

Assessing the efficiencies of alternative best management practices to reduce non-point source pollution for a sub-watershed in Louisiana, USA

Abstract

Alternative best management practices applied in an agricultural context are evaluated for cost-effectiveness in a sub-watershed in Northern Louisiana. A GIS-based watershed simulation model is coupled with a linear programming model to assess the effectiveness nine Best Management Practices (BMPs) based on implementation cost and phosphorus reduction. The optimization model is conducted at varying target phosphorus reduction levels, revealing the most cost-effective combination of BMPs to achieve that level of reduction. At lower levels of phosphorus reduction, nutrient management is the most cost-effective BMP. As phosphorus reduction targets increase a combination of several BMPs is needed to achieve target reductions.

Keywords: nonpoint source pollution, best management practices, economics, mitigation, optimization, water quality

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Introduction

The U.S. EPA (2012) estimates that 40% of waterways in the United States do not meet their intended use.¹ Though there are many factors influencing water pollution, an estimated 60% of these impairments are due to nonpoint source (NPS) pollution. Agriculture has been determined to be the primary source of NPS pollution in the United States. NPS pollution comes from a variety of sources, but is characterized by its diffuse nature and multiple sources. NPS from agriculture is due largely to runoff from fertilizer application, leaching nitrogen (N), phosphorus (P) and sediment (S) into waterways near agricultural land. Fertilizer leaching has been shown to lead to eutrophication and hypoxia, impairing local waterways for fish and wildlife, as well as contributing to cumulative problems such as the “dead zone” in the Gulf of Mexico. BMPs, defined as a diverse range of structural and management practices aimed to reduce NPS pollution, were identified and developed in order to reduce NPS pollution.² While BMPs have been implemented for several decades, factors determining which BMPs are most cost-effective are often not properly examined. BMP efficiency depends on several site-specific factors including weather conditions, soil hydrology and erosion as well as topography. To address these issues, researchers have developed and utilized Geographic Information System (GIS) based simulation models to estimate nutrient runoff and BMP efficiency, given site-specific input data. While several models have been developed (SWAT, SPARROW, HSPF and Mapshed), this study utilizes Mapshed, a model developed by Evans and Cardini at Pennsylvania State University to simulate effluent runoff and BMP-efficiency.³ This model has been adapted to several different states and countries by subsequent research teams.⁴⁻⁶ Mapshed has been to identify best management practices capable of reducing nonpoint source pollution in Pennsylvania coastal zone.⁴ Using a nonpoint screening optimization model, they identify that barren land and recreational field be planted with grass swales BMP or fitted with bioretention cells and stream bank erosion protection be chosen to reduce sediment pollution. AVGWLF (a precursor to Mapshed) is used to identify the sources of nitrogen, phosphorus and

sediment from point and nonpoint sources in Isreal’s Lake Kinneret watershed.⁵ GWLF (a precursor to Mapshed) is used to identify the sources of total nitrogen nonpoint source pollution and planning for optimal choice of best management practices to reduce nitrogen pollution.⁶

This study utilizes a simple linear programming algorithm to determine the most cost-effective management practices. While several studies have used more complex methods for estimating locally cost-effective BMPs, these methods have met with little application by policy makers.⁷⁻¹⁰ For example, all these three mentioned papers have used a genetic algorithm to identify optimal combination of best management practices.⁷⁻⁹ This study argues that spatial optimization can be determined with a linear programming model in combination with a GIS-based simulation model. We will use this model to determine the most cost-effective BMPs for Bayou Desiard, a sub-watershed in Northcentral Louisiana. Furthermore, we will develop a simple BMP evaluation tool that policy makers can utilize for decision-making.

Study area

The Bayou Desiard sub-watershed (HUC: 0804020702) is located in Northcentral Louisiana (Figure 1). Bayou Desiard is primarily located in Ouachita County, with small portions in Jackson and Caldwell counties. The sub-watershed covers an area of 56,806 hectares and centers around Bayou Desiard and Lake Bartholomew. The crop production area in the watershed measures 10,629 hectares with 42,000 meters of streambank. Both the LDEQ and EPA have listed Bayou Desiard as an impaired waterway. Bayou Desiard has an established TMDL. The TMDL asserts that Bayou Desiard does not meet fish and wildlife standards. The cause of impairment has been listed as low dissolved oxygen levels as well as organic enrichment.¹¹

The study area is located in the broiler production region of Louisiana. Poultry production is Louisiana’s largest animal industry, contributing an annual sum of 1.5 billion to the state’s economy.

Broiler production constitutes a large portion of the state's poultry production, contributing a gross farm value of \$876.1 million to the economy in 2012.¹² Over application of poultry litter as a fertilizer

is often a problem in areas with high poultry production. Over application leads to phosphorus leaching into groundwater, which then flows to surrounding waterbodies.¹³

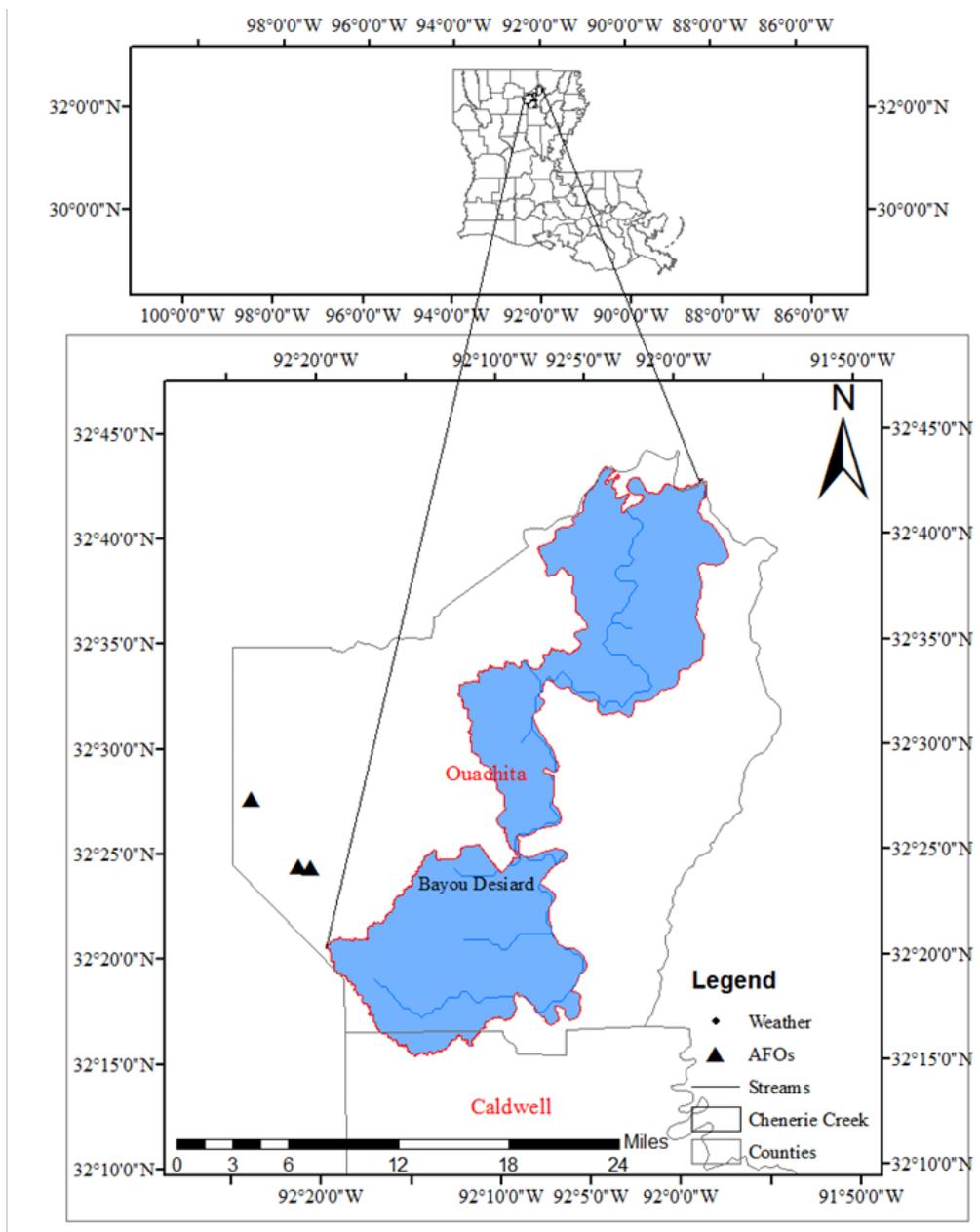


Figure 1 Bayou desiard sub watershed in Louisiana.

Methods

The Mapshed model is applied to estimate effluent runoff and BMP efficiency. This model utilizes various GIS layers containing data about the regions topography, soil characteristics, weather conditions and land use/cover to estimate nutrient and sediment runoff in the sub-watershed. This data is combined with BMP efficiency data from a comprehensive literature review, conducted by Evans & Cardini.³ The BMP efficiency estimates are combined with cost data, obtained at the county level, to estimate cost-efficiency in the watershed. The cost and BMP efficiency data are optimized using a simple linear programming model, which determines the most cost-effective level of BMP application at various levels of phosphorus reduction.

Mapshed and GWLF-E

The Mapshed model was developed by Pennsylvania State University as a tool for estimating effluent runoff and BMP characteristics in Pennsylvania. However, this model has since been utilized in several different geographic regions. Mapshed has been evaluated by the EPA as a “good mid-level watershed modeling tool” in a study comparing several watershed modeling programs.¹⁴ Mapshed is a distributed/ lumped parameter model, meaning that it is distributed parameter model in surface loading, considering various land use cover scenarios, and a lumped parameter model in sub-surface loading. The model is continuous with respect to weather, utilizing daily inputs. Erosion and sediment yield calculations are estimated

on a monthly basis and combined with transport capacity, based on watershed size and daily runoff, to determine sediment loadings. Dissolved phosphorus and nitrogen coefficients are applied to surface runoff estimates to determine surface nutrient losses. Subsurface losses are calculated by using phosphorus and nitrogen coefficients for shallow groundwater. Monthly nutrient loadings are averaged into yearly loadings, which are used to estimate average loadings over the entire 10-year period. A full description of all Mapshed components can be found in Evans & Cardini.³ When the necessary data layers have been added to Mapshed, the model uses them to estimate nutrient and sediment loadings for the given study area. These loadings are then used as inputs for GWLF-E, which can be used for BMP reduction estimates. Loadings are estimated for each of the six cropland BMPs (cover crops, conservation tillage, conservation crop rotation, grade stabilization structure, nutrient management and retirement of agricultural land) and three streambank BMPs (vegetative buffer, streambank stabilization and streambank fencing) from 0%-100% of cropland coverage (streambank length for streambank BMPs) at 2% increments. This yields a baseline loading of 0% BMP application and 50 load reduction estimates for each BMP. These load reduction estimates are regressed against total cropland (streambank length for streambank BMPs), using the ordinary least squares method, to yield a BMP efficiency coefficient for each BMP. This coefficient represents the per-hectare reduction for each BMP in the study area. Whenever watershed modeling is utilized, issues of model calibration arise. Nutrient and sediment loading data in Bayou Desiard are not yet available, making true model calibration impossible. To account for this problem we have calculated a range of BMP efficiencies from 10% less effective to 10% more effective. These results are also provided to give a broader perspective and better approximate true BMP performance in the area.

Linear programming based optimization model

The per-hectare efficiency estimates from the simulation model are combined with cost data from the area in a linear programming model. Cost is minimized, with nitrogen and sediment constrained to non-negativity and phosphorus constrained to different target levels of reduction, which are determined as a percentage of estimated total phosphorus loading in the area. Additional constraints include constraining cropland BMPs to total cropland area, constraining streambank BMPs to total streambank area, constraining agricultural land retirement to 10% of total agricultural land and vegetative buffer to 30% of total streambank length. Agricultural land retirement is constrained as retiring all agricultural land is impractical. Agricultural land retirement rates of approximately 7% were observed in 2007 (the last year data was collected for this area).¹⁵ Vegetative buffer is constrained to 30% of all streambank length because an adoption rate of greater than 30% was deemed unlikely as stated by local Natural Resources Conservation Services agents.

The linear programming model used in this study is formulated as follow:

$$\text{Min } \sum_{i=1}^j c_i B_i \tag{1}$$

Subject to,

$$\text{Nitrogen} : \sum_{i=1}^j n_i B_i \geq 0 \tag{2}$$

$$\text{Sediment} : \sum_{i=1}^j s_i B_i \geq 0 \tag{3}$$

$$\text{Phosphorus} : \sum_{i=1}^j p_i B_i \geq \alpha I_p \tag{4}$$

$$\text{Other} : \sum_{i=1}^j o_{i,k} B_i \leq R_k, \text{ for all } k = 1, \dots, K \tag{5}$$

$$B_i \geq 0 \tag{6}$$

where : c_i = Cost of BMP i

B_i = BMP i

c_i = Cost of BMP i

n_i = Nitrogen reduced by BMP i

s_i = Sediment reduced by BMP i

p_i = Phosphorus reduced by BMP i

α = Some fraction of total phosphorus

I_p = Total phosphorus loading

$o_{i,k}$ = Land unit covered by BMP i for land use k

R_k = Maximum allowable land useage for use k

BMP cost-efficiency estimate

An important step in determining the most cost-effective BMP combination for any study area is measuring the cost-efficiency of each BMP. While additional spatial, economic and environmental constraints may change the optimal combination of BMPs, having a metric of cost-effectiveness is a useful tool for the policy maker. We calculate the cost-efficiency estimate for each BMP by dividing the reduction per-hectare by the cost per-hectare, yielding the kg/\$ for N and P and the tons/\$ for S for each BMP. This tool is useful to the policy maker as a variable that may be difficult to quantify, such as local opinions about various conservation practices, may yield a different outcome than the optimization model. However, this metric should be used with caution as it will not always reveal the true optimal solution, if all appropriate constraints are considered. The BMP cost-efficiency numbers are presented in Table 1.

Table 1 Per hectare unit reduction costs for BMPs

BMP	N (\$/kg)	P (\$/kg)	S (\$/ton)
Cover Crop	\$67.24	\$100.49	\$353.30
Conservation Tillage	\$96.16	\$90.10	\$162.61
Conservation Crop Rotation	\$57.38	\$73.92	\$113.70
Grade Stabilization Structure	\$69.06	\$166.13	\$299.21
Nutrient Management	\$8.43	\$25.23	\$0.00
Agland Retirement	\$9.47	\$44.38	\$109.21
Vegetative buffer	\$15.08	\$51.03	\$94.78
Fencing	\$206.41	\$162.15	\$76.02
Streambank Stabilization	\$1,874.52	\$2,051.47	\$937.06

Results

The most cost-effective combination of BMPs varied at different levels of phosphorus reduction. At lower levels of phosphorus reduction (10%-30%), nutrient management was the most cost-effective BMP. At higher levels of phosphorus reduction, a more diverse range of BMPs was employed to achieve the desired nutrient reduction. The BMPs utilized at 50% and higher phosphorus reduction levels are grade stabilization, nutrient management, retirement of agricultural land, vegetative buffer and stream bank fencing. At lower levels of phosphorus reduction (10%-30%), total cost increases with greater phosphorus reduction while marginal and average costs remain constant. Total cost increases as more land is placed under a nutrient management plan, while marginal and average costs are constant as nutrient management plan is the only BMP being employed at these levels of reduction. When higher reduction levels are reached (50% and above), total, average and marginal costs increase sharply. This increase is caused by less cost-efficient BMPs, which have greater per-hectare efficiency, entering the solution. These less cost-effective BMPs are necessary to achieve reduction goals, as land constraints become more binding. Total, average and marginal costs are presented in Table 2. In addition to average rainfall amounts, a “wet” year with higher than average rainfall (2004) and a “dry” year with lower than average rainfall (2005) are also examined. The wet

year examined is the year with the greatest amount of rainfall over the 10-year study period, while the dry year is the year with the least rainfall over the 10-year study period. The findings from these years were as expected, with wet years producing more runoff and higher than average efficiencies and dry years producing less runoff and less efficient BMPs. Lower reduction costs lead to lower total, average and marginal costs, at any given reduction percentage, in wet years and greater total, average and marginal costs, at any given reduction percentage, in dry years. However, these numbers can be misleading, as total runoff is greater in wet years than average and dry years. Costs for wet and dry years are presented in Table 3 & Table 4, respectively.

In addition to standard reduction coefficients drawn from the Evans & Cardini³ literature review, estimates were given at + or – 10% BMP reduction efficiencies. These estimates are given to account for the lack of waterway loading data in the study area.³ As expected, lower reduction coefficients yield less efficient BMPs and increase total, average and marginal costs. Higher reduction coefficients yield more efficient BMPs and increase total, average and marginal costs. While these results may seem obvious, they nonetheless provide important information for policy makers, giving a range of costs to account for uncertainty, rather than a static number. High and low reduction coefficient costs are presented alongside standard coefficients in Table 2, Table 3 & Table 4.

Table 2 Summary of total pollutant reduction costs at different levels of targeted phosphorus reduction

Scenario	Cost (\$1000)	Reduction			Cost/ Unit		
		N (tons)	P (tons)	S (1000 tons)	N (\$/kg)	P(\$/kg)	S(\$/ton)
10%	137.7	16.3	5.5	0.0	\$8.43	\$25.23	\$0.00
10% D10	151.4	16.1	5.5	0.0	\$9.41	\$27.75	\$0.00
10% U10	126.2	16.3	5.5	0.0	\$7.73	\$23.13	\$0.00
15%	206.6	24.4	8.2	0.0	\$8.43	\$25.23	\$0.00
15% D10	227.2	24.2	8.2	0.0	\$9.41	\$27.75	\$0.00
15% U10	189.3	24.8	8.2	0.0	\$7.64	\$23.13	\$0.00
20%	275.4	32.7	10.9	0.0	\$8.43	\$25.23	\$0.00
20% D10	303.0	32.2	10.9	0.0	\$9.41	\$27.75	\$0.00
20% U10	252.4	33.1	10.9	0.0	\$7.64	\$23.13	\$0.00
30%	413.1	49.0	16.4	0.0	\$8.43	\$25.23	\$0.00
30% D10	467.5	48.5	16.4	0.2	\$9.64	\$28.55	\$104.82
30% U10	378.7	49.6	16.4	0.0	\$7.64	\$23.13	\$0.00
50%	2,262.6	82.3	27.3	11.1	\$27.51	\$82.91	\$183.54
50% D10	5,937.7	75.0	27.3	16.4	\$79.12	\$217.58	\$362.42
50% U10	979.5	88.2	27.3	16.7	\$11.11	\$35.89	\$86.10
Max (56%)	3,886.9	83.9	30.0	17.2	\$46.30	\$129.48	\$224.75
Max U10 (60%)	3,922.3	91.4	32.7	18.9	\$42.90	\$119.77	\$206.62

Note: “D10” and “U10” represent 10% decreased and increased BMP efficiency coefficients, respectively. “Max” represents the maximum reduction possible.

Table 3 Summary of total pollutant reduction costs at different levels of targeted phosphorus reduction in a wet year (2004)

Scenario	Cost (\$1000)	Reduction			Cost/ Unit		
		N (tons)	P (tons)	S (1000 tons)	N (\$/kg)	P(\$/kg)	S(\$/ton)
10%	133.2	26.2	8.5	0.0	\$5.16	\$15.60	\$0.00
10% D10	146.5	25.8	8.5	0.0	\$5.68	\$17.16	\$0.00
10% U10	122.1	26.5	8.5	0.0	\$4.61	\$14.30	\$0.00
15%	199.8	39.2	12.8	0.0	\$5.09	\$15.60	\$0.00
15% D10	219.8	38.7	12.8	0.0	\$5.68	\$17.16	\$0.00
15% U10	183.1	39.7	12.8	0.0	\$4.61	\$14.30	\$0.00
20%	266.4	52.3	17.1	0.0	\$5.09	\$15.60	\$0.00
20% D10	293.0	51.6	17.1	0.0	\$5.68	\$17.16	\$0.00
20% U10	244.2	52.9	17.1	0.0	\$4.61	\$14.30	\$0.00
30%	399.6	78.5	25.6	0.0	\$5.09	\$15.60	\$0.00
30% D10	439.5	77.4	25.6	0.0	\$5.68	\$17.16	\$0.00
30% U10	366.3	79.4	25.6	0.0	\$4.61	\$14.30	\$0.00
50%	1,810.4	139.8	42.7	13.5	\$12.95	\$42.41	\$112.91
50% D10	3,581.4	132.2	42.7	21.0	\$27.09	\$83.89	\$167.65
50% U10	839.0	146.6	42.7	7.1	\$5.72	\$19.65	\$61.81
Max (57%)	3,972.3	150.9	48.7	25.5	\$26.33	\$81.62	\$155.10
Max D10 (51%)	3,943.2	133.8	43.5	22.8	\$29.48	\$90.55	\$172.23
Max U10 (62%)	3,957.8	164.2	52.9	27.8	\$24.10	\$74.76	\$142.16

Note: “D10” and “U10” represent 10% decreased and increased BMP efficiency coefficients, respectively. “Max” represents the maximum reduction possible.

Table 4 Summary of total pollutant reduction costs at different levels of targeted phosphorus reduction for in a dry year (2005)

Scenario	Cost (\$1000)	Reduction			Cost/ Unit		
		N (tons)	P (tons)	S (1000 tons)	N (\$/kg)	P(\$/kg)	S(\$/ton)
10%	154.5	8.7	2.7	0.0	\$17.66	\$57.33	\$0.00
10% D10	170.0	8.6	2.7	0.0	\$19.70	\$63.06	\$0.00
10% U10	141.7	8.8	2.7	0.0	\$16.01	\$52.55	\$0.00
15%	231.8	13.1	4.0	0.0	\$17.66	\$57.33	\$0.00
15% D10	255.0	12.9	4.0	0.0	\$19.70	\$63.06	\$0.00
15% U10	212.5	13.2	4.0	0.0	\$16.01	\$52.55	\$0.00
20%	309.1	17.5	5.4	0.0	\$17.66	\$57.33	\$0.00
20% D10	340.0	17.3	5.4	0.0	\$19.70	\$63.06	\$0.00
20% U10	283.3	17.7	5.4	0.0	\$16.01	\$52.55	\$0.00
30%	486.6	26.2	8.1	0.2	\$18.59	\$60.17	\$188.34
30% D10	583.6	25.7	8.1	0.7	\$22.73	\$72.16	\$208.11
30% U10	425.0	26.5	8.1	0.0	\$16.01	\$52.55	\$0.00
50%	4,823.6	31.0	13.5	9.6	\$155.65	\$357.87	\$500.39
50% U10	2,534.7	37.1	13.5	7.2	\$68.28	\$188.05	\$322.79
Max D10 (48%)	1,908.8	31.6	10.8	4.9	\$60.34	\$177.02	\$333.12
Max U10 (54%)	3,953.6	33.7	14.6	10.2	\$117.26	\$271.59	\$386.68

Note: “D10” and “U10” represent 10% decreased and increased BMP efficiency coefficients, respectively. “Max” represents the maximum reduction possible.

Conclusion

Many watersheds in the United States suffer from nutrient and sediment pollution emanating from nonpoint sources. We examined the effectiveness of nine different BMPs in a sub-watershed in the broiler production region of Louisiana using GIS and linear programming model. In this sub-watershed nutrient management is the most cost-effective BMP at lower levels of phosphorus reduction, while at higher levels of phosphorus reduction a range of BMPs is employed to achieve the reduction goal at the least cost. Furthermore, this paper outlines a framework for using a simple linear programming algorithm to determine the cost-effectiveness of BMPs in a watershed. While this research utilizes targets phosphorus reduction, these tools could easily be used to target any other pollutant. This research provides several different important tools for decision makers. It provides the framework for a simple linear programming method, which could easily be used by decision makers to determine the cost-effectiveness of BMPs in an area. It further provides a range of per-hectare efficiency estimates and cost efficiency estimates for nine different BMPs in the region. As TMDLs are developed for a greater number of waterbodies in the United States, these simple but often over looked tools and estimates can be used to aid policy makers in decision-making.

Future studies can make use of updated data and more advanced technology to provide better estimates. This study proposes using a range of BMP efficiencies in order to account for a lack of calibration data; however, real world data is always preferable and should be incorporated into estimated models as soon as it becomes available. Therefore, experimental data on the effectiveness of each BMP in the study area would increase the validity of this study. GIS-technology is capable of estimating loadings over a smaller and smaller area. Conceivably, in the future it could pinpoint the exact hectare of land that is producing the most nutrient runoff. This can be done by identifying the critical source area and then simulating the effects of alternative best management practices adoption. Further spatial accuracy will help to increase the efficiency of BMPs and may change the optimal combination, as pinpointing land with the greatest amount of runoff becomes feasible. Improvements in spatial technology will greatly improve research of this nature.

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Conflict of interest

The authors declare that there is conflict of interest.

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