Evaluation and Spatially Distributed Analyses of Proposed Cost-Effective BMPs for Reducing Phosphorous Level in Cedar Creek Reservoir, Texas

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Abstract. *The assessment of BMP (best management practice) impacts using a watershed model has helped to establish a watershed conservation and protection plan that is projected to be required by government and decision makers. Cedar Creek watershed, located southeast of Dallas, Texas, was included in the 303(d) list as an impaired watershed due to high pH values. A number of efforts have been made to develop watershed protection plans by the North Central Texas Water Quality (NCTXWQ) project team. Tarrant Region Water District (TRWD) has monitored the water quality in the reservoir and found that chlorophyll-a has been increasing at an annual rate of 3.85%. Chlorophyll-a is a good indicator of algae growth, and TRWD, with 18 years of monitoring, revealed that the increase of chlorophyll-a needs to be a primary focus of the watershed protection plan. A stakeholder group and the project team suggested that total phosphorous (TP) reduction from the watershed should be targeted at 35% of current loading in order to preserve the water quality in the reservoir. In previous studies, flow and nutrients in the watershed were calibrated using SWAT (Soil and Water Assessment Tool). In addition, sensitivity analyses for each BMP were conducted such that each BMP was simulated in the model at a 100% adoption rate. The cost-effectiveness of each BMP was estimated and ranked by TP reduction. In this study, using the calibrated model and the cost-effectiveness analyses of the BMPs, the initially selected BMPs were simulated in SWAT to identify the reduction rate at the watershed outlet (reservoir) using a marginal adoption rate and to illustrate the spatially distributed impacts of each BMP at the subbasin scale. The results show that simulation of the eight selected BMPs in subbasins with higher TP loading can achieve the 35% reduction goal at the reservoir.*

Keywords. *Best Management Practices (BMPs), Cost-effectiveness, Phosphorous, SWAT, Watershed protection plan.*

The establishment of state water quality standards and the resultant Total Maximum Daily Load (TMDL) program provides challenges to water resource professionals. The modeling of BMP (best management practice) effectiveness plays an important role in developing a watershed protection plan. The spatially distributed impacts of BMPs can be helpful for decision makers and stakeholders to understand target areas and to identify the most suitable solution for a particular problem. The mitigation of water quality problems through the implementation of multiple BMPs in a watershed is a classic scenario in the protection of reservoirs. The ability to perform sensitivity analyses and determine the cost-effectiveness of BMP options allows for lower costs and increased flexibility in evaluation and planning prior to implementation.

The reduction of sediment and nutrients by BMPs has been researched for decades, and studies have documented the positive effects of BMPs. The representation of BMPs in a watershed model has also been conducted in many studies (Santhi et al., 2006; Bracmort et al., 2004; Munoz-Carpena et al., 2002; Brothers et al., 2001) based on field studies of BMP effectiveness. Model parameter settings to represent BMPs depend on watershed conditions and the characteristics of individual BMPs. In general, parameters are adjusted in such a way that a model represents the physical attributes of each BMP.

This study is part of the North Central Texas Water Quality (NCTXWQ) project, which is focused on developing a watershed protection plan to improve and preserve water quality in the Cedar Creek reservoir, Texas. Cedar Creek reservoir was listed on the 303(d) list as "impaired" in 2006 for high levels of pH by the Texas Commission on Environmental Quality (TCEQ, 2007). Tarrant Regional Water District (TRWD), one of the largest water suppliers for the Dallas-

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Fort Worth metropolitan area in north central Texas, has evaluated the water quality in Cedar Creek reservoir for 18 years and found that chlorophyll-*a* levels have increased at an annual rate of 3.85% since 1989 (Ernst and Owens, 2009). These findings support the idea that the increase of chlorophyll-*a* needs to be a central issue in the watershed protection plan. Chlorophyll-*a* is a good indicator of algae growth in a waterbody, and the increase of chlorophyll-*a* can be correlated to high nutrient levels, particularly phosphorous. Thus, the reduction of total phosphorous (TP) in the reservoir became one of the key elements of this project. Efforts have been made to collect information, identify the source of pollutants, and conduct public meetings with stakeholder groups in order to develop a watershed protection plan. The reduction goal for TP loading to the reservoir was established at 35%. This was based on the level of reduction that would be necessary to see a lowering of the concentration of chlorophyll-*a* in the reservoir. The 35% reduction of TP was shown to be statistically significant and is based on an annual average reduction of TP (NCTXWQ, 2009).

Therefore, the objectives of this study are (1) to identify the problem areas for BMP installation, (2) to rank individual BMPs by their cost-effectiveness in this watershed, and (3) to simulate the most cost-effective suites of BMPs in order to reach the targeted TP reduction goal with the best available solution in the watershed.

Description of Previous Modeling Efforts

Water quantity and quality assessment using SWAT (Soil and Water Assessment Tool; Arnold et al., 1998) has been conducted and calibrated for the watershed at two USGS gauge stations (08062800 and 08062900) and ten water quality monitoring sites operated by TRWD throughout the watershed (Narashimhan et al., 2010). SWAT is a physically based continuous model for simulation of a large watershed. In this study, a modified SWAT2000 was used for simulation (details of the modifications are provided by Narashimhan et al., 2010). A 30 m digital elevation model (DEM) was obtained from the USGS, soil data were a combination of SSURGO and CBMS (Computer-Based Mapping System), and land cover data were the 1992 NLCD (National Land Cover Dataset) enhanced by Landsat imagery in 2001. Ten weather stations are available within and around the watershed, and the weather data were enhanced with the NEXRAD (Next Generation Radar) dataset. Two USGS gauge stations (08062800 and 08062900) were used for flow calibration. Ten nutrient monitoring stations throughout the watershed provided tributary water quality data, and they were used for nutrient calibration. Flow and nutrient discharges from nine wastewater treatment plants (WWTPs) in the watershed were obtained from Alan Plummer Associates, Inc. (APAI, 2007) and included in the model as point sources.

The SWAT model, operated through the BASINS 3.0 (Better Assessment Science Integrating Point and Non-point Sources) interface (USEPA, 2001), delineated a total of 106 subbasins in the watershed (fig. 1). Target areas, local adoption conditions, and local parameters were analyzed based on this subbasin level. Flow calibration was conducted from 1966 to 1987 from the total modeling period (37 years) at the two USGS gauge stations, and the validation run of the model was conducted from 1980 to 2002 at the reservoir using mass balance measured by TRWD (TRWD, personal communication, 2009). The validation of flow was done with

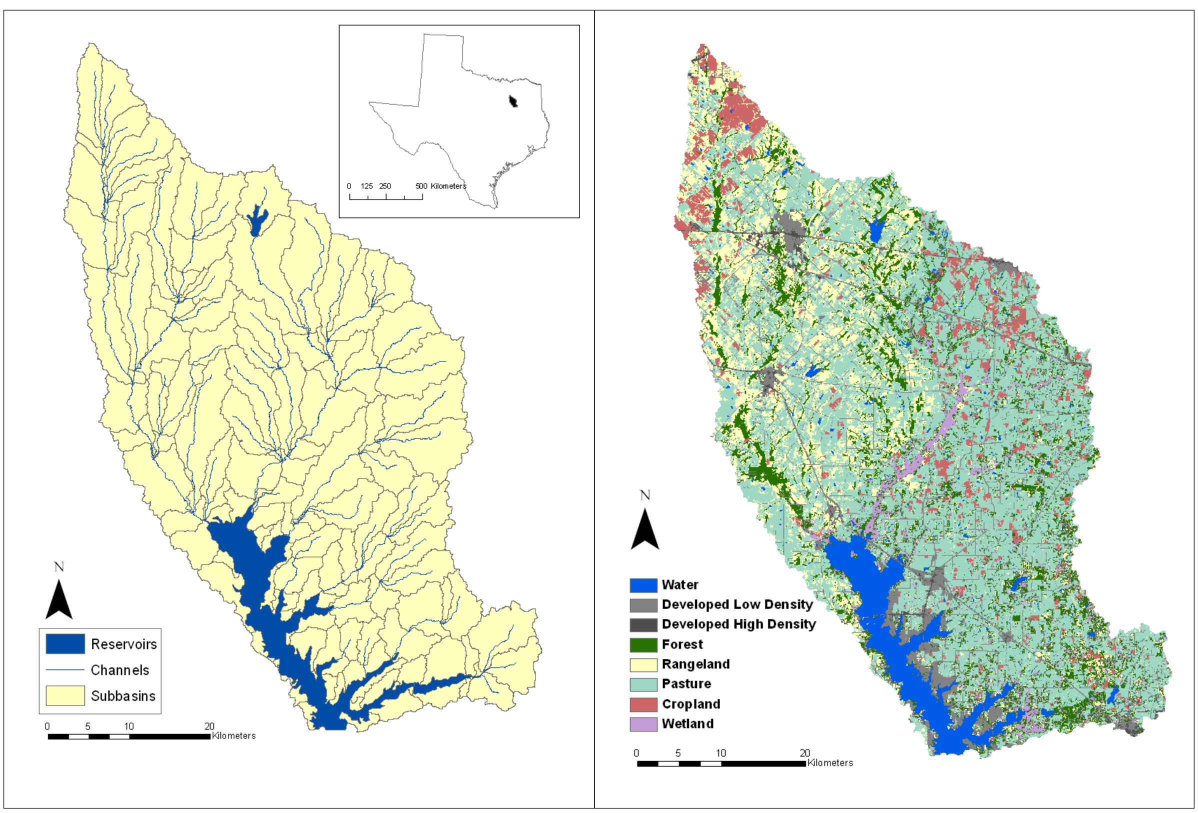

Figure 1. Cedar Creek watershed, subbasins and land use.

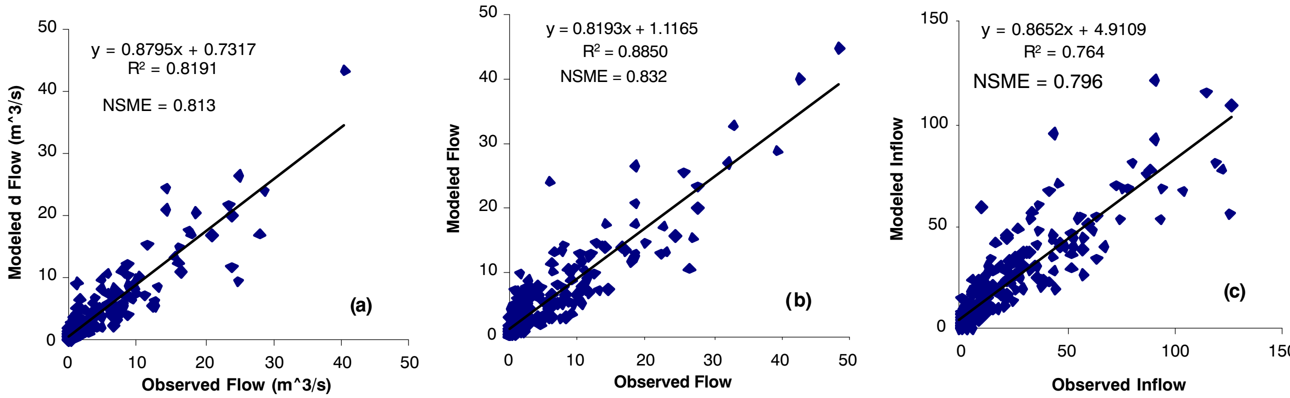

Figure 2. Monthly flow calibration and validation (Narashimhan et al., 2010): (a) at 08062800 (1966-1987), (b) at 08062900 (1966-1987), and (c) at the reservoir (1980-2002).

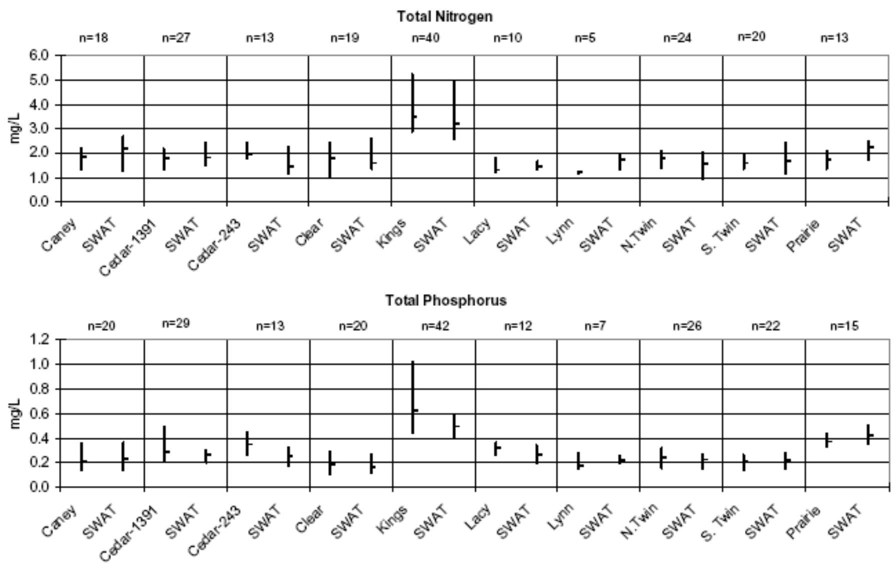

Figure 3. Nutrient calibration at each monitoring site (Narashimhan et al., 2010).

Table 1. Sediment and nutrients loading from each land use (source: Narashimhan et al., 2010).

Land Use	Area (%)	Sediment (%)	TN[a] Loading (%)	TP[b] Loading (%)
Cropland	6.2	40.8	23.4	42.4
Pasture	63.5	15.8	44.1	22.6
Urban	6.4	7.4	14.4	13.3
WWTP[c]	--	0.0	7.2	12.1
Channel	5.5[d]	34.8	5.4	9.2
Forest	15.5	0.7	3.5	0.2
Rangeland	1.1	0.4	1.4	0.1
Wetland	1.8	0.1	0.6	0.1
Total	100.0	100.0	100.0	100.0

[a] TN = total nitrogen.
[b] TP = total phosphorous.
[c] WWTP = wastewater treatment plant.
[d] 5.5% indicates the area of water including lakes.

inflow to the reservoir, not at the USGS gauge stations, because the records at both USGS gauge stations were terminated in 1989. The annual modeled average flow, sediment yield, total nitrogen (TN), and TP were 18.9 $m^3 s^{-1}$, 450,000 tons, 1,419,380 kg, and 188,670 kg, respectively, and those numbers were used as a baseline for the BMP scenarios. The correlation coefficients (r^2) of flow calibration at the two USGS gauge stations were 0.82 (08062800) and 0.89 (08062900), and the Nash-Sutcliffe model efficiency (ME) values were 0.81 and 0.83, respectively (fig. 2). The r^2 value for flow validation was 0.76, and the ME was 0.8. Nutrient calibration results at each monitoring site are shown in figure 3 (see Narashimhan et al., 2010, for calibration details). The model results indicated that the major sources of sediment and nutrients were cropland, which is located mostly in the upper part of the watershed, as well as pastureland, which is scattered throughout the watershed (fig. 1). Table 1 summarizes the sediment and nutrient loadings from each land use category (Narashimhan et al., 2010). Cropland contributes 42.4% of the TP from the watershed, while this land use comprises only 6.2% of the watershed area.

Materials and Methods

Study Area

Cedar Creek watershed, with an area of 2,600 km^2, is located southeast of Dallas in north central Texas (fig. 1). It is a part of the Trinity River basin and eventually discharges to the Gulf of Mexico. Major land uses are pastureland (63.5%), which is distributed throughout the watershed, forest (15.5%), urban (6.4%), and cropland (6.2%), which is distributed mostly in the upper part of watershed, as indicated in figure 1 and table 1. The elevation of the watershed ranges from 73 m to 217 m. Houston Black (clay) and Crockett (sandy loam) are two major soil types among more than 30 different types in the watershed.

BMP Formulation, Effectiveness, and Scenarios

The sensitivity analyses of the BMP effectiveness were conducted by simulating BMPs in the model at a 100% adoption rate (Narashimhan et al., 2007). Note that there were some existing BMPs in the watershed (table 4); the model calibration included the effectiveness of those existing BMPs. The 100% adoption rate is a hypothetical assumption and refers to simulating each BMP in all related land uses with particular conditions, if any (shown in table 2), in the subbasins. For example, terraces were simulated on all croplands with greater than 2% slope in all subbasins. The parameter values used to represent each BMP in the model are summarized in table 3. BMPs were categorized into six types, including cropland, pasture and rangeland, urban, channel, watershed, and WWTP, depending on where they would be installed. Conversion of cropland to pastureland refers to changing all cropland into pastureland to reduce sediment and nutrient loading to the waterbody. Critical pasture planting is planting grass in a highly erodible channel. WWTP levels II and III are BMPs in which the loads from the WWTPs in the watershed were reduced at two different levels using plant modifications. A 2,000 ft (609 m) buffer around the lake is a BMP that disallows the use of P fertilizer for both agricultural and individual households in that area and was applied to 14 subbasins adjacent to the reservoir. A 2,000 ft zone of regulation around the lake is currently in force by TRWD through its Waste Control Order granted by the Texas Commission on Environmental Quality, whereby TRWD regulates septic systems within 2,000 ft of the conservation pool of the reservoir. This jurisdictional area was established as a basis for adoption of a total ban of phosphorus fertilizer with–

Table 2. Effectiveness of BMPs at 100% adoption rates in Cedar Creek watershed (summarized from Narashimhan et al., 2007).

BMP Type	Name	Note	Annual Reduction Rate (%) Sediment	TN	TP
Cropland	Terrace	Cropland with slope larger than 2%	7.0	1.5	7.0
	Contour farming	Cropland with slope larger than 2%	6.0	1.0	6.0
	Crop residue management	Conventional till to minimum till	1.0	+0.1	+1.4
	Conversion of cropland to pasture	--	28.0	18.5	35.0
	Grassed waterway	Subbasins with more than 10% cropland	5.0	2.8	1.6
	Filter strips	15 m width	22.0	17.0	30.0
	Fertilizer/nutrient management	25% reduction in mineral P in cropland	0.0	0.0	2.0
Pasture and rangeland	Prescribed grazing	--	8.0	15.6	5.6
	Fertilizer/nutrient management	25% reduction in N application in pastureland	0.0	3.0	0.0
	Pasture planting	--	8.0	15.6	5.6
	Critical pasture planting	Pastureland planting only at critical area	4.4	6.3	2.8
	Critical area planting	Subbasins with more than 75% pasture	4.0	6.0	2.0
Urban	Urban nutrient management	Reduction on fertilizer use	0.0	10.0	13.0
Channel	Riparian buffer strips	--	23.0	4.3	5.3
	Sediment control basin	--	1.6	0.4	0.2
	Channel stabilization	--	23.0	4.3	5.3
	Streambank and shoreline protection	--	23.0	4.3	5.3
Watershed	Grade stabilization structures	--	2.4	1.6	2.3
	2,000 ft buffer around lake	No fertilizer within 2,000 ft from the lake	0.9	2.8	1.4
WWTP	Level II	--	0.0	1.6	4.6
	Level III	--	0.0	2.7	5.3

Table 3. BMP representation in SWAT model.[a]

BMP	SWAT Representation
Terrace	For all croplands with slope >= 2%, USLE_P changed to 0.5 and CN2 was reduced by 6
Contour farming	For all croplands with slope >= 2%, USLE_P changed to 0.5 and CN2 was reduced by 3
Filter strips	15 for FilterW in .mgt
Critical pasture planting	Manning's *n* of channel on *.sub changed from 0.014 to 0.15
Prescribed grazing	USLE_C in crop.dat is changed from 0.007 to 0.003
Cropland to pasture	CN2 changed appropriately from cropland depending on the soil class appropriate to pastureland (roughly -5), NROT changed to 2, and husc in mgt1.dbf changed to 0 for scheduling by heat units
Riparian buffer strips	Channel cover factor changed for channels above 0.1 to 0.1
Graded stabilization structures	HRUs with slope greater than 3% were changed to 3%
Pasture planting	USLE_C in crop.dat is changed from 0.007 to 0.003
2,000 ft buffer around lake	No fertilizer in the subbasins around the lake
WWTP level II	Replaced point source inputs with WWTP level II data

[a] Only some selected BMPs are shown in this table. Refer to Narashimhan et al. (2007) for more detail.

in that area. Due to the nature of the regulation, the 2,000 ft buffer around the lake is assumed be adopted either 100% or not at all.

The annual average reduction rates of sediment and nutrients for each BMP at a 100% adoption rate are shown in table 2. The largest TP reductions were gained by the conversion of cropland to pasture and by filter strips, with reduction rates of 35% and 30%, respectively. Both BMPs are targeted at cropland, which generates the largest TP load in this watershed even though the total area of this land use is only 6.2% of the watershed (table 1). Some BMPs showed the same effectiveness as each other (e.g., prescribed grazing and pasture planting) because they were represented by the same parameter setting in the model (table 3).

Economical Analyses and Adoption Rate

For economical analyses of BMPs, the adoption rates for each BMP were identified or estimated (table 4). The current rate indicates the existing BMPs in the watershed. The marginal adoption rate is the implementation rate at which each BMP would most likely be adopted in the watershed. The information for this rate was obtained from input by landowners and government agencies reflecting on current implementation and future prospects (Rister et al., 2009). The cost information for each BMP was assessed through consultations with professionals and agencies, was thoroughly discussed among project team members, and includes initial cost, design life, and maintenance of each practice (see Rister et al., 2009 for details). Each BMP was assessed by its cost per ton of TP reduction, and the BMPs were ranked by their costs to identify their relative cost-effectiveness (Rister et al., 2009). In order to determine how many BMPs are needed to achieve the 35% TP reduction goal, the initial TP reduction for each BMP was calculated based on its adoption rate. In this stage, the reduction rates for each BMP were simply added until the total reached 35%. The effect of a combination of BMPs was not considered, as the cost-effectiveness of individual BMPs was considered a priority. Eight BMPs were selected (table 4) out of 21 original BMPs (table 2). The initial TP reduction for each BMP was calculated as (Rister et al., 2009):

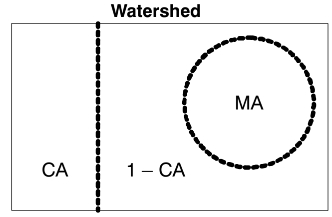

Figure 4. Illustration of equation 1, depicting marginal adoption (MA) area as a subset of the area (1 - CA) in which a BMP is not currently adopted (CA).

$$\text{Initial TP reduction} = \text{TP reduction at FA} \times \left[\frac{\text{MA}}{(1-\text{CA})}\right] \quad (1)$$

where FA is the 100% adoption rate, MA is the marginal adoption rate, and CA is the current adoption rate. The approach embodied in this equation recognizes that some BMPs have already been adopted for a portion (CA) of the area for which their adoption is being considered (fig. 4). An assumption is that the 100% adoption rate is associated only with the remaining portion (1 - CA) of the total possible area in the watershed. This is because the model calibration included the existing BMPs, as mentioned earlier. Discussions with project collaborators, stakeholders, and decision makers responsible for adopting and implementing the BMPs identified the most-likely marginal adoption (MA) rate, representing that portion of the total area in which a BMP is likely to be implemented, considering property owners' goals and objectives, economic incentives, and other germane considerations. Equation 1 facilitates translation of the MA proportion of the total potential remaining area to be treated with the BMP (1 - CA) after eliminating the area already treated (CA) and adjusts the SWAT estimate of TP reduction proportionally. For example, as shown in tables 2 and 4, terracing is currently estimated to occur on 50% of the acreage considered potential for terracing. If terraces were to be implemented on 100% of the remaining 50% of such acreage, then TP would be reduced by 7.0% of the total targeted TP inflow. However, since the most likely adoption level is 15% of the total such area, the projected reduction in TP is 15% divided by (1 - 50%) times the 7.0% total, or 0.3 × 7.0% = 2.1%.

Table 4. Selection of cost-effective BMPs, adoption rates, and initial TP reduction (summarized from Rister et al., 2009).

BMP	Cost Per Ton of TP Reduction[a] ($)	TP Reduction at 100% Adoption (%)	Current Adoption Rate (%)	Marginal Adoption Rate (%)	Initial TP Reduction[b] (%)
Filter strips	4,752	30.0	0.0	50.0	15.0
GSS[c]	8,066	2.3	0.0	100.0	2.3
Critical pasture planting	20,836	5.6	70.0	20.0	1.9
Terrace	31,572	7.0	50.0	15.0	2.1
WWTP level II	41,973	4.6	0.0	100.0	4.6
Cropland to pasture	53,307	35.0	0.0	20.0	7.0
Prescribed grazing	57,969	5.6	10.0	25.0	1.0[e]
2,000 ft buffer[d]	58,303	1.4	0.0	100.0	1.1
Initial and estimated total TP reduction					35.0

[a] Cost is based on TP reduction in metric tons, which was converted from English tons in the original source.
[b] Initial TP reduction was estimated by marginal adoption rate.
[c] GSS = graded stabilization structures.
[d] No P fertilizer application around the lake.
[e] Only 65% of adoption rate was applied.

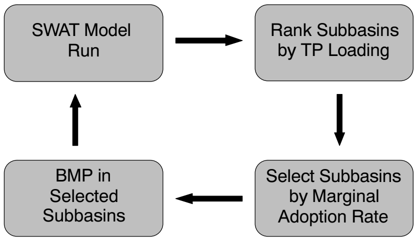

Figure 5. Simulating BMP by the order of cost-effectiveness.

Table 4 lists the selected BMPs, their cost, and their current and marginal adoption rates in order of cost per ton of TP reduction. Filter strips were the most cost-effective BMP in this watershed, with a cost of $4,752 to reduce a ton of TP at the outlet, while the 2,000 ft buffer costs more than 12 times as much ($58,303) to reduce the same amount of TP. Note that prescribed grazing was adopted at only 65% of its marginal rate, and the TP reduction rate was only 1.0% (originally 1.6%). This was because the implementation of a 2,000 ft buffer around the lake was simulated as either all or none, as mentioned earlier. When the 2,000 ft buffer was adopted at 100%, the adoption rate of prescribed grazing should be 65% of its 25% marginal adoption rate in order to achieve 35% TP reduction.

In the next stage, these BMPs were simulated in each subbasin in SWAT to obtain spatially distributed TP reductions and tested to verify that the 35% TP reduction goal was accomplished.

Cost-Effective BMP Simulation

Each BMP was simulated in the model based on the rank of its cost-effectiveness and marginal adoption rate. The most cost-effective BMP was simulated first, up to its marginal adoption rate, and then the next most cost-effective BMP was applied to the model scenario with the first BMP simulated. This series of simulations was conducted until the TP reduction at the watershed outlet reached the goal of 35%. Because none of the channel BMPs were among the eight selected BMPs (table 4), only TP loading from overland flow was considered when the subbasins were ranked by TP loading.

Figure 5 is a flowchart of the model simulation for cost-effective TP reduction. With the calibrated model, subbasins were ranked by TP loading. Then a number of subbasins was selected from the higher-ranked subbasins until their percentage of the total area (or hydrologic response units, HRUs) reached the marginal adoption rate of the BMP. The BMP was then simulated in those selected subbasins, and the model was run for the new TP reduction. For example, for filter strips with a 50% marginal adoption rate, 19 subbasins were selected because the sum of the cropland areas (filter strips were simulated only in cropland) in those 19 subbasins was about 50% of the total cropland area in the watershed (table 5). The SWAT model was then run again in order to re-evaluate the TP loading. After a new ranking of subbasins was obtained with the reduced TP loading, the next BMP was installed until the total area of the newly selected subbasins (or HRUs) reached the marginal adoption rate of the BMP. Note that the model setting with the next BMP included the BMP that was installed earlier. In some cases, such as graded stabilization structures, the adoption rate is 100% and the subbasins did not need to be ranked by TP loading. In addition, in the case of WWTP level II, a subbasin rank by TP loading was not generated because the WWTP had no impact on overland flow.

Table 5. Subbasin selection for each BMPs and TP reduction.

BMP	No. of Selected Subbasins	Note	Accumulated TP Reduction (%)
Filter strips	19	Only cropland	14.2
GSS	--	100% adoption rate	16.1
Critical pasture planting	6	Only critical area	17.1
Terrace	15	Only cropland	21.3
WWTP level II	--	No overland flow	25.9
Cropland to pasture	15	Only cropland	31.7
Prescribed grazing[a]	17→28	Only pastureland	32.8→33.1
2,000 ft buffer	14	Around the lake	34.6

[a] In the selection of BMPs (table 4), prescribed grazing was adopted at only 65% of its marginal adoption rate (25%). However, after SWAT simulation with all eight BMPs, all 25% was needed to achieve TP reduction close to 35%. The 2,000 ft buffer was simulated after prescribed grazing was simulated at the 25% adoption rate.

Results and Discussion

Watershed-Scale TP Reduction

As mentioned above, subbasins with the highest TP loading rates were selected up to the point at which the total area of the selected subbasins was close to the area that was allowed by the marginal adoption rate of each BMP. Table 5 shows the number of selected subbasins for each BMP and the accumulated TP reduction. Some of the BMPs were simulated only on particular types of land use (e.g., cropland BMPs were on only cropland), while watershed BMPs, such as graded stabilization structures, were installed on multiple land uses. Prescribed grazing was initially adopted at only 65% of its marginal adoption rate (25%) (table 4), but it was adopted at 100% of 25% here in order to reach the total TP reduction rate close to 35%.

Spatially Distributed TP Reduction

In addition to achieving the total TP reduction goal at the reservoir, the TP loadings from each subbasin (or local area) were illustrated to visualize the target area and the impacts of BMPs. Figure 6 is a series of maps showing the spatially distributed TP loading from each subbasin and the spatial impacts of BMPs. The maps were generated each time a BMP was added in the model. The maps demonstrate the impacts of each BMP in both a watershed-scale overview and in the area in which the BMP was simulated. The TP loading was categorized with quantile breaks, and the same categories were used on all maps.

Each BMP usually reduced TP only on some parts of the watershed because of installation limitations by land use and physical attributes (e.g., slope). Filter strips (fig. 6a) showed a reduction mostly on the upper watershed. This occurred because the upper watershed has higher TP loadings and because filter strips can be installed only on croplands, which are mostly distributed in this area. Graded stabilization structures and terraces (figs. 6b and 6d) can be installed only in area with higher slopes, and these BMPs generally had impacts on the southwestern part of the watershed where the slope is higher than in other parts of the watershed. In the case of the 2,000 ft buffer around the lake (fig. 6g), subbasin rank-

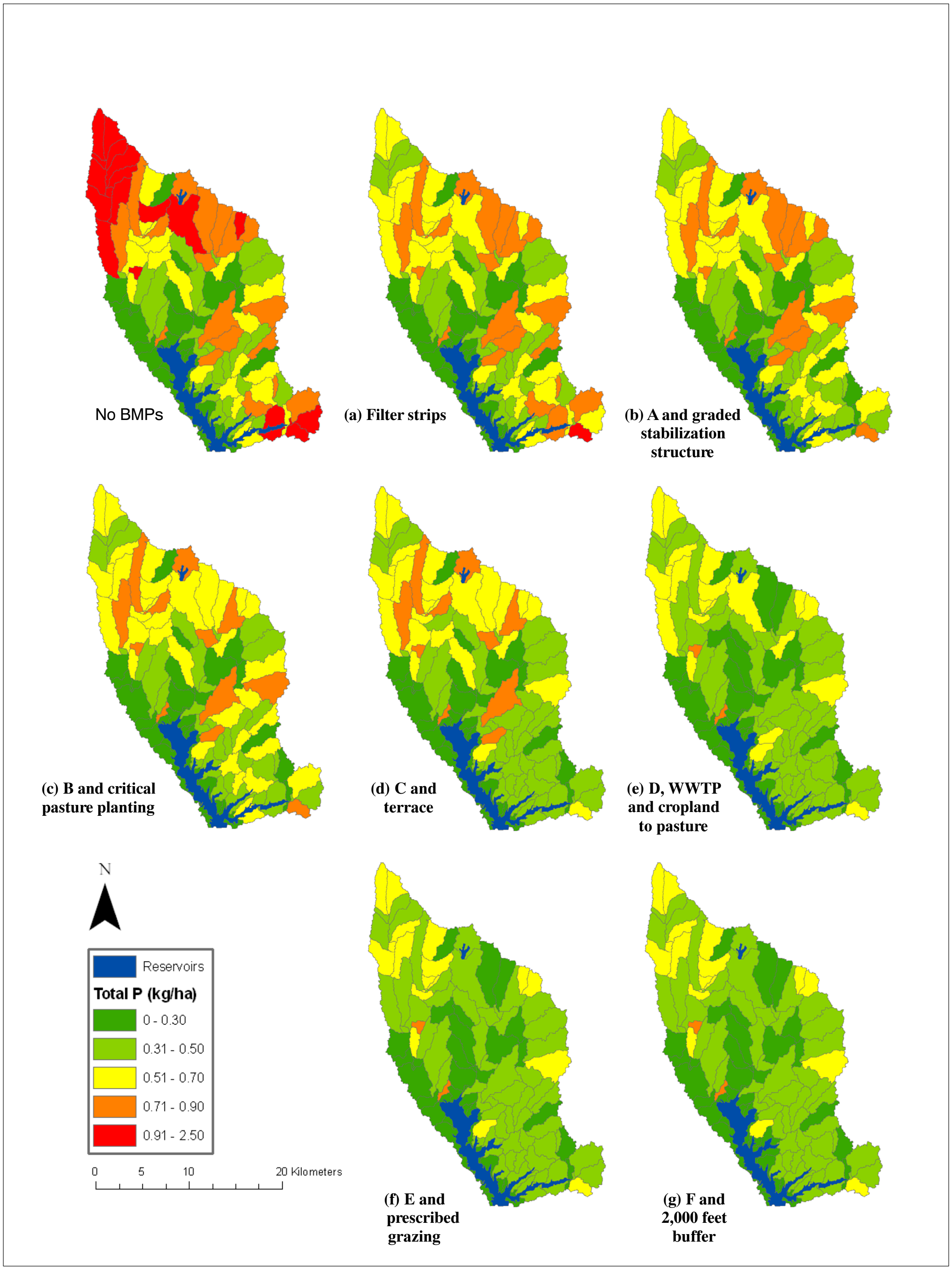

Figure 6. Spatially distributed TP reduction by BMPs.

ing by TP was not taken into account because of the geographical limitation of the practice. Two maps were combined (WWTP level II and conversion of cropland to pasture; fig. 6e) because the TP reduction by WWTP level II does not impact the overland loading, as mentioned earlier.

Table 6 compares the TP reduction by the individually selected BMPs (table 4) with the model simulation based on the subbasins with the highest TP loading rates (table 5). Note that the TP reduction by the selected BMPs is simply estimated by the relationship between TP reduction at 100% and the adoption rate, as shown in equation 1.

The effectiveness of BMPs in the simulation was expected to be much greater than with the initial BMP selection (table 4) because the BMPs were simulated on high-priority subbasins with higher TP loadings. However, the total TP reduction after simulating all selected BMPs was slightly less

Table 6. Comparison of initial TP reduction and model result.

BMP	Initial TP Reduction by Selected BMP[a] (%)	TP Reduction by Model Simulation (%)	
		Individual BMP Contribution[b]	Accumulated Reduction[a]
Filter strips	15.0	14.2	14.2
GSS[c]	2.3	1.9	16.1
Critical pasture planting	1.9	1.0	17.1
Terrace	2.1	4.2	21.3
WWTP[d] level II	4.6	4.6	25.9
Cropland to pasture	7.0	5.8	31.7
Prescribed grazing	1.6[e]	1.4	33.1
2,000 ft buffer	1.1	1.5	34.6
Total	35.0	34.6	-

[a] Values are from table 4 and table 5, respectively.
[b] Individual BMP contribution is obtained by subtracting previous accumulated reduction from new accumulated reduction.
[c] GSS = graded stabilization structures.
[d] WWTP = wastewater treatment plant.
[e] TP reduction at full marginal adoption rate (25%).

(34.6%) than the TP reduction in the initial BMP selection stage (35%). For example, filter strips were estimated to reduce 15% in the initial stage (table 4), but after simulating them in the top-ranked subbasins for TP loading, filter strips reduced only 14.2% (table 5) (Note that filter strip simulation at the initial stage did not consider any high-priority subbasins). This can be explained by several reasons. First, the rate of effectiveness in the initial stage did not consider combinations of BMPs. The sum of the reduction rates of two individual BMPs implemented separately would be larger than that of two BMPs installed at the same location. For example, if a filter strip with 30% TP reduction and a grassed waterway with 20% TP reduction were installed on the same area, their combined effectiveness would be less than a simple sum because the grassed waterway would reduce 20% of the TP that had already been reduced by 30% with the filter strip.

Another reason for the discrepancy between the initial estimation and the simulation results is that the TP reduction in the initial stage did not take into account the geographical location of the BMPs, and they were evenly spread throughout the watershed. Some individual BMPs reduced more and some reduced less than the estimated reduction due to their location, more specifically, their distance from watershed outlet. The reduction rate of filter strips, for example, was less than the initially estimated rate by 0.8% even thought they were simulated for only the top 50% of subbasins for higher TP loading. This is due to the fact that most of the cropland is located in the upper watershed (farthest from the outlet), and the effectiveness of the BMP at the reservoir could be reduced through the routing process. In fact, when filter strips were simulated in subbasins that were not originally selected (i.e., removing all filter strips from the selected subbasins and simulating them in subbasins not originally not selected), the result was a TP reduction of 15.8%, which gives 30% at 100% adoption rate by adding 14.2% and 15.8%. On the other hand, some BMPs that are close to the reservoir, such as the 2,000 ft buffer around the lake, showed higher reduction rates than the estimated rate because they preserved the reduction (i.e., there was minimum impact of routing). Finally, some BMPs showed much higher reduction rates on the top-ranked subbasins for TP loading. For example, terraces showed more effectiveness in the top-ranked subbasins because those subbasins had a higher slope, which was lowered to represent them in the model. This means that the effectiveness of terraces in the subbasins selected by the marginal adoption rate (15%) is greater than in the rest of the subbasins (85%). Finally, especially for the 2,000 ft buffer, the reduction in the simulation was greater than the reduction in the initial stage because it was represented by reducing fertilizer in mass, and the reduction was preserved until it reached the lake (note that the subbasins with this BMP discharge directly into the lake).

Conclusion

As a part of a watershed protection plan, BMP impacts in a watershed must be estimated before the BMPs are implemented. In addition, to gain the largest benefits, the BMPs should be implemented in critical areas first. Based on a previous study including the calibrated SWAT model, economical analyses, and surveys of adoption rates, this study showed optimized scenarios for implementing BMPs for nutrient reduction at the watershed outlet and for spatially distributed impacts on local conditions. In the model, the BMPs were simulated in high-priority areas to maximize the BMP impacts. The subbasins were ranked by TP loading each time a BMP was simulated. Spatially distributed maps of BMP impact were generated and provided an overview of the local impacts of each BMP.

The total TP reduction at the outlet after simulating eight selected BMPs was expected to be more effective than the initial reduction estimation because those practices were simulated in the top-ranked subbasins based on TP loading. However, the effectiveness of the BMPs was just below (34.6%) the initial estimation of 35%. This result can be explained by several reasons: (1) the decreased impacts of combinations of BMPs, (2) the geographical distribution of BMPs was not considered in the initial stage, (3) the BMPs did not have the same effectiveness in all subbasins or HRUs, and (4) for some BMPs, such as the 2,000 ft buffer around the lake, the TP reduction was preserved because this BMP was implemented very close to the lake.

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