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Article

Comparative Assessment of Stormwater and Nonpoint Source Pollution Best Management Practices in Suburban Watershed Management

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Abstract: Nonpoint source pollution control and stormwater management are two objectives in managing mixed land use watersheds like those in New Jersey. Various best management practices (BMPs) have been developed and implemented to achieve both objectives. This study assesses the cost-effectiveness of selected BMPs for agricultural nonpoint source pollution control and stormwater management in the Neshanic River watershed, a typical mixed land use watershed in central New Jersey, USA. The selected BMPs for nonpoint source pollution control include cover crops, prescribed grazing, livestock access control, contour farming, nutrient management, and conservation buffers. The selected BMPs for stormwater management are rain gardens, roadside ditch retrofitting, and detention basin retrofitting. Cost-effectiveness is measured by the reduction in pollutant loads in total suspended solids and total phosphorus relative to the total costs of implementing the selected BMPs. The pollution load reductions for these BMPs are based on the total pollutant loads in the watershed simulated by the Soil and Water Assessment Tool and achievable pollutant reduction rates. The total implementation cost includes BMP installation and maintenance costs. The assessment results indicate that the BMPs for the nonpoint source pollution control are generally much more cost-effective in improving water quality than the BMPs for stormwater management.

Keywords: suburban watershed management; stormwater BMPs; agricultural BMPs; cost-effectiveness; Neshanic River watershed; Soil and Water Assessment Tool; nonpoint source pollution

1. Introduction

Suburban watersheds in the United States have been experiencing over the last few decades substantial water resource degradation, such as water pollution and flash flooding. Deterioration in water resources is generally attributed to rapid urban development and substantial increases in imperious surface areas in those watersheds [1–3]. Nonpoint source pollution could intensify because of the nature of the mixed land uses in those suburban watersheds. Agriculture utilizes a significant amount of land in those watersheds and causes agricultural nonpoint source pollution. Urban development expands lawn or turf grass covers in those watersheds, which increases fertilizer and pesticide use. Controlling stormwater and managing nonpoint source pollution are two objectives in protecting water resources in suburban watersheds with mixed land uses. Various best management practices (BMPs) have been developed and implemented to achieve those objectives. Nonpoint source pollution BMPs can be used to reduce the pollutions at sources, interrupt runoff pathways and/or treat the polluted runoff before it is discharged to the streams. BMPs for stormwater management include disconnecting impervious surfaces to limit the source and make it manageable, increasing groundwater recharge to reduce stormwater runoff, promoting low impact development that works with nature and manages stormwater as close to its sources as possible, and retrofitting the existing stormwater infrastructure to control stormwater and reduce its impacts on streams and improve water quality. Impacts of BMPs on water resources are not necessarily mutually exclusive. It is common for a BMP to reduce not only nonpoint source pollution, but also stormwater runoff.

Stormwater and nonpoint source pollution BMPs have intertwined effects on water resources, but bear quite different characteristics that are determined by the nature of the problems each one faces. BMPs for nonpoint source pollution control generally require constant involvement of stakeholders, such as farmers and residents, in changing their attitudes and behavior toward land use and management practices, which means their impacts on water quality are not immediately visible. BMPs for stormwater management, however, are generally engineering-oriented, require only occasional maintenance, and have immediate and visible effects on water quantity and quality. Although both stormwater and nonpoint source pollution BMPs are important tools in the control of water pollution in suburban watersheds with mixed land uses, watershed managers and stakeholders generally favor stormwater BMPs over nonpoint source pollution BMPs because of their visibility and immediate effect in controlling stormwater runoff. National policies also help gear watershed management in suburban settings toward managing stormwater and other development-related issues [4,5].

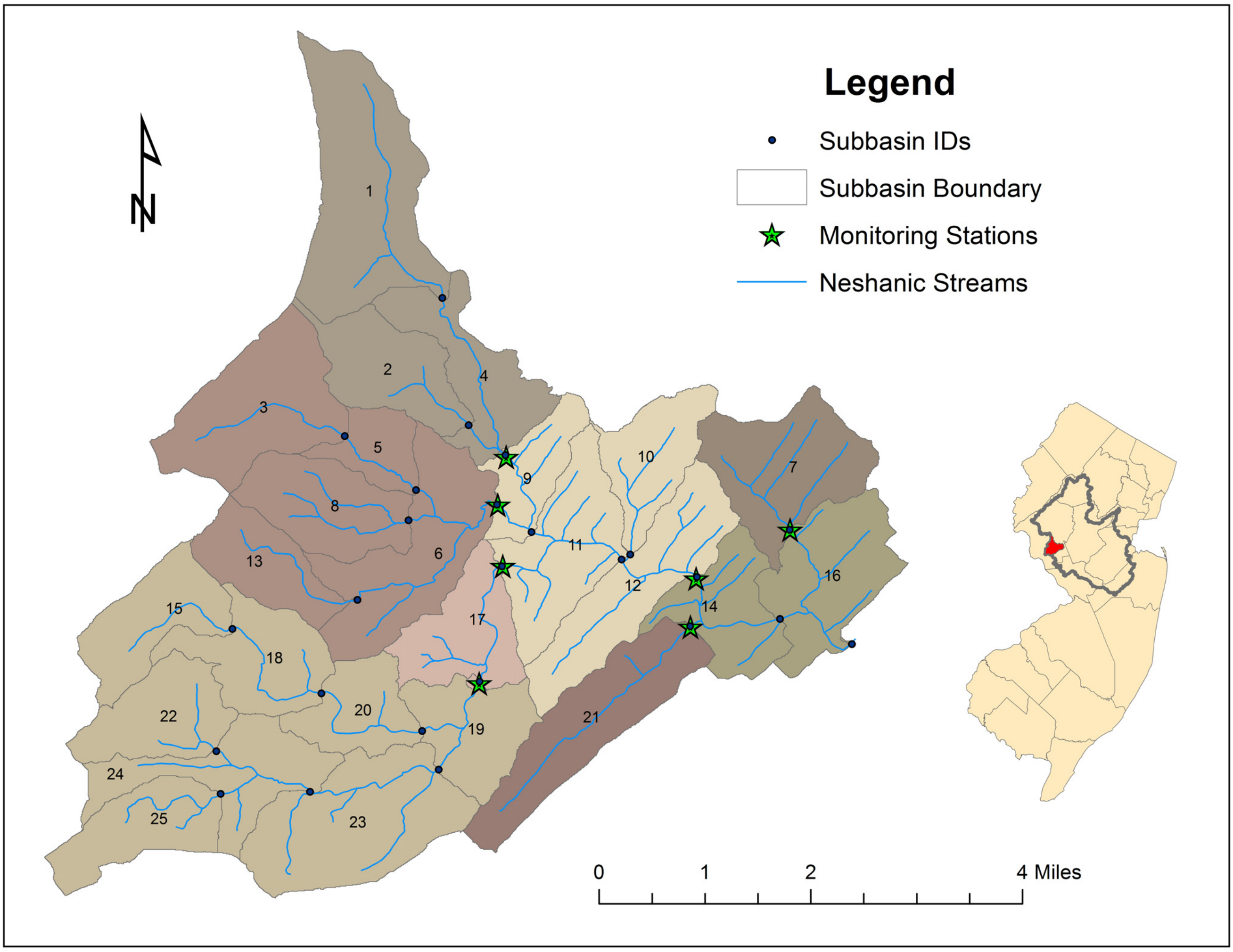
The objective of this study is to estimate the water quality effects and implementation costs of the selected BMPs for nonpoint source pollution control and stormwater management in the Neshanic River watershed, a typical suburban watershed with mixed land uses in central New Jersey, USA, compare the cost-effectiveness of those selected BMPs, and discuss the implications of the results for suburban watershed management. In selecting BMPs for nonpoint source pollution control, we exclude the source reduction measures to reduce nonpoint source pollution from urban lands. In New Jersey, state and local regulatory measures are taken to reduce the fertilizer application in urban lawns. The enacted 2011 New Jersey Fertilizer Law, A2290, requires that all lawn care professionals must be certified to apply fertilizer in New Jersey and that all fertilizer products for turf must contain at least 20% slow-release nitrogen and zero phosphorus, unless a soil test demonstrates a need for more. The local municipal ordinances often require that fertilizer with no phosphorus be applied. Such regulatory measures benefit water resources, but do not impose front-end costs on residents. Therefore, the analytical framework of cost-effectiveness is not applicable to such regulatory measures.

2. Materials and Methods

2.1. Study Area

The 7897-ha Neshanic River watershed is located in Hunterdon County in New Jersey, USA and is a headwater watershed in the Raritan River Basin (Figure 1). The Neshanic River is a tributary to the South Branch of the Raritan River, which drains into the Atlantic Ocean. The Neshanic River is classified as FW2-NT. "FW2" refers to the freshwater bodies used for: primary and secondary contact recreation; industrial and agricultural water supply; maintenance, migration, and propagation of natural and established biota; public potable water supply after conventional filtration treatment and disinfection; and any other reasonable uses. "NT" applies to the freshwater bodies that do not support trout production or trout maintenance due to the lack of the proper physical, chemical, or biological characteristics, but could support other fish species [6].

Figure 1. Subbasin delineation for SWAT modeling in the Neshanic River watershed.



Like many watersheds in New Jersey, this watershed has been experiencing urban development because of rapid suburbanization during the past decades. According to the land use data developed and maintained by the New Jersey Department of Environmental Protection (NJDEP), the percentage of urban land in the watershed increased from 17% in 1986 to 35% in 2007. The increase in urban land was accompanied by a loss in agricultural land in the watershed. While other land uses were relatively steady (forest, 20%; wetlands, 7%; water, 0.2% and barren land, 0.3%–1.6%), agricultural lands in the watershed decreased from 55% in 1986 to about 38% in 2007. Agricultural land in the watershed consists of row crops, hay and pasture. The percentage of agricultural land in the watershed is the highest in the headwater watersheds in the Raritan River Basin.

Urban development and agricultural operations have great impacts on water quality in the Neshanic River. Based upon numerous monitoring sources, including NJDEP Ambient Biomonitoring Network, the NJDEP water quality monitoring network, and the Metal Recon Program, the Neshanic River and its branches are impaired for dissolved oxygen, phosphorus, and total suspended solids (TSS) [7]. The Neshanic River has either the highest concentrations of constituents or the highest frequency of not meeting water quality standards for 13 of 17 evaluated constituents and is considered to be one of the worst water bodies in terms of overall water quality in the Raritan River Basin [8]. While many of the water quality problems in the watershed are attributed to rapid urban development, agriculture is still an important source of water pollution in the watershed. Therefore, controlling nonpoint source pollution from both agricultural and urban runoff is important for achieving overall water quality goals for this watershed.

2.2. Selection of BMPs

Nonpoint source pollution BMPs were selected from the *Natural Resource Conservation Service's Field Office Technical Guides* [9]. Selected BMPs for nonpoint source pollution control include cover crops, prescribed grazing, livestock access control, contour farming, nutrient management, and conservation buffers. Cover crops are grasses, legumes, forbs or other herbaceous plants established for seasonal cover and other conservation purposes. Cover crops reduce soil erosion, help maintain soil moisture and improve soil nutrients and organic content. Prescribed grazing is a system that manages grazing and browsing of animals to ensure there is always adequate ground cover and proper nutrition for livestock. It helps maintain healthy and productive pastures by reducing soil erosion and the resulting transport of phosphorus and pathogens in runoff. Livestock access control involves installing exclusion fencing along streams that cross pastures. Such fencing prevents livestock from directly accessing the streams and their riparian areas and therefore improves water quality. Contour farming uses ridges and furrows formed by tillage, planting and other farming operations to change the direction of runoff from directly downslope to around the hill slope. Contour farming reduces sediment from gully erosion and slows down surface water runoff, which, in turn, reduces the transport of sediment, phosphorus and other contaminants to surface waters. Nutrient management uses a soil test to determine fertilizer application rates and adjusts the fertilizer application schedule and methods to optimize crop growth and minimize adverse effects on water quality. Conservation buffers are structuralized vegetative mixtures of trees, shrubs and grasses placed in the landscape to maintain ecological processes and enhance ecosystem goods and services. Examples of conservation buffers include contour buffer strips, field borders, grassed waterways, filter strips and riparian forest buffers [10]. Farmers in the region readily adopted the selected BMPs.

Stormwater BMPs were selected from the *New Jersey Stormwater Best Management Practices Manual* [11], and include rain gardens, roadside ditch retrofitting, and detention basin retrofitting. These bio-retention systems retain stormwater and discharge it to stormwater systems and/or streams as necessary. These systems achieve substantial water quality benefits by treating the retained stormwater through various biological processes embedded in the system. A rain garden is a landscaped, shallow depression designed to capture, treat and infiltrate stormwater at the source before it reaches the stormwater infrastructure system or a stream. Roadside ditches are widely used to route stormwater into nearby streams in rural parts of the watershed. Due to the lack of maintenance and poor design, roadside ditches are generally eroded. Detention basins are constructed impoundments that are widely used in more developed parts of the watershed for reducing flooding and lowering the volume and velocity of stormwater flowing into streams immediately after a storm. Retrofitted roadside ditches and detention basins are very similar to constructed stormwater wetlands that have substantial water quality benefits. The selected stormwater BMPs have been widely promoted and implemented in the region by the Rutgers University Cooperative Extension.

2.3. SWAT Modeling

The Soil and Water Assessment Tool (SWAT) is a continuous, daily time-step spatially distributed hydrological basin scale model that simulates water, sediment, nutrient, chemical and bacteria transport in a watershed resulting from the interactions among weather, soil properties, stream channel characteristics, vegetation and crop growth, and land management practices; the SWAT model calculates pollutant loads from various nonpoint and point sources [12]. SWAT has been widely used to understand the hydrologic cycle and processes, simulate the hydrological and water quality impacts of land use and management practices, and evaluate alternative management strategies to improve water quality and ecosystem functions in watersheds [13–17]. Although the model was originally developed to simulate the water, nutrient, chemical and sediment movement in ungauged rural watersheds [12], various algorithms for urban land uses, such as urban build up/wash off equations, have been incorporated into the model to make it applicable to suburban watersheds with mixed land uses [17].

ArcSWAT [18], an ArcGIS extension that provides a graphic user interface for the SWAT2005 model, is used for setting up and conducting SWAT simulations in this study. The Neshanic River watershed was delineated into 25 subbasins (Figure 1) and 625 hydrologic response units based on the land use, soil and topographic conditions in the watershed. The SWAT model was calibrated using USGS streamflow and water quality monitoring data for TSS, total nitrogen (TN) and total phosphorus (TP) for the period 1997–2002 at the Reaville Gage Station (the outlet of subbasin 12) in the watershed. All model parameters except two algae-related parameters are within the default range. The calibrated model was validated using the USGS streamflow and water quality data monitoring data for the 2003–2008 period at the Reaville Station and the water quality monitoring data for TP, TSS, and TN during the period 2007–2008 at seven locations [*i.e.*, the Reaville Station and six other locations in the watershed (Figure 1)]. The Nash-Suttcliffe efficiency was 0.60 for daily and 0.68 for monthly streamflow during calibration period 1997–2002 and 0.37 and 0.69 during the validation period

2003–2008, respectively. The goodness of fit statistics indicated a satisfactory simulation of total streamflow and its two major components: surface runoff and baseflow. A graphical comparison of the simulated and measured water quality at all monitoring sites indicated that SWAT provided reasonably accurate simulations of TP, TSS and TN [19].

The calibrated and validated model was run for the period 1997–2008 to analyze the water quality impacts of land use and management practices in the watershed. The modeling results indicated that streamflow carried 1556 t of sediment out of the watershed each year. Streams were the primary source of sediments and contributed 926 t of sediment per year, which accounted for 60% of the total annual sediment load. The stream sediment sources include the stream banks and the sediments deposited in the streambed. The remaining 40% of sediments, roughly 630 t, came from various land uses in the watershed, including row-crop agriculture that accounts for almost 57% of the sediment, urban land (27%) and pasture and hay (15%). The SWAT assessment showed that 104 t of nitrogen and 5.6 t of phosphorus left the watershed through streamflow each year. The primary source of nutrient losses in the watershed was agricultural lands used for row-crop production, pasture and hay, accounting for 76% of TN and 60% of TP losses in the watershed. Fertilizers on urban lands were the second largest sources of nutrient losses, contributing 11% of TN load and 29% of TP losses in the watershed [19]. The SWAT-simulated pollutant loads was combined with the pollutant reduction rates achieved by various BMPs to estimate the amounts of pollutant reduction.

2.4. Cost-Effectiveness of Nonpoint Source Pollution BMPs

Cost-effectiveness was measured by the reduction in pollutant load in TP and TSS relative to the cost of implementing the selected BMPs. Therefore, the more cost-effective BMP has higher value in the measured cost-effectiveness. Each BMP was individually assessed in terms of its effects in reducing TP and TSS and implementation costs [20]. TP and TSS reduction for BMPs were based on the NRCS Performance Results System and literature [21,22] and were close to the lower bound of the pollutant reduction rate reported in literature. The BMP implementation costs are the actual costs for installing and maintaining the specific BMPs and were based on the BMP cost information in the *NRCS Agricultural Water Enhancement Program 2010* practice catalog. The implementation costs were estimated for the full lifespan of the BMPs at a proper scale (or assessment unit). The implementation costs for cover crops, contour farming, and nutrient management were estimated over a three-year assessment period, under the assumption that farmers would enter into three-year contracts to maintain the BMPs once enrolled in the programs. Lifespans were assumed to be five years for the facilities used in prescribed grazing and ten years for livestock access control. The lifespan of conservation buffers was assumed to be 15 years. The size of the assessment unit represents the average scale for implementing the specific BMP. For example, the assessment unit for cover crops is 25 ha, which is the typical size for implementation in the study area based on the experiences of local conservation professionals.

Cost-effectiveness of the nonpoint source control BMPs in the Neshanic River watershed were estimated assuming each BMP was individually applied to all suitable lands in the watershed by scaling up the assessment results on individual BMPs to the whole watershed (Table 1). The applicable unit is the total acreage of the agricultural lands the BMP can be potentially applied to. The total reductions in TP and sediment for a BMP were the sum of the products of the pollutant load reduction rates, the SWAT-estimated annual pollutant loads, and the area of suitable land to which that BMP can be applied across all applicable land use types. Water quality effects were measured by the annual average reduction in TP and sediment. Total watershed cost for an individual BMP was the product of the assessment unit cost (row 4) and the applicable unit (row 7) divided by the assessment unit (row 1). The total watershed costs were calculated for the lifespan of the BMPs or the effective assessment period. The annual watershed cost equaled the total watershed cost (row 10) divided by the years of the lifespan or the effective assessment period (row 5).

Cost-effectiveness for TP reduction equaled the annual average TP reduction divided by the annual watershed cost. Cost-effectiveness for sediment reduction was the annual average sediment reduction divided by the annual watershed cost. Therefore, cost-effectiveness measures the reduction in TP or sediment per $1000 spent on the BMP in the watershed. BMPs with higher cost-effectiveness should receive higher priority for implementation.

2.5. Cost-Effectiveness of Stormwater BMPs

The water quality effects, costs and cost-effectiveness of stormwater BMPs in the watershed were estimated assuming each BMP is applied to suitable sites in the watershed. The watershed has 3545 potential sites identified for rain gardens. The stormwater infrastructure inventory identified 853 segments of roadside ditches with an average length of 73.2 m and 153 detention basins with an average size of 0.28 ha. Several sites were selected for the site-specific assessment in terms of reduction in TP and sediment and implementation costs [20]. Water quality effects of stormwater BMPs were estimated by multiplying pollutant loads for urban lands and the corresponding pollutant reduction rates for each BMP found in the literature [11,23,24]. Implementation costs included installation and maintenance costs. Information on the individual stormwater BMP assessments was scaled up to assess the water quality effects, implementation costs and cost-effectiveness at the watershed scale for each BMP (Table 2). Specifically, the information on individual rain gardens is used to estimate the water quality impacts and watershed costs of all 3545 rain gardens in the watershed. The information for retrofitting a roadside ditch with the size similar to the average size of ditches in the watershed was scaled up to estimate the impacts of retrofitting all roadside ditches in the watershed. A similar approach was used to assess the water quality effects and costs for retrofitting all detention basins in the watershed. The lifespans for all stormwater BMPs are assumed to be 15 years. Annual watershed cost is total watershed cost divided by 15 years, which is the lifespan of the BMPs. The cost effectiveness of the stormwater BMPs are the annual reduction in TP and sediment divided by the estimated annual watershed cost.

3. Results and Discussion

Cost-effectiveness of TP reduction (row 12 in Table 1) is the annual TP reduction (row 8) divided by the annual watershed cost (row 11) for each BMP. Cost-effectiveness of sediment reduction (row 14) is the annual sediment reduction (row 9) divided by the annual watershed cost (row 11). Cost-effectiveness measures the average reduction in TP or sediment per $1000 of expenditure on each BMP in the watershed. Livestock access control has the highest cost-effectiveness in reducing both TP and sediment: $1000 spent on livestock access control could reduce TP by 21.70 kg and sediment by 2.49 t. Cover crops are the least cost-effective BMP in reducing both TP and sediment: $1000 spent on cover crops would only reduce TP by 0.89 kg and sediment by 0.18 t. Cost-effectiveness varies significantly across nonpoint source pollution BMPs. Livestock access control to streams is 24 times more cost-effective in reducing TP and 14 times more effective in reducing sediment than cover crops.

Table 1. Water quality effects, costs and cost-effectiveness of nonpoint source pollution BMPs in the Neshanic River watershed.

Row No.	Assessment Items	Cover Crops	Prescribed Grazing	Livestock Access Control	Contour Farming	Nutrient Management	Conservation Buffers
1	Assessment Unit	25.01 ha	12.14 ha	152.4 m	25.09 ha	25.09 ha	1.21 ha
2	TP Reduction Rate (%)	15	25	60	20	47	50
3	Sediment Reduction Rate (%)	20	25	75	40	0	50
4	Assessment Unit Cost ($)	18,526	9,576	3,868	5,580	5,580	12,882
5	Lifespan or Assessment Period (years)	3	5	10	3	3	15
6	Land Type Suitable for BMP	Row crops	Pasture	Riparian areas of pasture	Row Crops	Crops, hay, pasture	HSAs
7	Applicable Unit	1,623 ha	361 ha	7,517 m	747 ha	3,094	400 ha
8	Annual TP Reduction (kg)	355.4	172.5	414.0	230.0	1577.5	1678.3
9	Annual Sed. Reduction (t)	71.8	14.2	47.5	66.1	0.0	226.8
10	Total Watershed Cost ($)	1,198,487	284,726	190,793	166,140	688,082	4,242,472
11	Annual Watershed Cost ($)	399,496	56,945	19,079	55,380	229,361	282,831
12	Cost-effectiveness of TP Reduction (kg/$1,000)	0.890	3.029	21.701	4.153	6.878	5.934
13	Priority for TP Reduction	6	5	1	4	2	3
14	Cost-effectiveness of Sediment Reduction (t/$1,000)	0.180	0.250	2.492	1.194		0.802
15	Priority for Sed. Reduction	5	4	1	2		3

Table 1 gives the priority ranks for BMPs in reducing TP and sediment. Livestock access control is ranked first in reducing both TP and sediment. Nutrient management is ranked second in reducing TP and contour farming is ranked second in reducing sediment. Conservation buffer and contour farming are ranked third and fourth, respectively, in reducing TP, whereas conservation buffers and prescribed grazing are ranked third and fourth, respectively, in reducing sediment. The cost-effectiveness rankings indicate the order in which BMPs should be selected to reduce pollutant loads when there is a limited budget for watershed restoration. Pollution load reductions are estimated, assuming the BMPs are applied individually.

Table 2 presents the cost-effectiveness of stormwater BMPs. If $1000 is spent on detention basin retrofitting, TP would decrease by 1.99 kg and sediment would decline by 0.50 t. Rain gardens would only reduce TP by 0.027 kg and sediment by 0.004 t/$1000 spent on that practice. There are dramatic differences in the cost-effectiveness among the three stormwater BMPs. Detention basin retrofitting is 74 times more cost-effective in reducing TP and 111 times more cost-effective in reducing sediment than rain gardens. BMPs were prioritized based on their cost-effectiveness. The BMPs resulting in a larger reduction in pollutant load are given a higher priority for implementation. Priority ranks for reducing TP and sediment are the same for three stormwater BMPs. Detention basin retrofitting is ranked first, followed by roadside ditch retrofitting and rain gardens.

Table 2. Water quality effects, costs and cost-effectiveness of stormwater BMPs in the Neshanic River watershed.

Row No.	Assessment Items	Rain Garden	Roadside Ditch Retrofitting	Detention Basin Retrofitting
1	Assessment Unit	1 unit	1 unit	1 unit
2	TP Reduction Rate (%)	50	30	50
3	Sediment Reduction Rate (%)	90	60	90
4	Total Assessment Cost ($)	3,150	20,500	24,500
5	Lifespan of BMP (years)	15	15	15
6	Applicable Infrastructures	Potential Rain Garden Sites	Roadside Ditches	Detention Basins
7	Applicable Unit	3,545 units	853 units	153 units
8	Annual TP Reduction (kg)	20.0	89.0	499.7
9	Annual Sediment Reduction (t)	3.3	30.2	124.9
10	Total Watershed Costs ($)	11,166,750	17,486,500	3,773,000
11	Annual Watershed Cost ($)	744,450	1,165,767	251,533
12	Cost-eff. for TP Reduction (kg/$1,000)	0.027	0.076	1.987
13	Priority Rank for TP Reduction	3	2	1
14	Cost-eff. for Sed Reduction (t/$1,000)	0.004	0.026	0.497
15	Priority Rank for Sediment Reduction	3	2	1

Except for cover crops, all nonpoint source pollution BMPs are generally much more cost-effective than stormwater BMPs in reducing TP and sediment. The popular stormwater BMPs, such as rain garden and roadside ditch retrofitting, are very cost-ineffective. For example, livestock access control to streams is 284 times more cost-effective than roadside ditch retrofitting and 809 times more cost-effective than rain gardens in reducing TP. A similar result was obtained for the cost-ineffectiveness of sediment reduction with stormwater BMPs relative to sediment reduction with nonpoint source pollution BMPs. The only stormwater BMP that has comparable cost-effectiveness with nonpoint source pollution BMPs in reducing TP and sediment is detention basin retrofitting. The assessment results indicate that the BMPs for the nonpoint source pollution control are generally much more cost-effective than the BMPs for stormwater management. This assessment did not consider other hydrological and water quality benefits of BMPs. For example, in addition to their water quality benefits, stormwater BMPs such as rain gardens, result in large reductions in stormwater runoff and runoff velocity in receiving streams.

4. Conclusions

Nonpoint source pollution control and stormwater management are two objectives in managing mixed land use watersheds, such as those found in New Jersey. Various best management practices (BMPs) have been developed and implemented to achieve both objectives. This study assesses the cost-effectiveness of selected BMPs for nonpoint source pollution control and stormwater management in the Neshanic River watershed, a typical mixed land use watershed in central New Jersey, USA. The results indicate that nonpoint source pollution BMPs are generally more cost-effective than stormwater BMPs in reducing total phosphorus and sediment loads to receiving waters. Given the limited available funding available for water pollution control in watersheds, nonpoint source pollution BMPs should be given higher priority for implementation over stormwater BMPs because they are more cost-effective. Although both stormwater and nonpoint source pollution BMPs are important tools in managing suburban watersheds with mixed land uses, watershed managers and stakeholders generally favor stormwater BMPs over nonpoint source pollution BMPs because of their visibility and immediate effect in controlling stormwater runoff. The current tendency of being indifferent about the cost-effectiveness advantage of nonpoint source pollution BMPs over stormwater management BMPs and promoting the use of the latter could result in an inefficient use of limited water pollution control funds, thereby hindering the improvement of water quality.

Implementation of nonpoint source pollution BMPs requires substantial cooperation among stakeholders including farmers, resource conservationists, and various government agencies, which tends to negate their use. Cost is only one aspect of BMP implementation. In addition to the financial incentives, such as high cost-share rates (100% in this study area), other measures need to be taken to educate stakeholders regarding the role and cost-effectiveness of nonpoint source pollution BMPs, including encouraging farmers' participations in BMP adoption and facilitating communications among stakeholders during the implementation process.

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