution; however for better appreciation of the effect of the BMP application the daily results were also averaged at monthly and yearly scales. As in the Filter Strip BMP the period covered by the simulation was 1970/01/01 to 1995/12/31. The charts show a slight increase in the effect of the BMP. At the annual temporal scale, the decrease in NO₃ concentrations (after application of the 75 %-BMP) is around 1 mg/L.

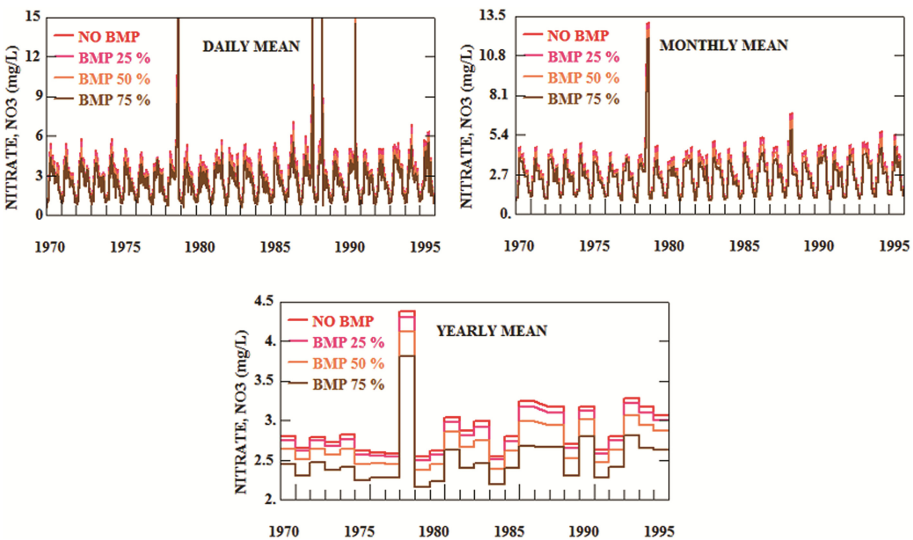


Fig. 6. Simulated NO₃ concentrations at the Mobile River watershed after implementation of a Stream Bank Stabilization and Fencing BMP to agricultural lands. (Color figure online)

Figure 7 shows simulated results for TAM concentrations occurring at the Mobile River estimated by the HSPF model. As in the Filter Strip case, TAM concentrations at a daily level did not show noticeable changes after a Stream Bank Stabilization and Fencing BMP implementation to agricultural lands. For that reason, Fig. 7 only shows mean TAM concentrations at monthly and annual temporal scales.

The application of a Stream Bank Stabilization and Fencing BMP to agricultural lands seem to have a stronger effect on NO₃ and TAM concentrations than the implementation of a Filter Strip BMP. To quantify these effects, Table 3 summarizes average NO₃ and TAM concentrations produced by the model for each of the BMP percentages

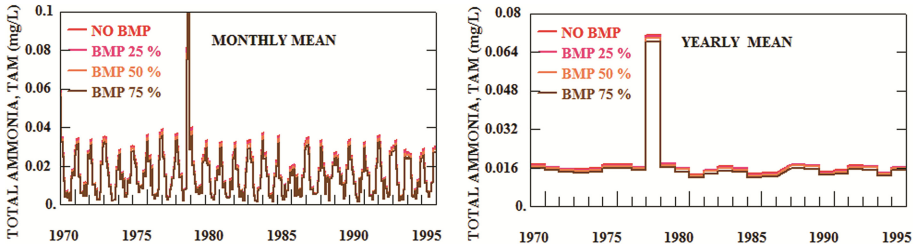


Fig. 7. Simulated TAM concentrations at the Mobile River watershed after implementation of a Stream Bank Stabilization and Fencing BMP to agricultural lands. As in the Filter Strip case, due to the negligible effect in TAM concentrations of the BMP at daily level, only monthly and annual averages are shown. (Color figure online)

(25, 50 and 75 %). Removal efficiencies were calculated with respect to the scenario where no BMP was implemented. The percent reductions achieved for Nitrate range from 1.82 % to 14.06 %, which were slightly higher than the reductions achieved with the Filter Strip BMP. As in the Filter Strip case, percent reductions in TAM concentrations range between 1 % and 8 %, showing that TAM concentrations are not affected significantly by the application of a Stream Bank Stabilization and Fencing BMP to agricultural lands.

Table 3. Nutrient concentration reduction after implementation of a Stream Bank Stabilization and Fencing BMP to agricultural lands.

Action	NO ₃ mg/L	TAM mg/L	% NO ₃ Reduction	% TAM Reduction
NO BMP	2.86	0.0240	0.00	0.00
BMP 25 %	2.81	0.0237	1.82	1.04
BMP 50 %	2.68	0.0229	6.25	3.37
BMP 75 %	2.46	0.0212	14.06	8.01

4 Conclusions

The computational exploration presented in this paper shows that the implementation of the most efficient management practices identified, at a sub-watershed level, by the Tombigbee River Basin Management Plan [5], do not work as well when applied to the entire Mobile River watershed. While the application of Filter Strip BMPs at sub-watershed scale was reported to show nutrient removals of 10.6 %, 29.0 %, and 43.4 % (for 25 %, 50 % and 75 % BMP application respectively), when Filter Strips were applied to agricultural lands throughout the entire Mobile River watershed, reduction of NO₃ concentrations were only 1.48 %, 5.56 %, and 12.24 % correspondingly. Reductions in TAM concentrations were even more modest: 0.84 %, 3.16 %, and 6.97 %, respectively. Removal efficiencies reported for Stream Bank Stabilization and Fencing (applied at the sub-watershed scale) ranged between 16.0 %, 36.2 %, and 54.0 % for BMP levels of 25 %, 50 % and 75 % BMP, correspondingly. However, applying this BMP to the whole watershed, NO₃ reductions were only 1.82 %, 6.25 %, and 14.06 %, respectively. TAM

concentration reductions were slightly higher than in the previous case: 1.04 %, 3.37 %, and 8.01 %.

The reasons for the discrepancy in the outcomes of BMP applications may be due to the fact that the BMPs used in [5] were specific to the sub-watersheds of that study. Therefore, extrapolating those BMPs to sites where the characteristics are different (topography, soils, stream regime, etc.) may change the impact of the applied BMPs. Also, watershed-wide aspects such as sub-basin-to-sub-basin or stream-to-stream interactions, are not accounted for at the sub-watershed scale. These results have important implications for design and implementation of water quality plans.

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