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Best Management Practice Effects for Phosphorus Control on a Dairy Farm: The Cannonsville Reservoir Watershed, New York

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Abstract. *Best Management Practices (BMPs) have been implemented on a farm-by-farm basis within the Cannonsville Reservoir Watershed (CRW), as part of a New York City watershed-wide BMP implementation effort to reduce phosphorus (P) losses to the water supply reservoirs. Monitoring studies have been carried out at selected locations and at the watershed outlet on one of the farms which spans an entire sub-watershed within the CRW, with the aim of quantifying effectiveness of the BMPs installed on the farm. This study applied the Soil and Water Assessment Tool (SWAT) and a recently developed BMP characterization tool to the farm over pre- and post-BMP installation periods with a view to determining the extent to which model results incorporating all installed BMPs match observed data, and the individual impact of each of the BMPs installed on the farm. The SWAT model generally performed well at the watershed level, with annual Nash-Sutcliffe coefficients ranging between 0.56 and 0.80 and monthly coefficients ranging between 0.45 and 0.78. The model also performed well at the field level, with simulated in-field P losses closely matching observed data. Because BMPs were included in the model as part of the input data, it was difficult to separate out individual BMP impacts based on SWAT simulations. It was, however, possible to determine the effects of BMP combinations such as nutrient management plans and rotations (31% dissolved P; 25% total P). For dissolved P, integration of BMP tool efficiencies allowed individual*

BMP impacts to be incorporated while still maintaining the same level of representation as was obtained using model simulations. As the SWAT model is often used with little or no post-BMP data to verify simulation results, this study served to validate SWAT model suitability for evaluating BMP impacts. The BMP tool was found to suitably complement the model by providing insights into individual BMP impacts, and providing BMP efficiency data where the model was lacking.

Keywords. BMPs, phosphorus, SWAT, BMP effectiveness

Introduction

Best Management Practices (BMPs) have been implemented on a farm-by-farm basis within the Cannonsville Reservoir Watershed (CRW, figure 1 inset), as part of a New York City watershed-wide BMP implementation effort to reduce phosphorus (P) losses to the water supply reservoirs. The CRW, is affected by eutrophication, with agriculture, wastewater treatment plants, and urban runoff being considered responsible for the high P levels in this reservoir (WAC, 1997; Tone et al., 1997). Excessive P loadings, though, are thought to be primarily the result of manure generated on surrounding farms. The manure is either accumulated in barnyards or applied to the land (WAC, 1997).

Efforts to address this problem led to a partnership between farmers and the City, and subsequently to the development of a Watershed Agricultural Program (WAP) that is implemented by the Watershed Agricultural Council. The main goal of the program is to protect the New York City water supply while also maintaining the viability of the agricultural industry. Under the WAP, Best Management Practices (BMPs) have been implemented on most farms within the watersheds, including cropland BMPs, such as strip cropping and crop rotations, as well as other BMPs focused on the livestock facilities areas. The latter include diversions and barnyard BMPs, such as paving, manure pack management and filter strips.

Of current concern is the need to establish quantitatively the impacts of the BMPs at the watershed scale. Previously, a number of model-based studies have been carried out with the aim of quantifying the effectiveness of BMPs within the watershed. Cerucci and Conrad (2003) used a combination of the Soil and Water Assessment Tool (SWAT, Arnold et al., 1998) and the Riparian Ecosystem Management Model (REMM, Lowrance et al., 2000) to determine the effects of riparian buffers in the Town Brook Watershed, a sub-watershed of the CRW. Also working in Town Brook, Gitau et al. (2004) and Gitau et al. (2005b) used SWAT in combination with a recently developed BMP characterization tool (Gitau et al., 2005a) and an optimization algorithm to determine optimal scenarios for BMP selection and placement at the farm and watershed level respectively. Other modeling studies in the CRW that have been carried out in relation to BMPs include Cerucci and Pacenka (2003) and Tolson and Shoemaker (2004).

One of the major drawbacks impacting modeling efforts is that there is often little or no post-BMP data, both at the watershed scale and at the field level. This makes it difficult to verify model outcomes where BMP effectiveness is concerned. Within the CRW, however, monitoring studies have been carried out in both the pre- and post- BMP periods on one of the farms (figure 1) about 160 ha of which spans an entire sub-watershed within the CRW. In particular, there has been continuous monitoring of flow, sediment and phosphorus at locations within the watershed and at the watershed outlet, thus providing the data necessary to verify model results at both the watershed, and the field and BMP levels. The farm and associated watershed were thus the focus of this study.

This study applied the Soil and Water Assessment Tool (SWAT) and the aforementioned BMP tool to the farm over pre-BMP and post-BMP installation periods with a view to determining (i) the extent to which model results incorporating all installed BMPs match observed data, (ii) the individual impact of each of the BMPs installed on the farm, and (iii) the extent to which model results incorporating efficiencies from the BMP tool matched observed data.

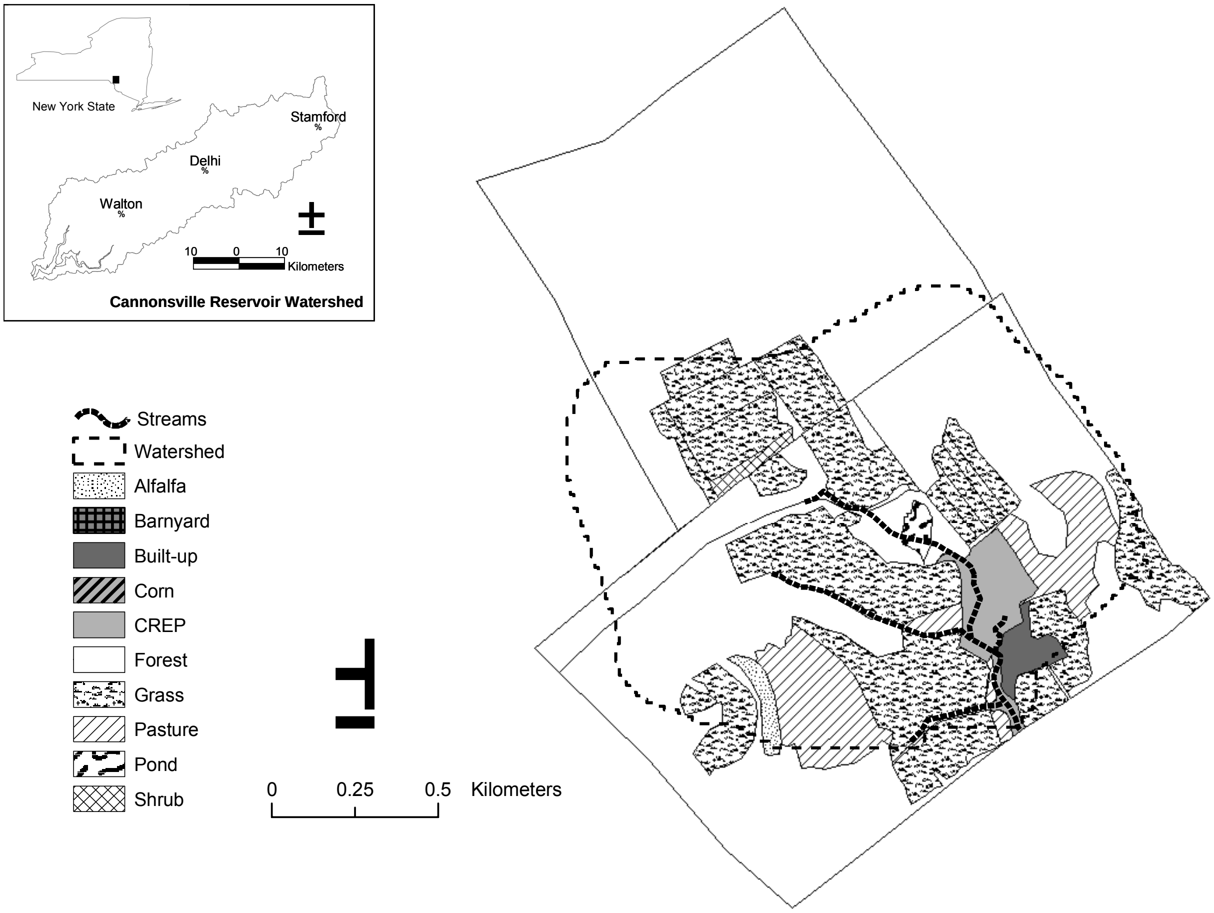

Figure 1: Watershed location and current (2005) land use.

Study area description

The study watershed is located in Delaware County, New York. The average annual precipitation in the region is approximately 1100 mm (15-year average). Precipitation occurs throughout the year with long-term monthly averages ranging between 60 mm and 117 mm. The region is characterized by low to moderate temperatures with long-term (15-year) means ranging from about -6˚C (21˚F) in January to 19˚C (66˚F) in July and August. Elevations on the farm range between 600-730 MSL. Soils are mainly silt loams with depths ranging between 0.5-1.8 m on the hill slopes, and 0.3-0.7 m nearer to the streams where the soils are fragipan-limited (Hively, 2004). The watershed is largely forested, covering about 50% of the land use area The primary activity, though, is dairy farming, with pastures, corn and hay being grown to support the dairying. With regard to pollution, the major concern is P accumulation in barns and near-stream areas, as well as losses from manure-spread fields (Hively, 2004). BMPs were implemented on the farm between June 1995 and November 1996, as part of a study established to determine the potential effects of BMPs on phosphorus control (Bishop et al., 2004, 2005; Hively, 2004).

Materials and methods

This study used the Soil and Water Assessment Tool (SWAT) to characterize P losses from the study watershed at both the watershed and field levels, for the pre- and post- BMP implementation periods. Simulated losses for both periods were then 1) compared with observed data to determine the adequacy of model simulations, and 2) compared with each other to determine individual as well as overall BMP impacts. Further, BMP tool efficiencies were incorporated into a baseline scenario giving an alternate evaluation of the post-BMP scenario. Processes and procedures used are detailed in ensuing subsections.

Base input data

Topography data (10-m Digital Elevation Model) was obtained from the New York City Department of Environmental Protection (NYCDEP). Detailed spatial 10-m field data were available from the Delaware County Soil and Water Conservation District (DCSWCD), with field boundaries for the years 1999, 2002, 2004 and 2005. Additionally, detailed crop data were available for the years 1993 through 2005. For this study, it was of interest to model each of the fields as unique land use areas, so as to allow BMP evaluation on a field basis and so as not mask small, but potentially high-P loss areas, as might be the case if the fields were lumped by their general land uses. Current (2005) field boundaries were used in defining the various land use units. These data were edited through digitizing to include the farm pond, roads and barn-yard areas, as well as any land use related features that might have been present in the other years but were not present in the 2005 data. In order to accurately define the progression from the pre-BMP to the post-BMP periods, field specific crop data from 1993 was used to provide the base land use data needed for setting up the model. Soil Survey Geographic (SSURGO) level soils data were obtained from the DCSWCD. These data are also available at the soil data mart (http://soils.usda.gov). Base climate data were obtained from the National Climate Data Center database (http://lwf.ncdc.noaa.gov/oa/climate/climatedata.html). Both precipitation and temperature data were obtained from the Delhi station (figure 1, inset), which is closest to the watershed. Other climate data used in the model (solar radiation, relative humidity and wind speed) were not available for the Delhi station. The SWAT model was, thus, set to generate these data using its built-in weather generator.

Definition of hydrologic response units

One sub-watershed, as defined in SWAT, was defined for this study. This was the same as the whole watershed, covering an area of 163 ha and encompassing a substantial portion of the study farm (figure 1). Each of the fields was then renamed as a unique land use based on the general land use and field number, following the SWAT convention for naming land uses. For example, two silage corn fields, field 1 and field 2, might be renamed as CSF1 and CSF2. The SWAT built-in crop database was then modified to accommodate these “new” land uses; Parameters for the new land uses were copied from the corresponding general land use as defined in the original SWAT database, thus parameters for silage corn (defined as CSIL in the SWAT database) would be copied into the CSF1 and CSF2 entries. For hydrologic response unit (HRU) definition, a 0% land use and 0% soil thresholds (0/0% definition) were used, thus further preserving all land use and soil areas. A total of 161 HRUs were defined for the watershed.

Hydrologic unit level data inputs

Key inputs at the HRU-level were those pertaining to management, including rotations, planting, harvesting and manure application, as well as to other BMPs installed on the watershed. Detailed rotation data for each field over the years 1995 to 2005 were obtained from the DCSWCD, while rotation data for 1993 and 1994 were determined based on information in Hively (2004). Tillage, planting and harvesting dates (table 1) were input based on information in Hively (2004) and from Dewing (2005).

Table 1. Planting, harvesting and grazing dates used in the model. Based on Hively (2004) and Dewing (2005).

Land use	Year	Plant/begin growing season	First harvest	Second harvest	Third harvest	Grazing
Alfalfa	1	1-May		15-Jul	25-Aug	
	2+	1-May	1-Jun	15-Jul	25-Aug	
Corn	All	15-May	1-Oct			
Grass	1	10-May		1-Jul	15-Aug	
	2+	10-May	20-May	1-Jul	15-Aug	
Grass (with grazing)	1	10-May		1-Jul	15-Aug	
	2+	10-May	20-May			Graze 1-Jun, 15-Jun, 15-Jul, 15-Aug
Pastures	All	1-May				Cows assumed to be uniformly spread over pasture areas
Pastures (intensive grazing)	All	1-May				Graze 10, 25-May, 10-Jun, 1,25-Jul, 25-Aug, 25-Sep

Notes: 1) Plow date = 1-May; 2) Cows are moved from pasture after 1 day and return to the same area after 14-30 days; 3) Cows reduce biomass by 50% when grazing; 4) Manure not spread on pastures when cows are grazing

Details of manure application were available from the New York State Department of Environmental Conservation (NYSDEC) including the amount of manure phosphorus spread on each field on a monthly basis, spreader capacity, the amount of phosphorus per load of manure, and for some years (1997, 1998, 2000, 2001, 2002), barn calendars giving the actual dates on which manure was spread on each field, and the corresponding number of loads of manure spread on each of the days. Additionally, information on grazing including dates, amount of manure per pastured herd per day and the amount of P in the manure was available. This information was used in defining manure application rates and dates for each field as well as the input from pastured cows.

Other BMPs installed such as barnyard management and tile drains were also included to the extent possible, based on information from the DCSWCD. In particular, tile drains were specified for five fields which had tiles installed. Barnyards on the farm were defined in the urban land use database, with associated parameters being set to be consistent with barnyard characteristics. Additionally, HRU slopes as calculated by SWAT were replaced with actual slopes, recalculated from the DEM, consistent with information in Gitau (2003) regarding the need to recalculate HRU slopes. Soil-based parameters such as labile P and the phosphorus availability index were defined based on available soil test data.

Performance evaluation

Flow, sediment, dissolved P (DP) and total P (TP) obtained from the NYCDEC, were used to calibrate the model. Data were used for the periods 6/1/1993 to 5/31/1995 (pre-BMP), and from 11/1/1996 to 10/31/2002 (post-BMP). The period between 6/1/1995 and 10/31/1996 was the BMP implementation period, thus no data was collected during this period (Bishop et al., 2004). The model was first calibrated considering the whole (pre-BMP through post-BMP) period. The pre- and post-BMP periods were then separated and re-evaluated to determine the adequacy of the determined set of calibration parameters for each of the periods. Model performance was evaluated using the Nash-Sutcliffe coefficient (NS, Martinez and Rango, 1970) and the index of agreement (d, Willmott, 1984) as well as graphical plots.

BMP impacts

The impacts of BMPs were evaluated by compiling annual DP and TP losses (kg/ha) for all land uses (fields) for all the years. These data were then averaged separately for the pre-BMP (1993-1995) and post-BMP (1997- 2002) periods. Losses were then aggregated by fields and implemented BMPs, and BMP effectiveness (percentage by which P is reduced) determined by subtracting post-BMP losses from pre-BMP losses and dividing these by the pre-BMP losses. Similarly, overall BMP impacts were determined from computing total losses (kg/ha) from the land use areas and computing effectiveness as previously described.

Incorporating BMP tool efficiencies

For this study detailed data was available for simulating BMPs as needed, and for verifying the accuracy of the output. This is, however, not often the case. Additionally, there are some BMPs that are either not defined, or only defined in part (such as filter strips) within SWAT. For these reasons, the direct incorporation of potential BMP effectiveness based data from the BMP tool was investigated. The tool provides literature-based estimates of BMP effectiveness, which can either be obtained as average values or based on site soils and slopes. For these analyses, the model was set to run through the pre- and post-BMP periods using only the pre-BMP set-up. BMP efficiencies were then applied to post-BMP field-level outputs as appropriate. Resulting annual loads were then compared with observed data and tested for performance as previously described.

Results and discussion

Figure 2 shows monthly plots of simulated stream flow, sediment, DP and TP in comparison to observed data. Based on this figure, the model simulated stream flow very well and simulated sediment and phosphorus with reasonable accuracy. For both DP and TP, however, the model performed better in the post-BMP period as compared to the pre-BMP period. This better performance in the post-BMP period was also evident from and analysis of annual phosphorus loads (figure 3) and computed performance statistics (table 2). While both the NS and d statistics were computed, only the NS is shown in table 2. Values of d ranged from 0.80-0.97 for the combined periods, 0.68-0.94 for the pre-BMP period, and 0.85-0.98 for the post-BMP period. This indicated an overall good model performance, while also showing better performance for the post-BMP than for the pre-BMP period.

These results indicated a need to review the calibration parameter set or the pre-BMP period. A separate simulation was thus set up, for the pre-BMP period, which had the parameter set from the previous (pre- and post- BMP) calibration as its initial dataset. On re-calibrating the pre-BMP period, it was found that changing the phosphorus extraction coefficient from calibrated value 250 m^3/Mg to 175 m^3/Mg for the pre-BMP period was sufficient to improve model simulations of both DP and TP in the pre-BMP period (table 3). This was thought to be attributable to land use changes within the watershed, with there having been more area in cultivated crops in the pre-BMP period (18% in 1993; 1% in 2002) and more pastures and grass in the post-BMP period (30% in 1993; 43% in 2002). The extraction coefficient was then expected to have a lower value in the pre-BMP period than in the post-BMP period, consistent with information in Sharpley et al. (2002). Further analyses were thus carried out using outputs combined from separate model runs of the pre- and the post-BMP periods.

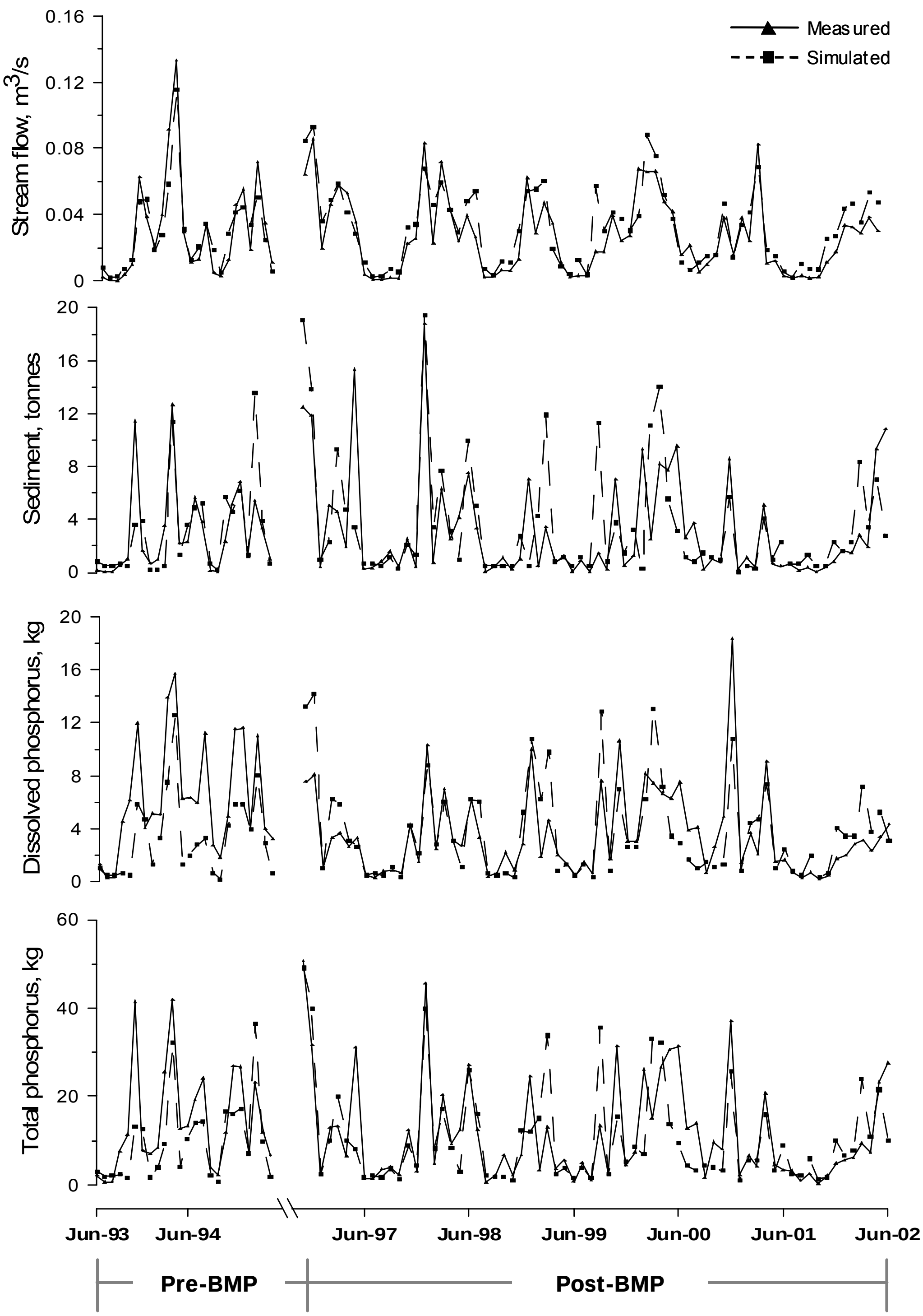

Figure 2: Comparison of monthly stream flow, sediment and phosphorus with observed data in the pre- and post-BMP periods.

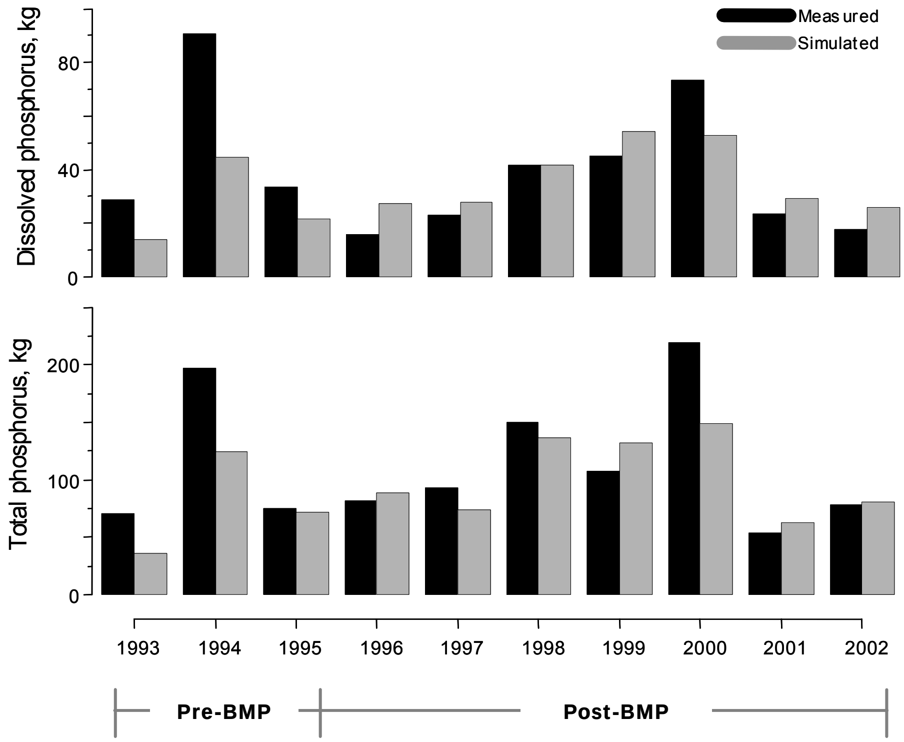

Figure 3: Simulated and observed phosphorus loads in the pre- and post-BMP periods.

Table 2: Nash-Sutcliffe coefficients for combined and individual pre- and post-BMP periods.

	Monthly			Annual		
	Combined	Pre-BMP	Post-BMP	Combined	Pre-BMP	Post-BMP
Stream flow, m^3/s	0.78	0.86	0.72	0.80	0.83	0.80
Sediment load, tonnes	0.26	0.40	0.23	0.70	0.77	0.66
Dissolved P, kg	0.43	0.19	0.46	0.41	-0.05	0.70
Total P, kg	0.45	0.38	0.47	0.56	0.36	0.66

Table 3: Performance statistics for dissolved and total phosphorus simulation in the pre-BMP period following a change of the phosphorus extraction coefficient.

	NS		d	
	Previous	Re-calibrated	Pre-BMP	Re-calibrated
Monthly				
Dissolved P, kg	0.19	0.50	0.76	0.87
Total P, kg	0.38	0.47	0.80	0.84
Annual				
Dissolved P, kg	-0.05	0.60	0.68	0.87
Total P, kg	0.36	0.62	0.78	0.87

Field level performance

Figure 4 shows a comparison of DP and TP concentrations in runoff as simulated by the SWAT model in comparison to observed data as reported in Hively et al. (2005). In general, simulated DP and TP concentrations corresponded well to observed data, based on this figure. For barnyards (omitted from the figure because of the magnitude of losses from these areas) simulated DP and TP were 4.1 and 16.1 mg/l respectively, compared with observed concentrations of, respectively, 11.9 and 13.7 mg/l documented in Hively et al. (2005). In general, simulated and observed data were comparable with regard to both absolute losses and order of magnitude, thus the SWAT model could be said to perform well at the field level.

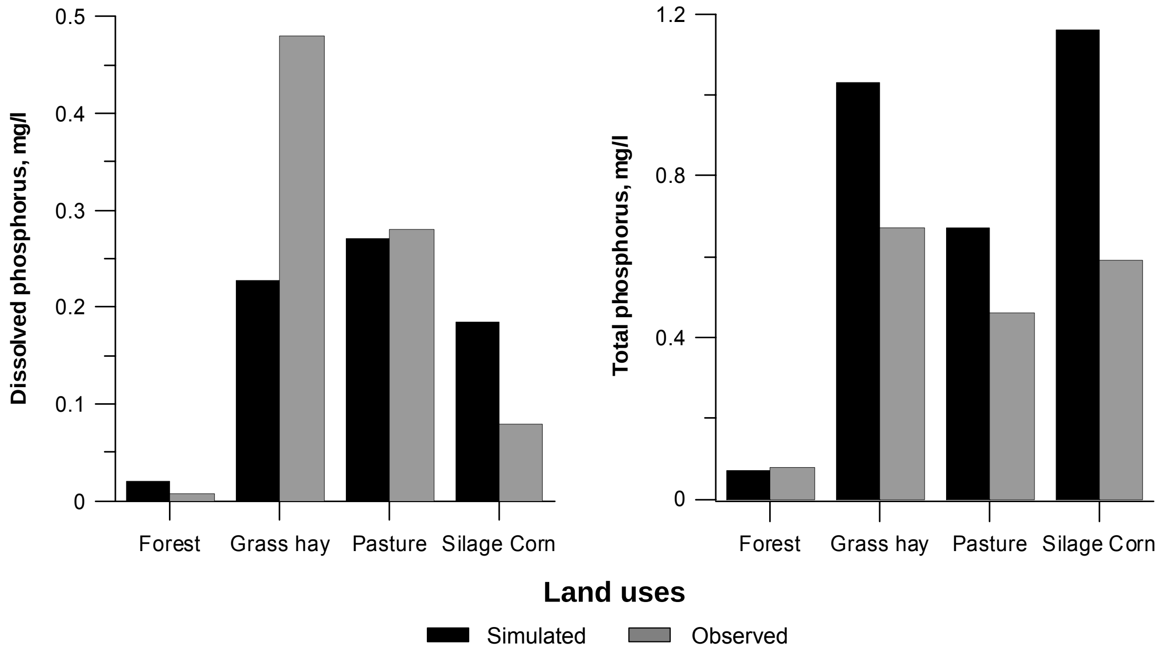

Figure 4: Comparison of simulated and observed (Hively et al., 2005) phosphorus runoff concentrations summarized by the various land uses.

BMP impacts

Impacts of BMPs as determined from analyses of model outputs are as shown in table 4. From this table, the BMPs were able to reduce DP losses by between 15% and 41% and TP losses by between 2% and 52%. However, an increase of 192% in TP losses was observed, this being associated with strip cropping. This was thought to be because corn was included within the strips in 1995 through 1998, where as, in the immediate pre-BMP period (1993-1994), the field had been in alfalfa. Efficiencies determined for tile drains show their impacts on losses in surface runoff. It should be noted, however, that benefits derived from tile drains may be counteracted by losses occurring through tile drainage discharge. For this reason the WAC has recently removed tile drains from its list of BMPs (Bishop et al. 2005).

Overall, BMPs could reduce DP losses by an average of 31% , and TP losses by an average of 21%, based on the simulations. It was, however, difficult to determine individual BMP impacts when the BMPs were included as part of the SWAT input data. In this case, most of the fields had a combination of at least two BMPs, usually nutrient management plans and crop rotations.

Incorporating BMP tool efficiencies

As previously discussed, it was of interest to this study to evaluate the possibilities of incorporating BMP tool-based efficiencies in evaluating post-BMP scenarios. This was particularly with regard to determining their use in situations where available post-BMP data was insufficient for BMP evaluations, as well as for integrating BMPs not included in the model. In light of the difficulties encountered in determining individual BMP impacts based on model runs, the use of the BMP tool in providing estimates of individual BMP impacts was also evaluated.

Figure 5 shows a DP and TP loads as computed by applying tool efficiencies to the post-BMP period in comparison to observed data. From the figure, the application of BMP tool efficiencies for DP gave an overall reasonably good output, with a NS = 0.54 being obtained, comparable to NS = 0.69 obtained through calibration. Additionally, the annual plot obtained using BMP tool efficiencies for DP was comparable to that obtained through calibration (figure 3). For TP, however, BMP impacts were overestimated when BMP tool efficiencies were used, thus simulated TP loads were far lower than corresponding observed loads (figure 5). This was thought to be because BMP efficiencies from the tool were obtained using data that was mainly collected at the field or field plot level – in which case BMP impacts on sediment and, therefore, TP loads might have been exaggerated when data was aggregated at the watershed level. Further investigations would, however, need to be carried out to establish with accuracy the reason behind the over estimation of BMP impacts on TP.

Table 4: BMP effectiveness as determined from SWAT model simulations.

	BMP efficiencies	
	DP	TP
Barnyard management*	15%	21%
CREP	39%	52%
Rotations, nutrient management plans	31%	25%
Rotations, nutrient management plans, Strip cropping, tile drains	35%	4%/27%Ŧ
Strip cropping**	23%	-192%
Tile drains**	41%	2%
Overall	31%	4/21% Ŧ

*Barnyard management impacts estimated by incorporating efficiencies from Gitau et al. (2005).
**Effects calculated for affected fields and include rotation and nutrient management practice effects.
Ŧ Represent values with and without year 2002 data.

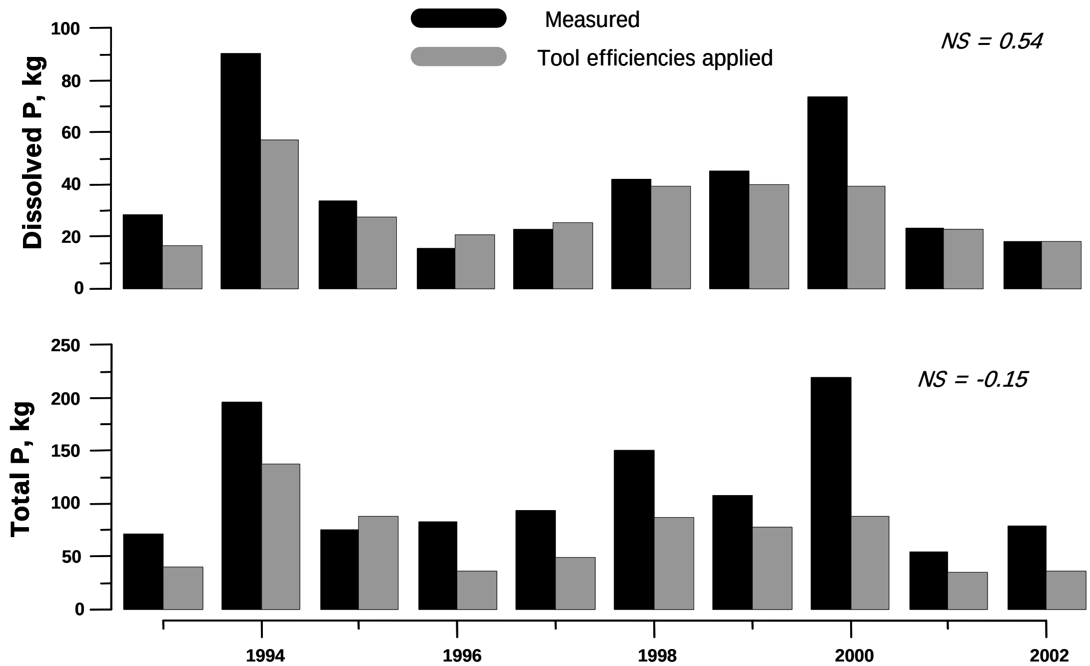

Figure 4: Comparison of DP and TP as computed by applying tool efficiencies (post-BMP period) in comparison to observed data.

Summary and conclusions

When simulations were carried out for the combined pre- and post-BMP periods, model performance was excellent for stream flow and adequate for sediment and phosphorus. With this set-up, the model performed far much better in the post-BMP than in the pre-BMP period, especially with regard to sediment and phosphorus simulations. The model performed appreciably better in the pre-BMP period when this period was run separately, and the phosphorus extraction coefficient adjusted to reflect more cropland than grass in the pre-BMP scenario, as compared to the post-BMP scenario. As only the phosphorus extraction coefficient needed to be changed to improve model performance, this study suggests that there is a need to offer more flexibility in specifying the parameter. The model currently allows only one value of the parameter for the whole watershed; This would be better defined as one that can be specified independently for the various land uses, consistent with suggestions for future work documented in Gitau (2003) and Arnold et al. (2005).

There are other areas in SWAT for which added flexibility in inputs would be desirable. For example, with tile drains; these are set up at HRU level, thus there is no flexibility in terms of modeling a scenario in which tile drains are introduced within the simulation period, without splitting the simulations. A similar example would be with regard to simulating land use changes. While time-based changes in agricultural and forested land uses are readily modeled by specifying the crop as needed, modeling a change such as one from agricultural or forested land use to urban land use is not as straight forward. While this change can be modeled by setting up a new simulation, it would be more realistic, and possibly more accurate, if model set-up would allow this change to be specified in a continuous manner.

The SWAT model has often been used to investigate BMP impacts without sufficient post-BMP data to verify the results. For this study, pre- and post-BMP data were available in sufficient detail, both at the watershed outlet and within the fields to allow an investigation into the adequacy of SWAT for simulating BMP impacts. This study found that the SWAT model could adequately represent pre- and post-BMP periods, both at the watershed outlet and for in-field losses, when compared with observed data. Based on SWAT simulations, the BMPs installed on the watershed were found to reduce DP by an average of 31% and TP by an average of 21%, consistent with findings from observed data.

While the impacts of the BMPs installed on the watershed were determined, it was difficult to separate out individual BMP impacts, when the BMPs were included as part of the input data for simulation runs. Determination of individual BMP impacts is important for identifying the BMPs that are really having or are likely to have an impact, and thus in determining which BMPs need to be on the watershed at the same time, as well as where the BMPs would be best placed in order to have the most impact (Gitau, 2003; Gitau et al., 2005b). In this regard, efficiencies from the BMP tool were found to adequately represent BMP impacts on DP. Tool efficiencies, however, tended to overestimate TP impacts.

This study found that the SWAT model could justifiably be used in simulating BMP impacts at the watershed scale. Additionally, BMP tool efficiencies could be used to complement modeling efforts by providing insights into individual impacts of BMPs, as well as data on BMPs not included directly in SWAT.

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