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Modelling of Best Management Practices in Agricultural Areas

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1. Introduction

Concern over water and pollutants influencing human health has been increasing in the last few decades. Nonpoint source (NPS) pollution, especially, led to water quality degradation in watersheds; therefore, water quality in streams or rivers has been made subject to government regulations (e.g., the Clean Water Act). Typically, watersheds are composed of various land uses; agricultural areas were a possible major source of phosphorus in a watershed [1,2]. Approximately 50% of NPS is from agricultural areas, since 52% of total nitrogen, 47% of total phosphorus, and 46% of sediment in U.S. streams are from agricultural areas [3]. A high concentration of total nitrogen came from agricultural areas in the watershed, and fertilization during cropping in an agricultural area led to a high concentration of high nitrate and orthophosphate [4,5]. Pollutants from three watersheds were compared [5]: agricultural watershed (95% agriculture and 5% urban), mixed watershed (43% agriculture and 57% urban), and urban watershed (1% agriculture and 99% urban) (Figure 1). Nitrate and soluble phosphorus concentrations in a stream were higher in the agricultural watershed, the other nutrients' concentrations (total suspended solids, turbidity, and pH) were higher in the urban watershed [5]. In addition, total phosphorus and ammonium concentrations did not display much difference by watershed types. They indicated that agricultural activity such as fertilization led to the higher nitrate and soluble phosphorus concentrations in the agricultural watershed; that the pollutant loads of nutrients and sediment were significantly variable by sites and land uses due to flow quantity; and that pollutant load quantification can be difficult since it varies by sites, land uses, season, and flow. Therefore, best management practices (BMPs) to reduce or manage pollutant loads in watershed have been studied in the last few decades [6–9]. In this chapter, recent research of BMPs in agricultural areas in various water-

sheds, with various optimization techniques and hydrologic models, were introduced to provide the rationale via which the researchers estimated the impact of BMPs in agricultural areas and to identify the processes by which the researchers optimized BMPs in watersheds.

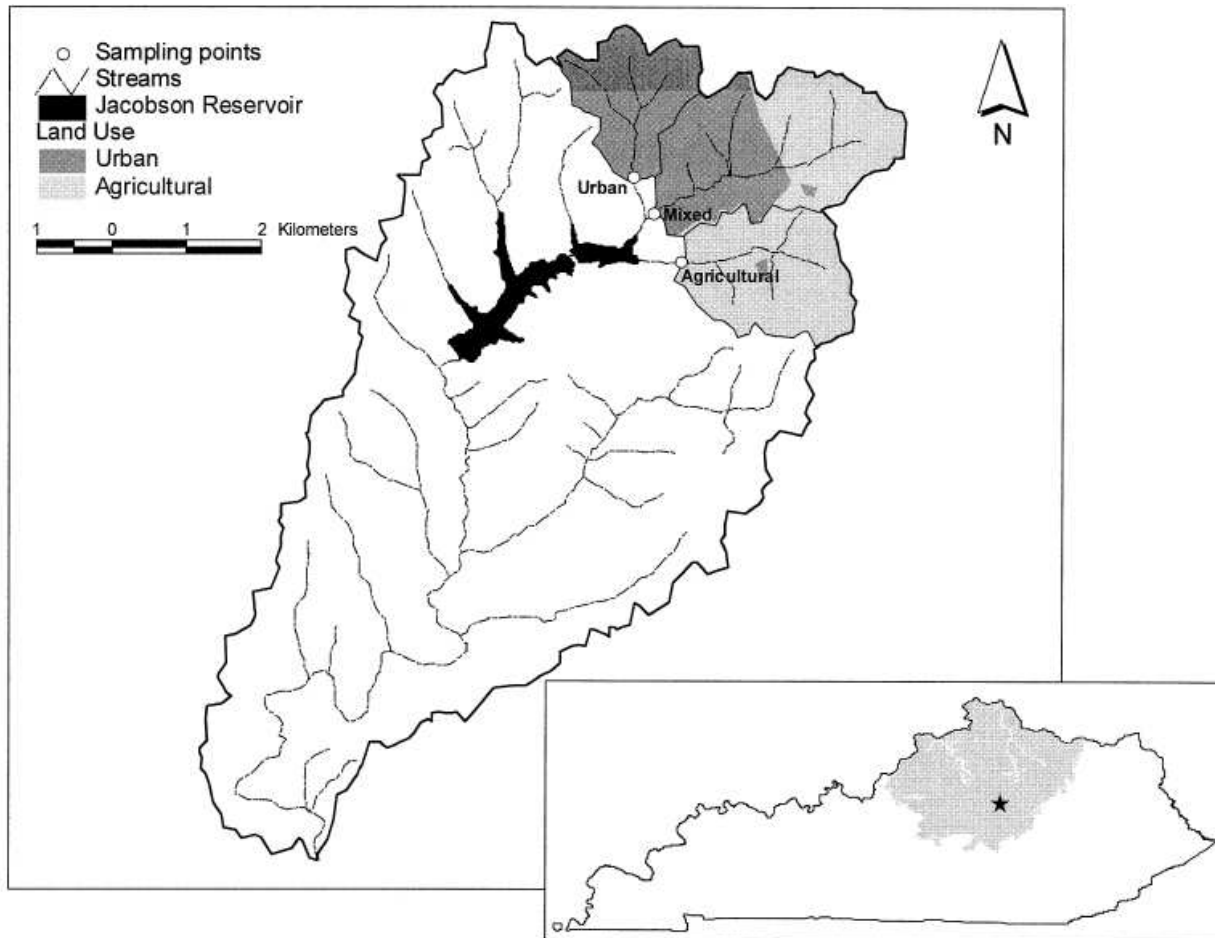


Figure 1. Agricultural, mixed, and urban watersheds in the State of Kentucky (adapted from [5])

2. Best management practices and pollutant control in watersheds

2.1. Best management practices in watersheds

BMPs were originated for soil erosion control [10] and have recently been implemented to control other NPS [11–14]. It can be readily found that BMPs were optimized using a hydrology model with either a straightforward or a sophisticated approach [15–18]. According to the study by Rao et al. [2], Variable Source Loading Function (VSLF) [19] was applied in a 164 ha agricultural area to estimate BMPs for dissolved phosphorus and total phosphorus. VSLF defines hydrologic response units (HRUs) by the soil wetness index and land uses; BMPs can be applied by pollutant reduction coefficients (or ratio). Three BMPs (crop rotation, strip cropping, and filter strip) for agricultural area were applied, and pollutant reduction coeffi-

coefficients were defined based on BMPs and soil wetness index. BMPs were implemented in the middle of a model simulation period, therefore the VSLF model was calibrated through the period prior to BMP implementation, and the pollutant reduction coefficients were calibrated through the period subsequent to BMP implementation. The study pointed out that BMPs led to decreases runoff losses.

A Soil and Water Assessment Tool (SWAT) [20] model was applied to a watershed of 50 km², and 55% of the watershed was an agricultural area [21]. The effect of four BMPs (crop rotation, reducing nutrient application, reduction of livestock density, and buffer strip) were estimated for annual total nitrogen, sediment, and total phosphorus. Annual total nitrogen reduction ranged from 9.9% to 46.7%, however, the BMPs were not effective at reducing sediment and total phosphorus due to the fact that annual sediment reduction by BMPs ranged from 0.82% to 11.9% and that annual phosphorus reduction by BMPs ranged from 1.1% to 13.6% (Table 1). Since both BMP effectiveness and BMP implementation costs are important, BMP implementation costs were analysed for the watershed based on establishment and maintenance costs. In the study, it was concluded that 1) crop rotation was not applicable since the implementation cost was extremely high, and 2) BMPs were not effective for annual sediment and total phosphorus reduction, while BMPs were effective for annual total nitrogen reduction.

BMPs	Total nitrogen	Sediment	Total phosphorus
Crop rotation	9.9%		4.6%
Reducing nutrient application	8.6%	0.8%	1.1%
Reduction of livestock density	15.6%	3.5%	3.9%
Filter strip	12.9%	4.9%	5.3%
Combined BMPs	46.7%	11.9%	13.6%

Table 1. Nutrient reductions by BMPs

There are several rationales to focus on regarding BMP implementations in agricultural areas. One is that the agricultural area is typically one of the major sources of NPS in a watershed. There are several research studies indicating that the pollutant loads from agricultural areas are more severe than those from urban areas in watersheds [5,22], since agricultural activities increase pollutant concentrations (or loads) during the cropping season [5,23], and the exposed soil surface has more soil erosion potential [24].

The other rationale to implement BMPs in an agricultural area is the cost. BMP implementation costs can be estimated by the Equations 1 [25] or 2 [26], for instance, which require an establishment cost (or capital cost). The costs for urban BMPs are typically more expensive than the costs for agricultural BMPs (Table 2). Reference [18] estimated the impact of BMPs for a watershed; the most cost-effective BMP was a filter strip for an agricultural area reducing 147.5 kg/year for \$7,650, while the impact of a filter strip on urban areas was estimated to reduce 1 kg/year for \$2,040. Therefore, the BMP implementation in agricultural area are typically more cost-effective than in urban.

$$A_{BMP} = \frac{Z \cdot \left(\frac{s}{100}\right)}{1 - \left(1 + \frac{s}{100}\right)^{-td}} \quad (1)$$

$$c_t = c_0 \cdot (1 + s)^{td} + c_0 \cdot rm \cdot \left[\sum_{i=1}^{td} (1 + s)^{(i-1)} \right] \quad (2)$$

Where A_{BMP} is the annual cost for a BMP, Z is the capital cost (\$) of a BMP, s is the interest rate (%), td is the BMP design life, c_t is the BMP implementation cost (\$/ha), c_0 is the establishment cost (%/ha), and rm is the ratio of annual maintenance cost to establishment cost (i.e., the percentage of establishment cost).

Land uses	BMP	C_0	rm	Reference
Cropland	Contour farming	15	1	[23]
	Filter strip	21	10	[24]
	Reduced tillage systems	7	1	[25]
Forest	Site preparation/hydro mulch/seed/fertilizer	3707	1	[26]
	Site preparation/straw/crimp/net	35,481	1	[27]
Feedlots	Filter strip	21	10	[24]
Urban	Alum treatment	1,112	0	[28]
	Grass swales	1,730	5	[29]
	Infiltration basin	7,413	3	[29]
	Infiltration trench	22,239	5	[29]
	Porous pavement	592,015	1	[30]
	Sand filter	25,946	12	[29]
	Vegetated filter strips	2,224	4	[29]
	Weekly street sweeping	14,947	7	[30]
	Wetland detention	6,178	2	[29]

Table 2. BMP costs for land uses [18]

2.2. Optimizations of best management practices

The previous sections introduced why BMP simulations were often applied in agricultural areas and how BMP implementation costs could be estimated, since BMP implementations at watershed are required to be cost-effective. In this section, several related research results are reviewed and presented to introduce how BMPs were optimized to be cost-effective BMP scenarios.

Gitau et al. [35] optimized three BMPs for an average annual loading reduction of dissolved phosphorus of 60%: which were contour strip cropping, having a nutrient management plan,

and riparian forest buffers. To demonstrate BMP optimization, a farm of 300 ha was selected: which is located at the Town Brook watershed in New York State. Cropland and pasture areas are 44% and 19% in the study area, BMP implementation was considered for cropland and pasture areas. The BMP optimization process comprised four components. The first component was a SWAT model to simulate dissolved phosphorus and BMPs in the study area. BMPs were assigned for each HRU, since the model divides a watershed into sub-watersheds and HRUs defined by land use, hydrologic soil group, and slope. The second component was the BMP tool [36]. The BMP tool has a database of BMP effectiveness data for 32 BMPs, which were collected from published BMP monitoring studies. The BMP effectiveness database contains particulate phosphorus, dissolved phosphorus, total phosphorus, nitrogen, sediment, and runoff reduction by BMPs. The BMPs can be categorized into eight classes: animal waste systems, barnyard runoff management, conservation tillage, contour strip crop, crop rotation, vegetated filter strips, nutrient management plans, and riparian forest buffers. The third component was computing annual BMP implementation costs considering capital cost, interest rate, and BMP design life. Annual costs were \$11/ha for contour strip cropping, \$27/ha for nutrient management plan, and \$1,942/ha for riparian forest buffers. Contour strip cropping was considered for cropland and pasture, a nutrient management plan for cropland and pasture, and riparian forest buffers for all agricultural areas bordering a stream. The last component was a genetic algorithm (GA). The study area was divided into 168 HRUs, and 149 HRUs which were croplands or pastures. The GA optimized the BMPs for the HRUs of cropland and pasture based on the annual implementation costs.

Two solution scenarios to implement BMPs were established (Figure 2). Both scenarios were able to reduce 60% of dissolved phosphorus at the cost of \$1,430/year and \$1,683/year, respectively. One of the scenarios required slightly lower costs, since the scenario applied BMPs to a smaller study area than the other scenario did. The authors mentioned that the BMP optimization technique they used is applicable for other studies to optimize BMPs on the level of average annual estimation. However, they also mentioned that their results were site-specific; therefore, the method cannot be used directly if land uses or site characteristics are different.

In the study of Maringanti et al. [37], two BMPs were optimized at Wildcat Creek Watershed located in Indiana, for atrazine reduction. Atrazine is one of the herbicides used in corn production and is used for broadleaf weed control. The watershed, the Wildcat Creek Watershed, is comprised of 74% of agricultural area, 21% of pasture, and 3% of urban. The watershed area is 1,956 km²; corn is cultivated in 743 km² (38% of the entire watershed area), and soybeans are cultivated in 704 km² (36% of the entire watershed area). Atrazine led to water quality problems in Indiana, since the high atrazine level has degraded water quality in many watersheds. Therefore, the researchers studied BMP optimizations for atrazine reduction where it is used as a pesticide. The BMP optimization process of the study was also composed of four components. The first component was a SWAT model to estimate pesticide concentration, and BMPs that were buffer strips and tillage practices. The watershed was divided into 109 sub-basins, and 403 HRUs were identified in the watershed. The second component was BMP effectiveness (Table 3).

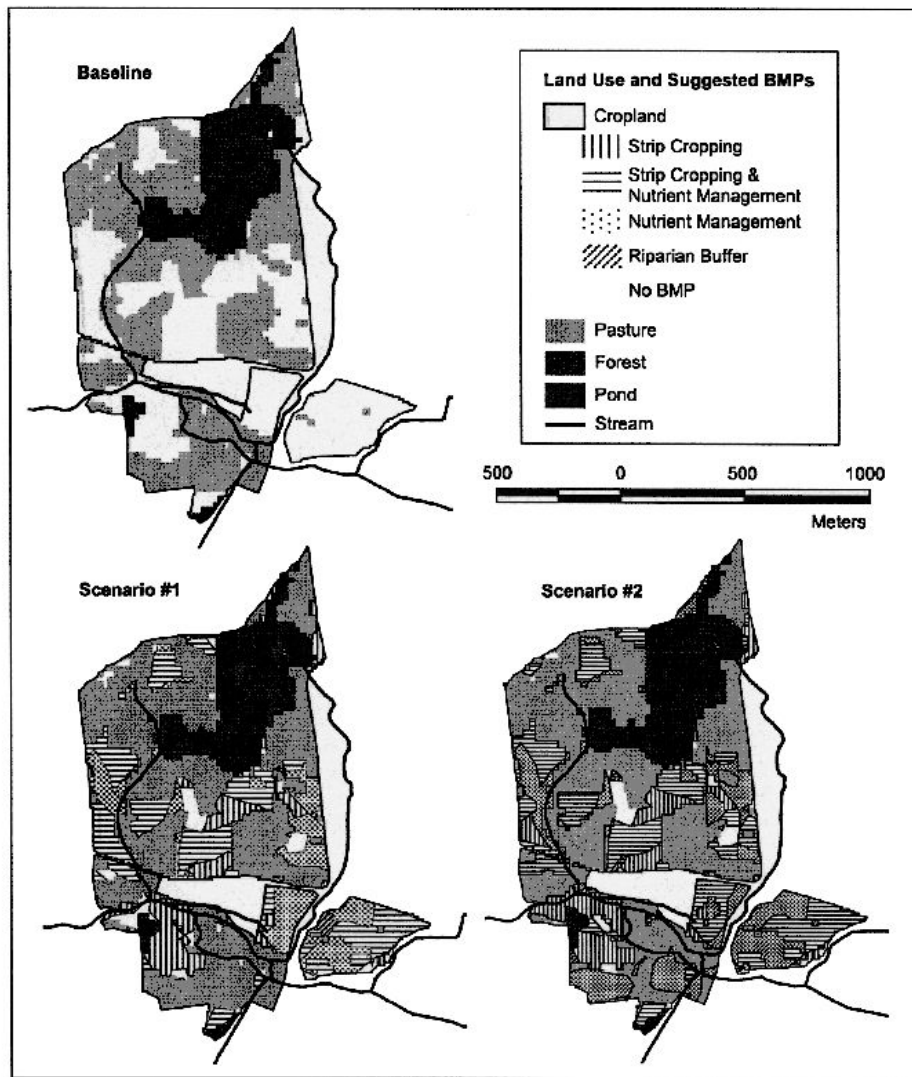


Figure 2. Optimized BMPs for the Cannonsville Reservoir watershed in New York State [35]

BMPs		Pesticide reduction	Net cost increase
Buffer width	Tillage practice	%	\$/ha
0 m	Conventional	-	-
0 m	No-till	7.1	3
20 m	Conventional	41.9	245
20 m	No-till	41.4	242
27 m	Conventional	45.7	327
27 m	No-till	44.4	324
30 m	Conventional	46.9	409
30 m	No-till	45.4	406

Table 3. Pesticide reduction effectiveness and net costs

Regarding BMP simulations and optimizations, the researchers made five assumptions. The first assumption was that the BMP effectiveness in terms of HRU levels in the SWAT model is identical to (or only marginally different from) the BMP effectiveness in watershed level. The assumption was derived from the SWAT model characteristic that the model computes hydrology at an HRU level and that the model is watershed scale model. The second assumption was that the effectiveness of BMPs does not vary temporally or seasonally. For instance, the pollutant reduction by buffer strips might vary based on the growth (or height) of vegetation in buffer strips; however, it was limited to considering the variance of BMPs. The third assumption was that only atrazine pesticide was considered, since the SWAT model does not allow consideration of multiple pesticides, whereas multiple pesticides may in fact be applied in the fields. The fourth assumption was that stream routing processes can be disregarded. The fifth assumption was that BMPs are watershed-specific.

The third component was implementation costs using Equation 2. The interest rate was 6.5%, maintenance rates were 1% for buffer strips, and the design life for buffer strips was 10 years. The fourth component was the multi-objective GA. The 403 HRUs were the variables to be determined, satisfying the two objective functions of minimizing pollutant loading and net cost increases.

Two solution scenarios to implement BMPs were found. Figure 3 (c) displays the base scenario that does not contain any BMPs. The scenario shown in Figure 3 (a) required a net cost increase of \$97/ha, and the scenario shown as Figure 3 (b) required a net cost increase of \$35/ha in the study area. The study indicated that the BMP optimization by a multi-objective GA performed well; however, the approach using a multi-objective GA may rule out some solutions, an inherent drawback of the multi-objective GA.

Similar to the case study discussed above, Maringanti et al. [38] optimized BMPs in the Wildcat Creek Watershed, Indiana State. An identical model to simulate pollutants and an identical optimization technique to optimize BMP implementation plans were used, which were SWAT and a multi-objective GA. However, BMP implementation plans were to reduce nitrogen, phosphorus, sediment, and pesticide. Eight BMP combinations were prepared for 2 BMPs in the previous study. [37]; however, 160 BMP combinations were prepared for a HRU with multiple BMPs [38]. The 160 BMP combinations were developed from the conditions of five filter strips, two contour farming, four residue managements, two parallel terraces, and two tillage types (Table 4).

Distinct features were found in the study. The first feature was that contour farming without a filter strip had a negative impact by increasing the total nitrogen and total phosphorus. The second feature was that a filter strip with a parallel terrace was very effective for pollutant reduction. Residue management did not provide pollutant reduction, and contour farming was effective only for pesticide reduction. No-till was effective for pesticide reduction, but did not reduce total phosphorus.

The researchers investigated four pollutants (nitrogen, phosphorus, sediment, and pesticide) and cost; therefore, they were able to summarize their results in a spider plot spatially representing different costs for BMPs in the watershed (Figure 4 and 5). The numbers in Figure

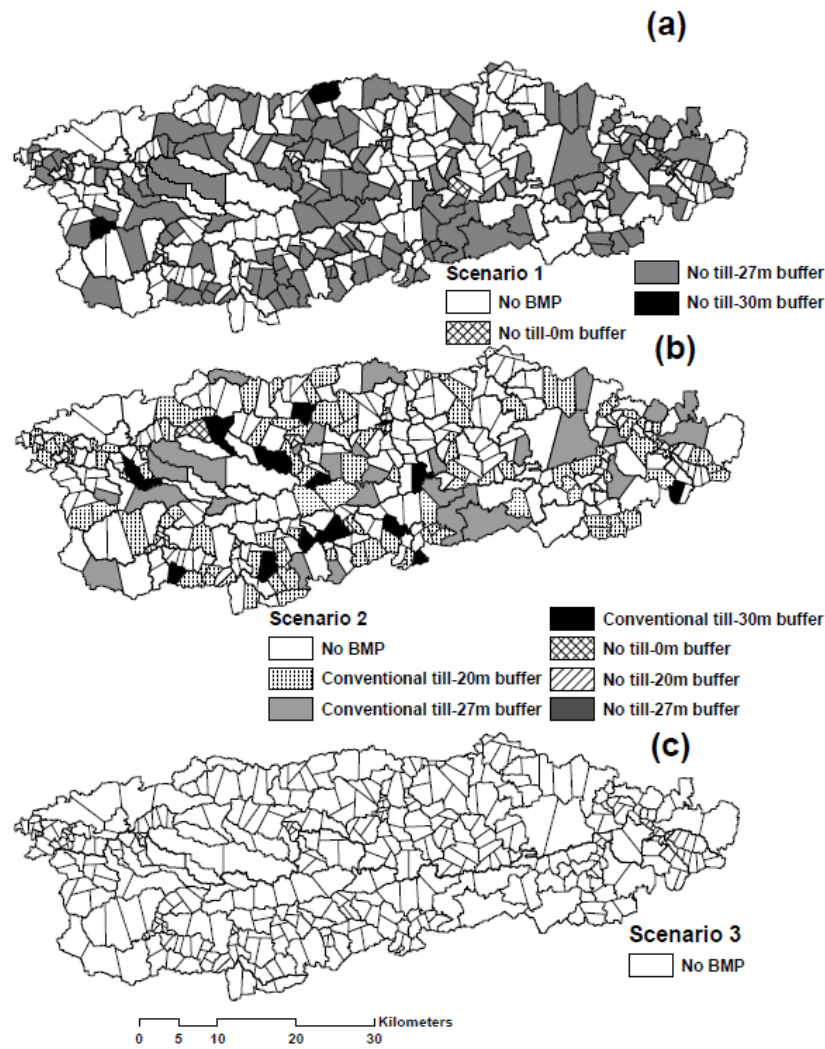


Figure 3. Optimized BMPs for the Wildcat Creek Watershed in Indiana State [37]

5 are the number of BMP combinations: for instance, BMP combination number 1 was comprised of ‘residue management of 1,000 kg/ha’ and ‘conservation till’, number 33 was comprised of a ‘filter strip of 10 m’.

BMP	BMP Type	Cost	Unit
Filter strips	0, 5, 10, 20, 30	12.2	\$/ha/m
Contour farming	Not present or present	16.8	\$/ha
Residue management	1000, 3000, 5000, 7000 kg/ha	0.0	\$/ha
Parallel terrace	Not present or present	74.9	\$/ha
Tillage	Conservational, No-till	53.1	\$/ha

Table 4. BMPs and BMP implementation costs [38]

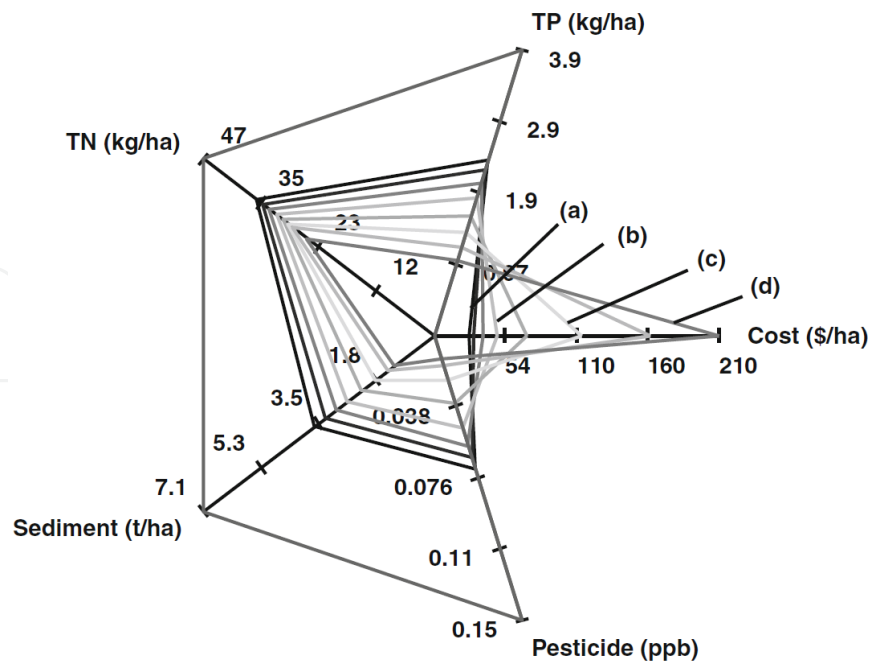


Figure 4. Spider plot representing the different nonpoint source pollutant loads after the final generation by multi-objective GA [38]

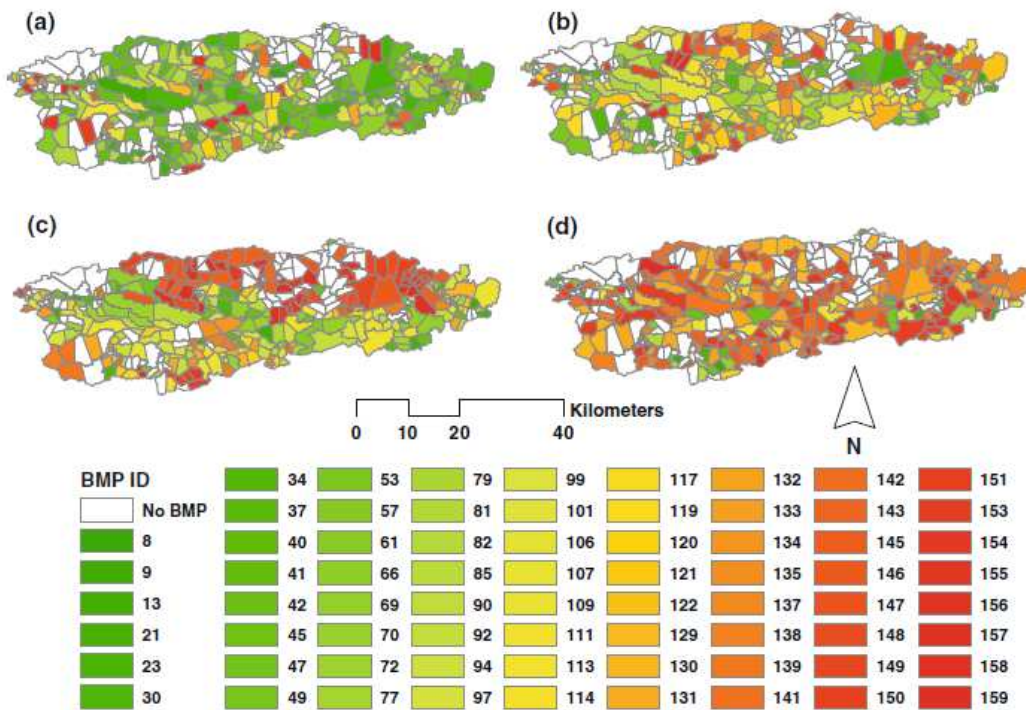


Figure 5. Locations and types of optimized BMPs in the Wildcat Creek Watershed [38]

Veith et al. [1] optimized BMP locations in a watershed of 1,014 ha located in the State of Virginia. An approach using the universal soil loss equation (USLE) with a sediment delivery ratio was used to estimate sediment loads, and GA was used to optimize BMP locations in the study area. BMPs were, of course, optimized by pollution reduction and BMP implementation costs. However, distinctive feature of the study was that the variance of crop production by BMP implementations was considered by two additional criteria. One was that the preference of feed production and nutrient management requirement was applied to the farms; the other was that it avoided applying BMPs to a few farms.

In the study performed by Srivastava et al. [39], two BMP optimization processes were compared which used design storm and continuous climate data with a model to estimate pollutant loads. An Annualized Agricultural Nonpoint Source pollution model (AnnAGNPS) [40] was used to estimate sediment, sediment nitrogen, dissolved nitrogen, sediment organic carbon, and sediment phosphorus in a watershed of 725 ha located in Northumberland County, Pennsylvania. The study area was comprised 47% cropland. Fifteen current crop rotations were considered, two design storms (69.85 mm as 2 year return period storm event, and 88.90 mm as 5 year return period storm event), and climate data for five years were used for BMP optimizations, since the hypothesis of the study was that a BMP scheme with an optimization process using accumulated pollutant loads from continuous simulation would be more applicable than the process using pollutant loads from several critical (or extreme) storms. Based on the results supporting the hypotheses, the authors suggested that long-term pollutant loads from continuous simulations need to be considered in a BMP optimization analyses.

A simple technique to optimize BMPs in a watershed was used by Park et al. [18]. They optimized BMPs for a watershed of 129.1 km², based on annual BMP implementation costs computed by Equation 1. Sophisticated techniques (e.g., a genetic algorithm) are often used in BMP optimization processes. The researchers, however, performed the optimization process by a straightforward approach using BMP implementation costs for unit mass reduction (or cost per 1 kg reduction of pollutant). The study had two applications with potential area for BMPs. One was that it is possible to apply a filter strip of up to 100% of the agricultural area (79 km²), the other was that it is possible to apply a filter strip on up to 10 km² and reduce tillage systems in up to 10 km² of agricultural area. In the first application, pollutant reduction met the requirement for application of 17 km² filter strip at an estimated annual cost of \$12,870. In the alternate application, the estimated annual cost was \$17,400, which resulted from \$7,650 for 10 km² of a filter strip in the agricultural area, \$7,710 for 10 km² of reduced tillage system in the agricultural area, and \$2,040 for 4 km² of vegetative filter strip in the urban area. The applications were to demonstrate the fact that BMP scenarios and implementation costs can vary by watershed conditions.

In this section, several recent research studies optimizing BMPs were introduced. Optimization techniques are complex but are used widely to solve problems; GAs, for example, have been applied in BMP optimizations with various hydrologic models. On the other hand, BMP optimizations have been performed by adopting a straightforward approach based on BMP

implementation costs for unit mass reduction. Moreover, various hydrologic models were used to predict pollutant loadings and the impact of BMPs on watersheds. Complexity in optimization techniques or hydrology models was not crucial for BMP optimization processes. However, it was found that BMP optimization processes typically required four components regardless of which hydrology models and optimization techniques were selected. In other words, the processes were composed of 'selecting available BMPs for the watershed', 'gathering and computing annual BMP implementation costs', 'identifying optimization technique', and 'selecting a model to estimate pollutant loads and the impact of BMPs'.

3. Summary and discussion

NPS pollution has caused water quality degradation in streams and rivers, therefore, various research projects were concerned to perform NPS reduction. Research indicates that agricultural areas were typically major source of NPS in watersheds; therefore, there is a need to perform BMP implementations. Models (or computer software) and sophisticated techniques were often used to suggest optimized BMPs for watersheds. It can be stated that the BMP optimization processes are typically composed of four components: selecting available BMPs for the watershed (or site), gathering and computing annual BMP implementation costs, identifying optimization technique, and selecting a model to estimate pollutant loads and the impact of BMPs. The first two components are site-specific, since some BMPs have a limited application in certain watersheds, and BMP costs vary by location. As the researchers mentioned, BMPs optimized in other research studies cannot be selected and implemented identically without consideration of regional characteristics. Pollutant behaviours can differ by the locations of the source area in a watershed; thus, the locations of BMPs would be one of the important factors to consider. To summarize, BMP optimization processes should answer the following questions: 'what BMPs need to be selected?', 'what size of BMP needs to be applied?', 'where do BMPs need to be placed?', and 'how much does it cost to implement BMPs?'. The process will be very complex and will require a lot of effort; an optimization technique would therefore be required to examine varying BMP impacts, and this is why optimization techniques are often employed. Although optimization techniques provide convenience in BMP evaluations, recognizing limitations in hydrology models and optimization techniques is still required.

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