FINAL CONTRACT REPORT

DEVELOPMENT OF A STORMWATER BEST MANAGEMENT PRACTICE PLACEMENT STRATEGY FOR THE VIRGINIA DEPARTMENT OF TRANSPORTATION

Shaw L. Yu, Ph.D.
Professor

Jenny Xiaoyue Zhen
Graduate Research Assistant

Sam Yanyun Zhai
Graduate Research Assistant

Department of Civil Engineering
University of Virginia

Project Manager
Michael A. Perfater, Virginia Transportation Research Council

Contract Research Sponsored by the
Virginia Transportation Research Council

Virginia Transportation Research Council
(A Cooperative Organization Sponsored Jointly by the
Virginia Department of Transportation and
the University of Virginia)

Charlottesville, Virginia

October 2003
VTRC 04-CR9

NOTICE

The project that is the subject of this report was done under contract for the Virginia Department of Transportation, Virginia Transportation Research Council. The contents of this report reflect the views of the authors, who are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of the Virginia Department of Transportation, the Commonwealth Transportation Board, or the Federal Highway Administration. This report does not constitute a standard, specification, or regulation.

Each contract report is peer reviewed and accepted for publication by Research Council staff with expertise in related technical areas. Final editing and proofreading of the report are performed by the contractor.

ACRONYMS, ABBREVIATIONS, AND SYMBOLS

ADF	Allowed Discharge Fraction
BMP	Best Management Practice
EMC	Event Mean Concentration
CWA	Clean Water Act
DEM	Digital Elevation Model
FHWA	Federal Highway Administration
GA	Genetic Algorithm
GIS	Geographic Information System
MS4	Municipal Separate Storm Sewer Systems
NPDES	National Pollutant Discharge Elimination System
NPS	Nonpoint Source
OCL	OptQuest™ Callable Library
TMDL	Total Maximum Daily Load
TSS	Total Suspended Solids
USEPA	United States Environmental Protection Agency
UVA	University of Virginia
VDOT	Virginia Department of Transportation
VTRC	Virginia Transportation Research Council

ABSTRACT

Since the implementation of the federal and state stormwater management regulations, the Virginia Department of Transportation (VDOT) has constructed hundreds of best management practices (BMPs) for controlling stormwater runoff from highways and its other facilities, such as maintenance headquarters, storage areas, etc. In recent years, the U.S. Environmental Protection Agency (USEPA) has promoted the watershed approach in controlling pollution from various sources in a watershed. One of the key elements of the watershed approach is to include the participation of all stakeholders in the planning and implementation of control measures. The USEPA expects stakeholders, such as regulators, pollutant dischargers, citizens, etc., to work together to develop the best strategy for pollution control with the entire watershed as a planning unit. The Virginia Department of Transportation is such a stakeholder in many watersheds in Virginia.

In the present study, a holistic methodology for determining the cost-effective placement and configuration of stormwater BMPs for VDOT was developed. The methodology involves the coupling of a comprehensive watershed simulation model with an optimization technique. Specifically, the methodology consists of three interacting functional components: a watershed simulation model, a BMP simulation module (the impoundment routine), and an optimization model.

A highway application case study was conducted using the VDOT Rt. 288 Project in Chesterfield County, Virginia. The results showed that the current VDOT BMP placement approach (which consists of on-site treatment of stormwater runoff from highways), might not be cost-effective in terms of protecting the water quality at the watershed level. The results of the case study indicate that if VDOT were to work with other stakeholders in developing a BMP placement strategy for the entire watershed, greater cost-effectiveness would be achieved as a result of fewer BMPs being required for VDOT to construct than would otherwise be the case.

The methodology developed in the present study can be modified and expanded into a decision support system, which can include more types of BMPs and which would allow more BMP placement scenarios.

INTRODUCTION AND BACKGROUND

Best management practices have long been used to control nonpoint sources of pollution, including stormwater runoff from highway areas. Since the enactment of the various federal, state and local stormwater management and nonpoint pollution control regulations in late 1980s and early 1990s, there have been tens of thousands of detention ponds built in this country. It has been estimated that more than 3,000 detention ponds were in use in the metropolitan Washington, D.C., area alone in 1989 (Yu et al., 1993). In Charlottesville, Virginia, a relatively small city, there are currently more than 100 detention ponds in use. The number of BMPs will continue to grow in light of the announcement of the recent federal National Pollution Discharge Elimination System (NPDES) Phase II stormwater regulations, which took effect on March 10, 2003. Many small municipalities and construction sites, which were not regulated under the NPDES Phase I program, will now be included.

Over the years VDOT has constructed or installed hundreds of BMPs, mostly detention ponds, in all parts of the state to comply with various regulatory requirements. The synergetic impact on, or water quality benefits to water bodies in the watershed, which can be attributed to these BMPs has not been studied.

Since the early 1990s, the USEPA has promoted the watershed approach in controlling pollution from both point sources (mainly wastewater effluents) and nonpoint sources (e.g., stormwater runoff from highways). One of the key elements of this total maximum daily load, or TMDL, pollution control strategy is the involvement of all stakeholders in the planning and implementation of various action plans. The USEPA expects stakeholders, such as regulators, pollutant dischargers, interest groups and citizens, etc., to work together in developing a best pollution control strategy for an entire watershed. The Virginia Department of Transportation is a stakeholder in many Virginia watersheds.

One aspect of the present study is to determine how the BMPs can be placed in an optimum way in a watershed so that the combined water quality benefits of these BMPs will be maximized at the least cost. Such a configuration of stormwater management BMPs will be considered the cost-effective strategy.

To date, most BMPs have been installed at the local, or on-site, stormwater management level, instead of the regional, or watershed level. The synergetic effects of these BMPs with respect to both stormwater control and water quality benefits has not been studied. Therefore, a key question is: How should BMPs be strategically placed in a watershed in order to meet specific water quality goals?

Currently, on-site BMPs are designed based on a performance expectation such as "80% total suspended solids removal." The new USEPA TMDL program requires a "water quality based" implementation of BMPs. The collective effects of BMPs on water quality at the watershed level will need to be determined.

Literature information on BMP planning at the watershed scale is relatively scarce. One recent study by Tilley and Brown (1998) compared wetland treatment areas required to treat various pollutants at different spatial watershed scales. Three scales were compared: the neighborhood, or on-site scale (10-100 ha); the sub-basin or regional (100-1,000 ha) scale, and the basin (>1,000 ha) scale. Tilley and Brown applied their method to urbanized watersheds in Miami, Florida. Their results indicated that in general, the basin scale required the least wetland treatment area as a percentage of the total watershed area, the neighborhood scale required the most, while the sub-basin scale required an area in between the other two. The study provided some insight into the scaling effect on BMP planning and optimization.

This study compares several watershed BMP spatial placement strategies. The same basic BMP design was applied to each of the BMP spatial strategies. The cost-effectiveness of the various BMP placement scenarios was examined using either the unit cost of pollutant removal or the total cost of pollutant removal over the entire watershed.

Literature Review

A thorough literature review was conducted in the areas of GIS applications; BMP performance and modeling; and the use of optimization methods in stormwater management. The following paragraphs present a brief summary of the literature.

GIS Applications

The general purpose of using geographical information systems is to collect, analyze, manipulate, and display spatial data with their associated attributes.

Hydrologic parameter determination is currently the most active area in the application of GIS technology in hydrology. In addition, the spatial analysis and visualization capability of GIS offers a better means for utilizing and presenting hydrologic simulation results, and thus allows more efficient analysis of information and decision-making. Most work that has been done in using GIS tools in hydrologic modeling involves object-oriented linkage/interfacing between existing hydrologic models and GIS packages, such as Arc/Info (Liao and Tim, 1997), ArcView, and GRASS (Manguerra and Engel, 1998).

Some more function-specific GIS packages have been developed to assist with topographic evaluation and watershed parameterization in support of hydrologic modeling and analysis. TOPAZ (Topographic ParameteriZation) (Garbrecht and Campbell, 1997) is one of those software packages. One application of TOPAZ, called TOPAGNPS, has been developed to generate flow net for AGNPS (Bingner et al., 1998).

BMP Performance and Simulation

The ideal way of assessing the impact of BMP is to establish a long-term comprehensive field-monitoring program. However, for most cases, it is not feasible to install long-term monitoring systems. Thus, models are needed to assess the long-term non-point source (NPS) pollution control effects of BMPs on a watershed-wide basis.

Detention ponds, retention ponds, wetlands, filter strips, etc., are commonly-used structural BMPs. In many studies the effectiveness of BMPs is indicated as an average removal efficiency, which is obtained from the literature. In addition to the average removal efficiency approach, two general techniques have been developed to predict the long-term pollutant removal performance of these structural BMPs. These techniques are: 1) the modeling approach, and 2) the statistical approach.

Among the conventional BMPs, detention/retention ponds are the most widely used and have been extensively studied. Several deterministic models were developed to simulate detention pond processes and pollutant removal performance (Wu, 1992). In the storage/treatment block of the SWMM model (Huber et al., 1975), detention basins are modeled as completely mixed or plug flow reactors. In the completely mixed mode, the pollutant removal efficiency is determined through the use of exponential removal equations. In the plug flow mode, the particle size distribution and settling velocities are required as inputs and the removal is computed by the use of the Stokes deposition equation. The impoundment module in AGNPS (Theurer, 2000) also assumes a completely mixed condition and estimates the sediment removal efficiencies based on Hazen's surface loading theory. Recently, more complicated two-dimensional detention pond simulation models have been developed (Wu, 1992).

The accuracy of BMP performance evaluation is usually limited due to the uncertainties resulting from random characteristics of rainfall events, watershed runoff, and pollutant generation processes. Furthermore, Earles (1999) stated that incorporating detailed BMP evaluation results into a watershed scale analysis to determine the impact of BMPs on water quantity and quality is very difficult because the scales are quite different in time and space between the BMP and the entire watershed. For long-term evaluation, the time step required in the NPS watershed model is usually much longer than that in the BMP simulation models.

Statistical methods predict pond performance based on regression relationships between pond performance and causative parameters such as rainfall or runoff, drainage basin detention pond characteristics, etc. These methods can be applied to evaluate the long-term performance of BMPs with less computational effort than is required by the modeling simulation approach. Examples of statistical methods include those described by Driscoll (1982), Loganathan et al. (1985, 1994), Segarra-Garcia and Loganathan (1992), and Yu et al. (1992).

The extrapolation of the individual BMP performance to assess the watershed-scale or synergetic impact was generally accomplished in two ways:

- Assuming a percentage reduction according to literature values, as described by the Northern Virginia Planning District Commission (NVPDC, 1990). For example, Earles (1999) developed the equivalent land use (ELU) approach to account for the effect of BMPs by changing the land use conditions for those areas treated by BMPs in the watershed model.

- Combining BMP simulation models with a watershed model. Examples include the storage/treatment block in the Stormwater Management Model or SWMM (Huber, 1975), the impoundment simulation module in AnnAGNPS (Bingner and Theurer, 2000), and the detention pond routing and swale simulation programs in the VirginiA STorm model (VAST) (Tisdale et al., 1996). However, the lack of consideration on pollutant accumulation and resuspension by these BMP simulation models limits the accuracy of their assessment of BMP long-term performance.

Application of Optimization Techniques in Stormwater Management

In recent years, the development of modern meta-heuristic search techniques, such as genetic algorithms and scatter search, has greatly attracted the attention of researchers wanting to address the real world planning/design issues using optimization tools. The meta-heuristic techniques are much less restrictive in problem formulation and can be used for complex systems. One major drawback of these new techniques is the demand for extensive computing time. However, with the rapid development of computer power and speed in recent years, this weakness has become of less and less concern.

Scatter search is another meta-heuristic search techniques that has been explored and used in optimizing complex systems (Glover et al., 1999) and attracting more attention in recent years. Scatter search focuses on generating relevant outcomes without losing the ability to produce diverse solutions due to the way the generation process is implemented (Glover and Laguna, 1999). A commercially-available software product, OptQuest^{TM} Callable Library (OCL), which employs the scatter search technique, was determined to be the most suitable method for performing the optimization analysis in the present study.

A study done by Kook et al. (1987) compared the local vs. regional BMP design approaches in terms of peak flow reduction efficiencies by examining the simulation results of event scenario runs. The study also established the simulation-optimization linkage to select optimal size and locations of BMPs under flow reduction constraints by using the complex search technique.

PURPOSE AND SCOPE

The goal of this research was to develop an approach to determine the optimal placement of the BMPs so that the combined effects of the BMPs will provide the cost-effective way of treating stormwater from highways and other sources. GIS-based watershed models were used to simulate the hydrology and water quality changes resulting from various BMP placement scenarios. The effectiveness of a BMP placement scenario was judged according to the overall amount of pollutant reduction by the BMPs at the watershed scale. The costs, including construction, operation and maintenance of the BMPs, were also used as a parameter in determining the cost-effectiveness of each placement scenario.

METHODS

The following tasks were undertaken in the present study:

Task 1. Test and select suitable watershed models.

Task 2. Develop a method to evaluate BMP long-term performance in the context of a watershed.

Task 3. Test BMP placement scaling effects on nonpoint source (NPS) pollution control cost effectiveness at the watershed scale.

Task 4. Develop a cost-effective BMP placement strategy.

Task 5. Perform two case studies to test the application of the optimization methodology.

RESULTS AND DISCUSSION

Select and Test Watershed Models

Most watershed models have the following basic components (Novotny and Chesters, 1981):

- A surface runoff generation component, which describes the transformation of rainfall into runoff and its overland surface flow.
- A soil and groundwater component, which describes movement of water through the unsaturated soil zone and into saturated zones.
- An erosion component that estimates soil loss from pervious areas.
- A component that addresses particle accumulation and wash-off from impervious areas.
- A soil pollutant partitioning component which determines the distribution of adsorbed and dissolved fractions of pollutants in soils.

After reviewing the various models for their suitability to be used in the present study, it was decided that the continuous version of the AGNPS model, known as AnnAGNPS, and the VAST model were to be used. The AnnAGNPS model was used for a generic analysis, while the VAST model was used for a specific highway case study. For both analyses the optimizer program was the scatter search methodology described earlier in this section.

Develop a Watershed BMP Long-term Evaluation Method

A simulation approach was used to evaluate the long-term performance of BMPs. The watershed model AnnAGNPS has a continuous simulation option and has an impoundment module for detention pond simulation. Therefore, AnnAGNPS is capable of evaluating BMP performance on a long-term basis. However, the impoundment module embedded in

AnnAGNPS does not account for pollutant (e.g., sediment) accumulation and resuspension, which affects the performance of the detention significantly. Consequently, the impoundment module within AnnAGNPS was modified to allow accounting for sediment accumulation and resuspension.

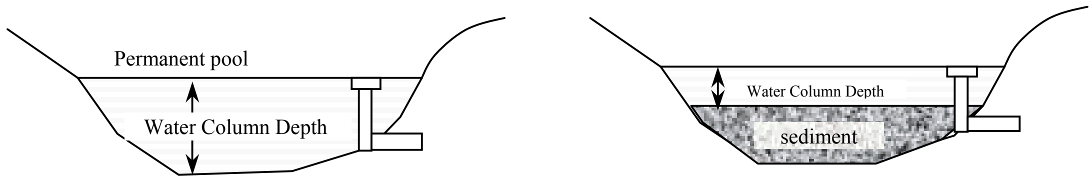
The computation procedure of the modified module is similar to the original one, but has new components added to: 1) “memorize” the amount of sediment accumulated in the pond and update the pond geometric parameters that have changed due to sediment accumulation, and 2) determine the effect of sediment resuspension.

Some assumptions were made in order to modify the impoundment model. For example, the following assumptions were made in the development of the modified impoundment routine for a wet detention pond:

- The permanent pool consists of clean water and does not contribute to the outflow.
- Only a fraction of the permanent pool water would be mixed with the inflow water. The fraction is indicated by a mixing coefficient.
- The average outflow discharge rate is approximately one-half of the peak discharge rate, which implies that a linear discharge ~ time relationship applies for the outflow hydrograph.

Effects of Sediment Accumulation

The AnnAGNPS model, with the modified impoundment module, was then used to simulate long-term detention pond performance under the assumption that sediment will accumulate, and sometimes resuspend, in a detention pond. Figure 1 shows how sediment accumulation can affect the performance of a pond by reducing the “effective” permanent pool storage volume.



a) Clean wet pond b) Wet pond with accumulated sediment

Figure 1. Schematic diagram showing the effect of sediment accumulation (wet ponds).

The modified impoundment module subtracts the total sediment volume from the original permanent pool storage volume. The reduced permanent pool storage volume lessens the dilution effect, and potentially causes a higher chance of sediment resuspension as the water column depth is reduced.

Effects of Sediment Resuspension

Sediment resuspension is an important factor that influences the performance of all detention-type BMPs, such as stormwater ponds (Langan and Yu, 1999; Stopinski and Yu, 2000). Sediment resuspension occurs when the entrainment flux of sediment from the bed surface is greater than the deposition flux to the bed, due to turbulence and friction caused by the advective flow velocity.

In the present study, a simplified method for estimating the resuspension effect was developed in which resuspension is considered as a separate process from sedimentation. It is also assumed that once the sediment is entrained, it will be evenly distributed into the water column. The amount of sediment resuspended is added to the original inflow to obtain a pseudo inflow sediment concentration. The pseudo-inflow concentration, which replaces the original one, is routed through the BMP to generate the outflow concentration, as illustrated in Figure 2.

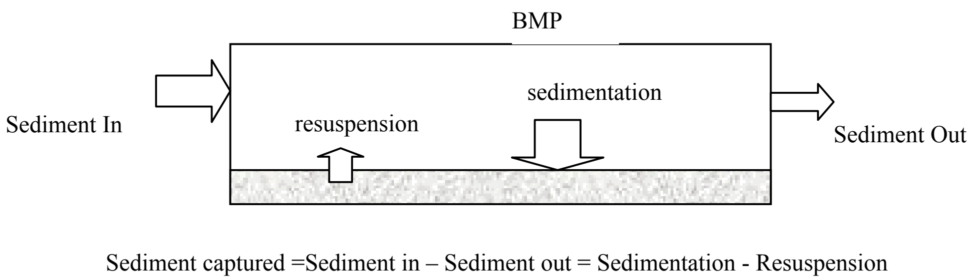


Figure 2. Sediment deposition and resuspension in a BMP (zero-dimensional conceptual model).

The methodology developed in the present study was tested with data obtained for a detention pond monitored by the U.S. Department of Agriculture (Zhen, 2002).

Figure 3 illustrates the results of the simulation, and shows that the trap efficiency is reduced as the sediment accumulation depth increases. In addition, a comparison of the reduction in simulated sediment trap efficiency due to accumulation of sediments with and without considering resuspension, shows that the reduction in efficiency without considering resuspension was about two orders of magnitude lower than that when resuspension was considered. This shows that, for a wet pond with a permanent pool, the reduction in the trap efficiency is due to increased resuspension rather than from decreased dilution effect. The findings suggest that in order to prevent sediment resuspension, a deeper wet pool and/or timely clean up to remove the accumulated sediment is needed.

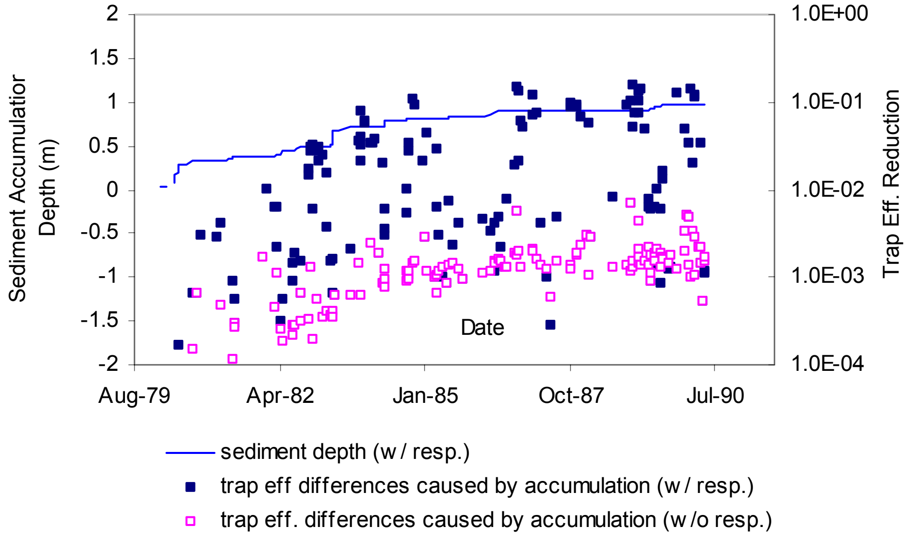


Figure 3. Simulated trap efficiency reduction due to accumulation with and without considering resuspension (Zhen, 2002).

BMP Placement Scaling Effect on NPS Control

This study considered three application/placement levels for treatment control BMPs: 1) on-site, 2) regional, and 3) sub-watershed, as shown in Figure 4.

1)

2)

3)

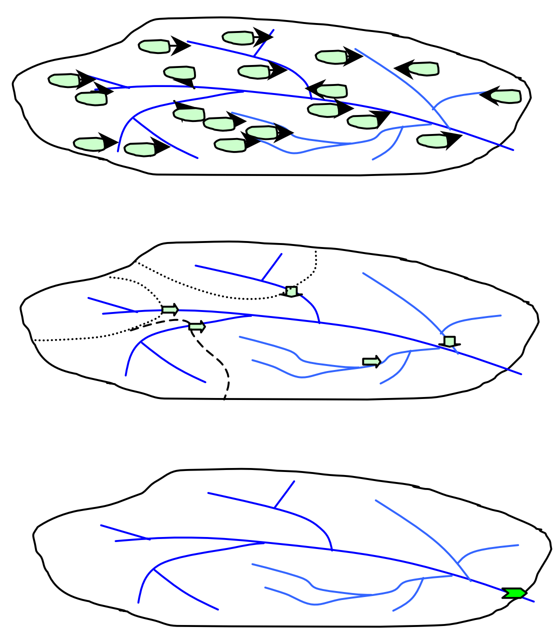


Figure 4. Schematic diagram showing spatial arrangement of: (1) on-site; (2) regional; and (3) sub-watershed BMPs.

The three levels of BMP implementation, together with information on the sizes of areas treated and the applicable stream orders, are listed in Table 1.

Table 1. Three levels of BMP application: on-site, regional, and sub-watershed.

BMP Application Level	General description	Order of water course included	Approximate area controlled
On-site	Treat stormwater runoff from small areas before it drains into the receiving water network	No	1~100 acres
Regional	Treat runoff from catchments which have first or second order water courses included	1~2 order	100~1,000 acres
Sub-watershed	Treat runoff from 3rd or higher order watersheds	3~4 order	1,000~10,000 acres

Current VDOT stormwater management practices fall mainly into the on-site category (i.e., building BMPs along stretches of highways as needed in a linear fashion). In almost all cases, VDOT only treats runoff from highways (including the right-of-way). At the present time, there is no mechanism available for VDOT to work with other entities (such as local governments, environmental groups, etc.) to plan BMP placement at the regional or the sub-watershed levels.

Watershed modeling, using the AnnAGNPS model, was used to examine the scaling effects on water quantity and quality at each of the various BMP placement levels. Six test watersheds, representing various topographic, land use and other physical features, were used in the modeling analysis. The peak flow rate and sediment load at the watershed outlet, generated for each of the three BMP placement levels, i.e., on-site, regional and sub-watershed, were calculated and compared.

The results show that the BMP placement level does affect the water quantity and quality at the watershed outlet. On-site placement of BMPs would lead to lower peak flows because of enhanced storage effects associated with longer channel reaches as a result of placing numerous on-site BMPs throughout the watershed. On the other hand, the BMP placement impact on water quality is not as definite. While longer channel reaches are expected to enhance sediment deposition, the same long reaches could potentially lead to more bank erosion and resuspension. Therefore, on-site placement may or may not be the most beneficial in terms of water quality.

Optimal BMP Placement Strategy

Problem Formulation

The objective of the optimal BMP placement study was to determine the locations and design configurations of stormwater ponds in order to minimize the total cost of the system while satisfying water quality constraints.

Placing BMPs at different spatial levels (i.e., on-site, sub-regional, and regional), affects the cost-effectiveness of the stormwater control system (Zhen and Yu, 2001). Therefore the location of a BMP is an important factor in the optimization framework. Potential BMP locations can be pre-selected based on an inventory of NPS pollution critical source areas, and the availability of spaces for BMP installation. For each pre-selected location, ***i***, one set of decision variables is assigned. The decision variable vector (BMP_i) for location ***i*** represents the existence and the configuration of the BMP. Because the existence of a detention pond can only be represented or described by a discrete variable, the optimization of stormwater control systems naturally falls into the category of an integer or a discrete problem.

Mathematically, the optimization model can be expressed as:

Objective:

$$\text{Minimize } \sum_{i=1}^{n} \cos t(BMP_i) \qquad (1)$$

Subject to:

$$L_k \leq Lmax_k \qquad (2)$$

$$BMP_i \in \text{ feasible range} \qquad (3)$$

Where:
- cost = average annual cost, including costs of construction and maintenance;
- BMP_i = a set of BMP decision variables for pre-selected location i;
- L_k = long-term average annual pollutant load at a reference point k, with the implementation of BMPs;
- $Lmax_k$ = maximum average annual pollutant load allowed for the reference point k.

In this study, selected decision variables are the detention-time for a user-specified design storm and the depth of a pond. Detention time is discretized between zero and a maximum value at a constant increment, with a zero detention-time representing that the pond is not built at the site.

The cost function calculates the long-term average annual cost of BMPs, including both the initial construction cost and the annual operation and maintenance (O&M) cost, over the planning time period. The construction cost is distributed evenly to every year of the lifetime duration of a BMP to normalize the cost to an annually based number.

The water quality constraint, $Lmax_k$ was based on existing federal, state and local watershed pollution control schemes, such as a TMDL point and NPS control framework for the watershed being examined. The annual pollutant loads (L_k) at a designated check point (k) determines the pollutant removal effectiveness of the potential BMP alternatives. The AnnAGNPS model, a continuous watershed hydrology and water quality simulation model, was then used to simulate the pollutant load generation and transport in the watershed. Simulation of the detention pond pollutant removal process during each storm event was performed on a continuous basis by the modified impoundment routine embedded in AnnAGNPS.

The objective function (cost function) and the water quality constraint are discrete, non-linear, and involve comprehensive watershed simulation, making it challenging to find a tractable mathematical formulation and corresponding solution procedure. To deal with such a complex problem, a meta-heuristic optimization technique – (a scatter search) was selected and applied to find the optimal or a near optimal solution.

The Optimization Framework

The structure of the optimization framework is illustrated in Figure 5, which consists of three functional components: namely, an initialization run of AnnAGNPS, the system evaluator, and the optimizer, i.e., the OptQuest^{TM} Callable Library (OCL), which performs the optimization search process.

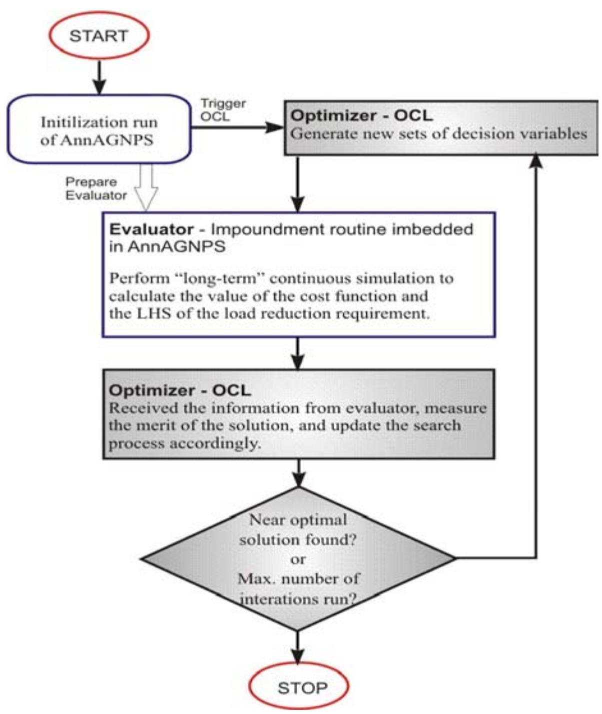


Figure 5. Optimization Framework.

Application of the Optimization Methodology - A Generic Case Study

Study Area and BMP Strategy

The study area is a 1,172-ha watershed, which is a sub-watershed of the Ivy Creek watershed (Figure 6) located in Albemarle County, Virginia. The land slope of this area is very mild. The dominant land uses of the hypothetical watershed are grazing pasture and forest. A single loamy texture soil type covers the study area. The statistics of the precipitation data are: annual average precipitation = 1,084 mm (42.7 in.), rainfall depth of the 1-yr, 24-hr storm = 56 mm (2.2 in.), and rainfall depth of the 10-yr, 24-hr storm = 122 mm (4.8 in.). The temporal rainfall distribution is the SCS Type-II distribution.

AnnAGNPS was used to simulate the watershed hydrology and NPS pollutant loading, and to provide results for the identification of the critical areas, which are the areas with the most significant amount of pollution. The study area was divided into 155 cells. The average cell size was 7.56 ha. Each cell was assumed to be homogenous in terms of soil type and land cover. The GIS tool package – AnnAGNPS Input Data Preparation Model (AIDPM) (Darden and Bingner, 2001; Darden et al., 2001) was used to calculate the drainage area; average land slope; average elevation; overland flow length and slope; shallow concentrated flow length and slope; concentrated flow length and slope; and the length-slope (LS) factor for each cell. The reach

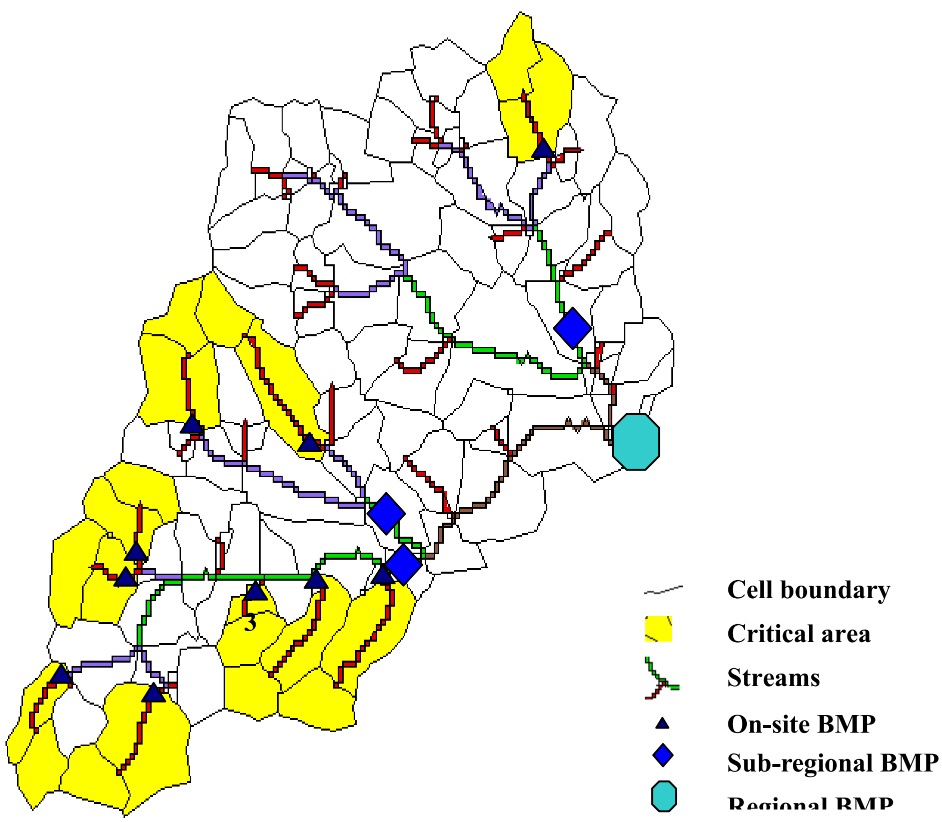


Figure 6. Study area: critical areas and potential BMP placement locations.

length and reach slope were also automatically obtained by applying AIDPM. Three years of synthetic climate data were used in the watershed hydrology and water quality simulations. Suspended sediment was selected as the pollutant of concern.

A critical area was defined as an area (or cell) with a unit area pollutant load greater than the average unit area load for the entire watershed. According to the results from the simulation runs, ten sub-watersheds were identified as critical areas (see Figure 6). The critical areas had unit area sediment loads ranging from 0.542 to 0.994 ton/ha/yr, which are greater than the average value of 0.379 ton/ha/yr for the entire watershed. Three sub-regional locations, and one regional location were selected as potential BMP installation sites.

BMP Selection – Extended Dry Ponds

The dry extended detention (ED) pond was selected as the appropriate BMP at all the potential sites. For a dry ED pond the outlet size is selected to yield a desirable runoff detention time for a design storm. The detention time can be determined by taking into account the ponded volume and the average hydraulic head in the temporary pool. Extended detention basins are designed to not only reduce the rate of runoff discharge from given design storm events, but also to detain runoff from smaller, more frequent storm events so that some water quality benefits are realized.

The detention time for a user-specified design storm (a 1-yr, 24-hr storm in this case) and the average pond depth are the two parameters that were optimized by the model. These are the most important design parameters contributing to the performance of a detention pond. Other less important design features were either estimated based on the current knowledge of pond design practices (Stahre and Urbonas, 1990; Schueler and Claytor, 1990) or assumed for the sake of simplicity. For instance, the pond length-to-width ratio was taken to be 3:1, a bed slope of 0.015 was used, and the pond sidewalls were assumed to be vertical.

For the hypothetical watershed, suspended solids (SS) was the target pollutant, and the reference location, or checkpoint, was the watershed outlet. The optimization model for this case is described mathematically as:

$$\text{Min Cost} = \sum_{i=1}^{14} C(T_{d\,i}, H_i) \tag{4}$$

Subject to:

$$\frac{\text{SS load at outlet w/ BMPs}}{\text{SS load at outlet w/o BMPs}} \leq ADF \tag{5}$$

Where: T_{di} = design storm detention time of the pond at location i;
H_i = depth of the pond at location i;
C = cost function to calculate the total cost of the pond, including construction and maintenance costs;
ADF = Allowed Discharge Fraction of the existing load.

For the ten on-site ponds (i = 1-10), the design storm detention time (T_{di}) ranged from 0 to 72 hours with a 24-hour increment. For the three sub-regional ponds (i = 11,12, 13) T_{di} ranged between 0 and 48 hours, with a 3-hour increment. For the regional pond (i = 14), T_{di} ranged between 0 to 12 hours, with a 1-hour increment. Different increments of T_{di} are used for ponds at different spatial levels since the effect of the same increments of designed detention time on the system cost, as well as on the pollutant load reduction, are dramatically different due to significant differences in the drainage area. For instance, for the hypothetical example the drainage area of the regional pond is the entire watershed, which is 1,172-ha. In contrast, the drainage area of the on-site pond is in the order of 10 hectares. Thus, the design runoff volume for the regional pond is about two orders of magnitude greater than the design runoff volume for the on-site pond. Hence, an increase in the detention time of the regional pond would cause a much greater increase in storage volume than would be caused with the same increase in detention time for the on-site ponds. Therefore, in order to reduce the gap caused by decision variables of ponds at a higher spatial level, and not to sacrifice the search efficiency at the same time, shorter time increments were used for ponds at higher spatial levels. The depth of the ponds ranged between 2 and 3.5 m, with a 0.5 m increment when sediment resuspension was considered in the impoundment routine.

Cost Functions

Cost estimation is an essential part of a cost-effectiveness evaluation of stormwater control systems. However, due to the short history of BMP applications, a comprehensive and standard cost estimation method is not yet available.

In the present study, the concept of annual life-cycle cost was employed to formulate the cost functions. For the present study, the annual life-cycle cost is the annual construction cost, which is calculated as the initial capital cost divided by the length of service life, plus the annual O&M cost, less the annualized salvage value. In the cost formulations, the present value was not computed due to the current low discount rate, and also because all BMP placement alternatives are compared on the same basis, hence neglecting the present value would not affect the optimization results. In addition, land cost was not included in the cost because it varies dramatically from location to location. However, it should be noted that land costs could represent a significant portion of the total initial cost, particularly in highly developed urban areas. Therefore, it could possibly influence the optimization results, especially if the land costs for different potential BMP locations vary significantly.

The initial capital cost, namely the construction cost associated with stormwater ponds, is usually estimated as a function of the pond storage volume (V_s). It is calculated either as a power function (e.g., cost = αV_s^{β}), or as a linear function (e.g., cost = αV_s) with the multiplier being the cost per unit volume. Table 2a shows some of construction cost functions available in the literature. The information about annual O&M costs is seldom available on a comprehensive basis. It is usually estimated as a percentage of the construction cost (Table 2b).

Table 2a. Selected construction cost functions for stormwater ponds.

BMP	Cost ($)	Variable Unit	Sources
Dry Ponds	$C = 7.47V_s^{0.78}$	V_s in ft^3	Brown and Schuler, 1997
	$C = 55{,}000V_s^{0.69}$	V_s in Mgal	Young et al. (1995)
Wet Ponds	$C = 18.5V_s^{0.70}$	V_s in ft^3	Brown and Schuler, 1997
	$C = 61{,}000V_s^{0.75}$	V_s in Mgal	Young et al. (1995)

Table 2b. Selected annual operation and maintenance cost for stormwater ponds.

BMP	% of Construction Cost	Sources
Dry Ponds	<1%	EPA, 1999
Wet Ponds	3%~6%	EPA, 1999
	3%	Clar, 2000

Clar (2000, unpublished data) reported that stormwater ponds are long-lasting facilities and usually have a service life of more than 20 years. Another estimate of the service life for both dry and wet stormwater ponds was 50 years (USEPA, 1990). In this study, the service life for an extended dry pond is assumed to be 50 years. The salvage value was assumed to be zero.

Results of the Case Study

Figure 7 illustrates the costs of the optimal policies found for various water quality goals. The water quality goals are indicated by the allowed discharge fraction (ADF) of the existing sediment load. One can clearly observe the trade-off relationship between the cost and the ADF. The trade-off curve has a steeper slope at the lower end of the ADF. This means the sensitivity of the cost to the ADF is greater for the higher water quality goal (lower ADF). In other words, a unit variation in ADF at the lower ADF values has a greater effect on the costs than a unit change in ADF at higher ADF values. For example, increasing ADF from 0.3 to 0.35 (representing a change in the allowable load from 30% to 35% of the original load), reduces the cost by about $11,000, while increasing ADF from 0.7 to 0.75 only reduces the cost by only $3,500.

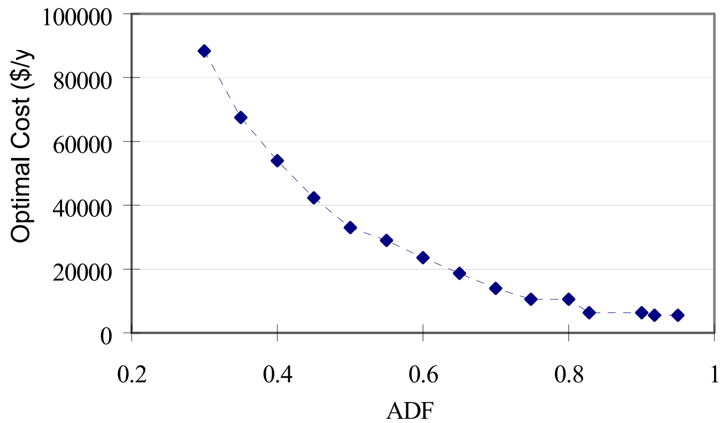


Figure 7. Optimal cost for various allowable discharge fractions (ADF) of the existing sediment load.

Figure 8 compares the optimal costs of the pond systems generated with and without considering sediment resuspension effect. Considering sediment resuspension in the optimization function resulted in higher system costs for the same water quality goal. The magnitude of the cost difference decreases as the ADF is increased (i.e., the water quality goal becomes less stringent). This is because the larger sediment particles, such as sand, are easier to remove than smaller particles, and they are less likely to resuspend. At higher ADFs, the larger-sized sediment particles form the bulk of the total sediment removed, while fine particles, which are easier to resuspend, must be removed to attain lower ADFs. Therefore the sediment resuspension effect has less effect on the optimal cost of BMPs that attain higher ADFs.

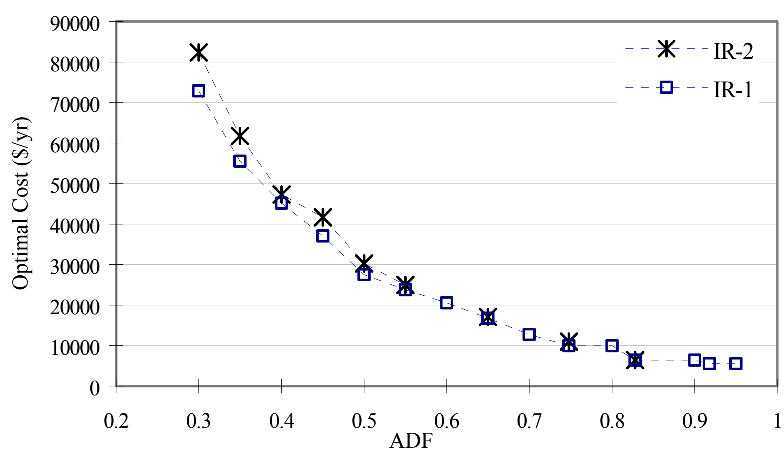


Figure 8. Optimal cost for various allowed discharge fractions (ADF) of the existing sediment load using different impoundment routines (IR-1 = without resuspension; IR-2 = with resuspension).

Figure 9 shows the optimal or near optimal solution of stormwater pond systems at various ADFs. These solutions were obtained considering the sediment resuspension effect. The figure suggests that for an optimal cost strategy, BMPs should be built in the sequence of regional, sub-regional, and finally on-site as the water quality requirement becomes higher and higher.

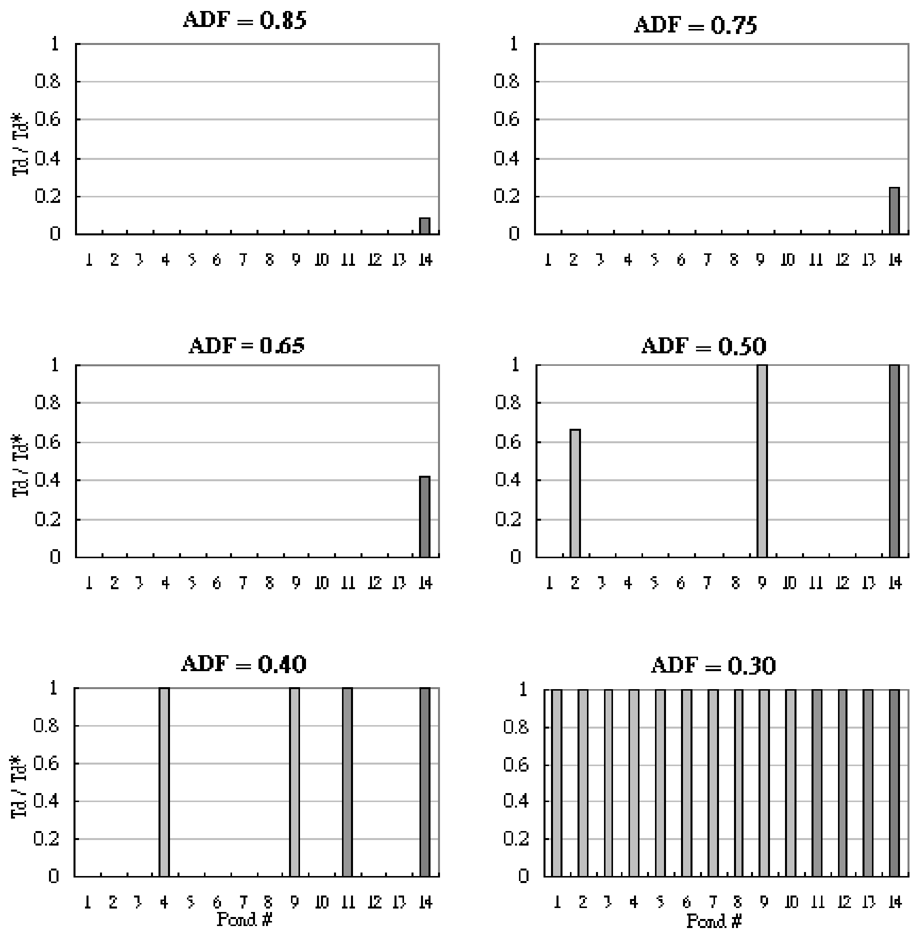


Figure 9. Optimal stormwater pond placements as normalized detention time, i.e., the design detention time (T_d) relative to its upper limit (T_d*), for various ADF values.

Application of the Optimization Methodology – A Highway Case Study

Background

The methodology developed in the present study was applied to a highway case study to demonstrate its potential use in planning VDOT stormwater management strategies. The case study involved the Rt. 288 road extension project near Richmond, Virginia. For the past few years, VDOT has been building the section of Rt. 288 that provides a link between Rt. 95 and Rt.

64 west of Richmond. A stretch of Rt. 288, including the interchange with Rt. 76, passes through the watershed of the Swift Creek Reservoir, a major drinking water reservoir for Chesterfield County. To comply with stormwater regulations, VDOT is applying typical erosion and sediment controls such as silt fences, rock check dams, sediment traps and basins, and seed and mulch during construction. For post-construction BMPs, VDOT consultants have already developed a stormwater management plan which includes over thirty detention ponds, of which a majority is within the Swift Creek Reservoir watershed. In order to test the BMP placement methodology developed in the present study, a number of assumptions and simplifications were made:

- The case study was conducted for Little Tomahawk Creek, one of the tributary watersheds to the Swift Creek Reservoir.
- Since the new section of Rt. 288 has not been entered into the existing GIS database, the road alignment was arbitrarily drawn onto the GIS-created map of the watershed.
- It was assumed that BMPs are placed along the highway in a linear fashion, at approximately one-mile intervals.

Study Approach

The case study analysis was conducted according to the following steps:

Step 1. Select an appropriate watershed model

The old version VirginiA STorm (VAST) model has been significantly improved recently in terms of Graphic User Interface (GUI), data preparation and storage, and output. The new version, called WinVAST, uses widely accepted algorithms in simulating the hydrology and pollutant wash-off processes for a given storm event. With all its enhanced capabilities, the WinVAST was considered the appropriate model for the case study.

Step 2. Use ArcInfo (GIS) to prepare the data

In this project an ARC INFO Toolbox has been developed to prepare the necessary data for running the WinVAST model.

Step 3. Use Scatter Search to find the Optimal Solution

The optimizer program described earlier in this report was used to determine the optimal BMP placement strategy for the Rt. 288 highway project.

Objective and Cost Functions

.

The Objective function was:

Minimize BMP Construction Cost;

Subject to: The Settlement Solids removal efficiency ≧ Requirement;
The placement of BMPs ∈ the potential BMPs locations;
The BMPs ∈ detention pond, grassy swale or both.

Construction Cost functions for BMPs:

1. Detention Pond:

$C1=18.5*V^{0.7}$

Where: C1 is the Construct Cost of the Detention Pond ($);
V is the Total Volume of the Detention Pond (ft^3).

2. Grassed Swale:

$1,850/acre; (Schueler, 1987)

From 1987 to 2002, the inflation rate for each year is (%): 4.4, 4.4, 4.6, 6.1, 3.1, 2.9, 2.7, 2.7, 2.5, 3.3, 1.7, 1.6, 2.7, 3.15, 3.3, and 2.8.
(Source: http://www.neatideas.com/info/inflation.htm)
Therefore in 2003, the construction cost of grassy swale was assumed to be $3,090/acre.

Optimization Analysis and Results

Several BMP placement scenarios were tested in the Rt. 288 case study, which were based on the premise that VDOT will work as a stakeholder under the watershed approach to pollution control as described at the beginning of the present report. With the new approach, VDOT will no longer build BMPs only within the right-of-way, but will work with other stakeholders to develop an optimal placement for the watershed as a whole.

Following the principles of the watershed approach, three basic BMP placement scenarios were devised:

- Scenario 1: The current practice under which BMPs are placed along the highway in a linear fashion.

- Scenario 2: A revised current strategy under which BMPs can be built along the highway sections, and also in sub-watersheds hydraulically connected to the highway sections through highway drainage systems.

- Scenario 3. A new strategy under which BMPs can be built either along the highway or in any sub-watershed within the Little Tomahawk Watershed.

The Little Tomahawk Creek Watershed was divided into 59 sub-watersheds for the case study. The section of Rt. 288 that passed through the Little Tomahawk Creek Watershed was divided into eleven 1-mile sections. It was assumed that each sub-watershed was a potential BMP site for either a detention pond or a grassed swale, or both depending on water quality requirements. To illustrate the methodology, the water quality requirement was set at 20% removal of total suspended solids at the watershed outlet, or an ADF of 0.8.

Result of Scenario 1: BMPs are placed in only 11 sections of Highway

In this scenario, BMPs can only be constructed on the 11 sections of highway. The simulation shows that a detention pond and a grassed swale are required for each of the eleven sections of the highway, as shown in Figure 10.

The total cost is $40,910.

BMP Placement: Highway
Each of the 11 sections of highway contain both ◆ (wet pond) and ▲ (grassed swale)
Watershed: None

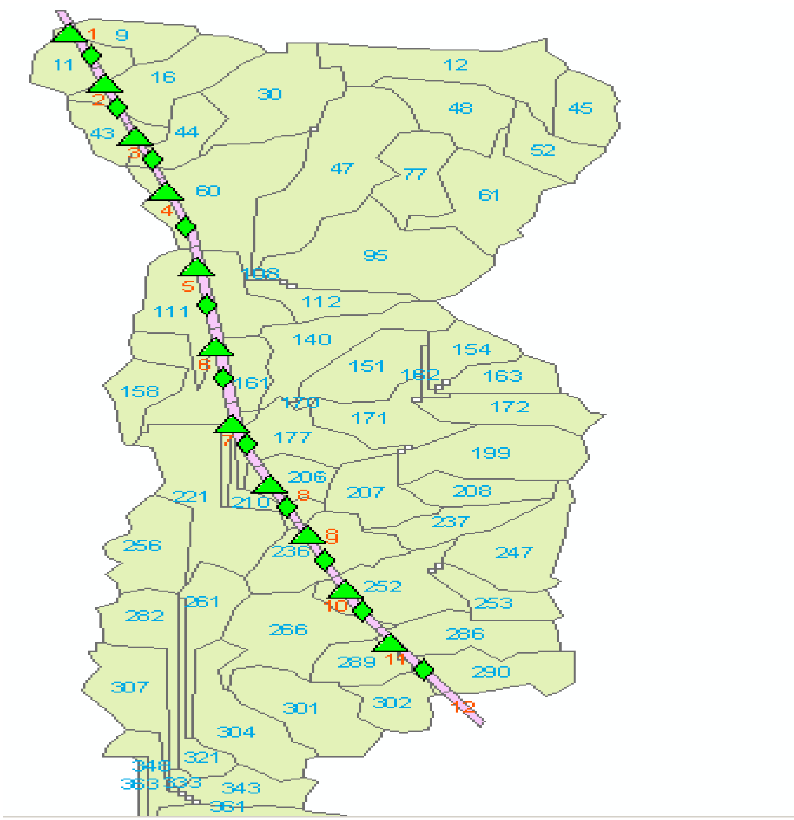


Figure 10. BMP Placement under Scenario 1.

Result of Scenario 2: BMPs can be built only in the 11 Sub-basins adjacent to the highway.

In this scenario, BMPs can only be constructed within the 11 sub-basins adjacent to the highway. The simulation shows that detention ponds should be constructed along the highway in two sub-watersheds and away from the highway in two others. The simulation also shows that a grassed swale should be constructed along the highway in six sub-watersheds. The results are shown graphically on Figure 11.

The total cost is $31,353.

BMP Placement:
Highway: 1 - ▲ (grassed swale), 2 - ▲, 3 - ◆ (detention pond), 5 - ▲, 9 - ▲, 10 - ▲, 11 - ▲◆
Watershed: 44 -◆261- ◆

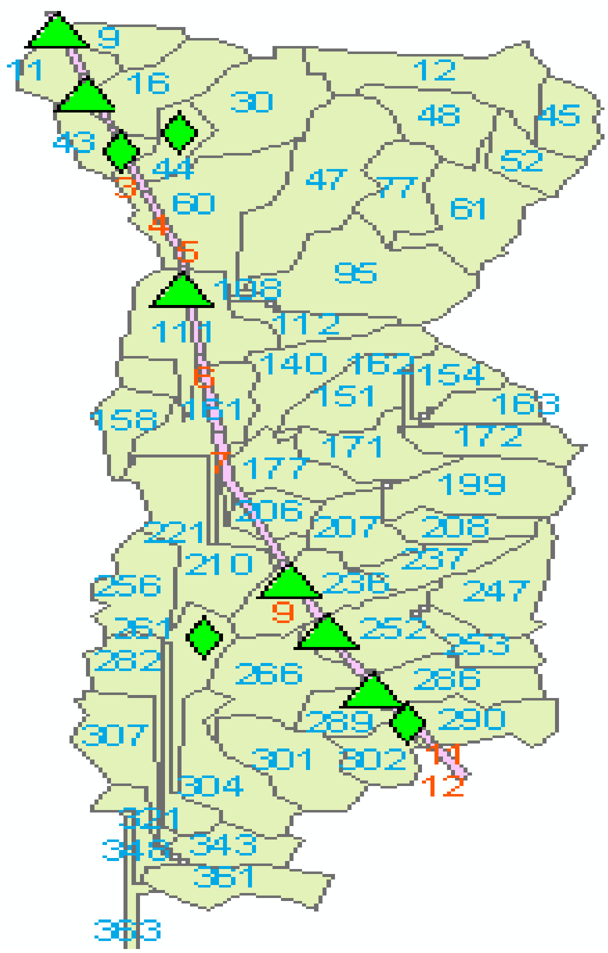


Figure 11. BMP placement under Scenario 2.

Results for Scenario 3: BMPs can be built both along the highway and within a sub-watershed

Under Scenario 3, BMPs can be built in any sub-watershed and also along the highway. The results, given in Figure 12, show the optimal strategy consists of constructing grassed swales along the highway in three sub-watersheds and away from the highway in three sub-watersheds. The optimal strategy also consists of constructing detention ponds along the highway in one sub-watershed and away from the highway in one sub-watershed. The total cost of the optimal strategy is lower than the cost either of Scenario 1 or Scenario 2.

The Total Cost is: $ 25,833.

BMP placement:
Highway:1 -▲ (grassed swale), 6 - ◆ (detention pond),▲, 7 -▲
Watershed: 111 - ◆, 108 -▲, 333 -▲, 342 -▲

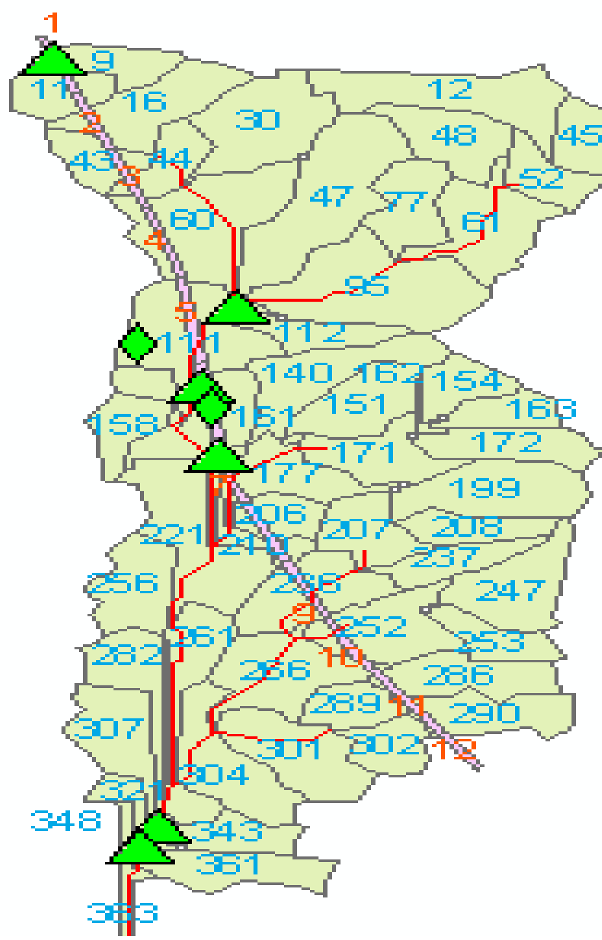


Figure 12. BMP placement under Scenario 3.

To examine the change in total cost when the water quality requirement is changed, a placement strategy for a 50% removal (an ADF of 0.5), under Scenario 3 was obtained. The results are shown in Figure 13. The total cost for this placement strategy was $68,090.

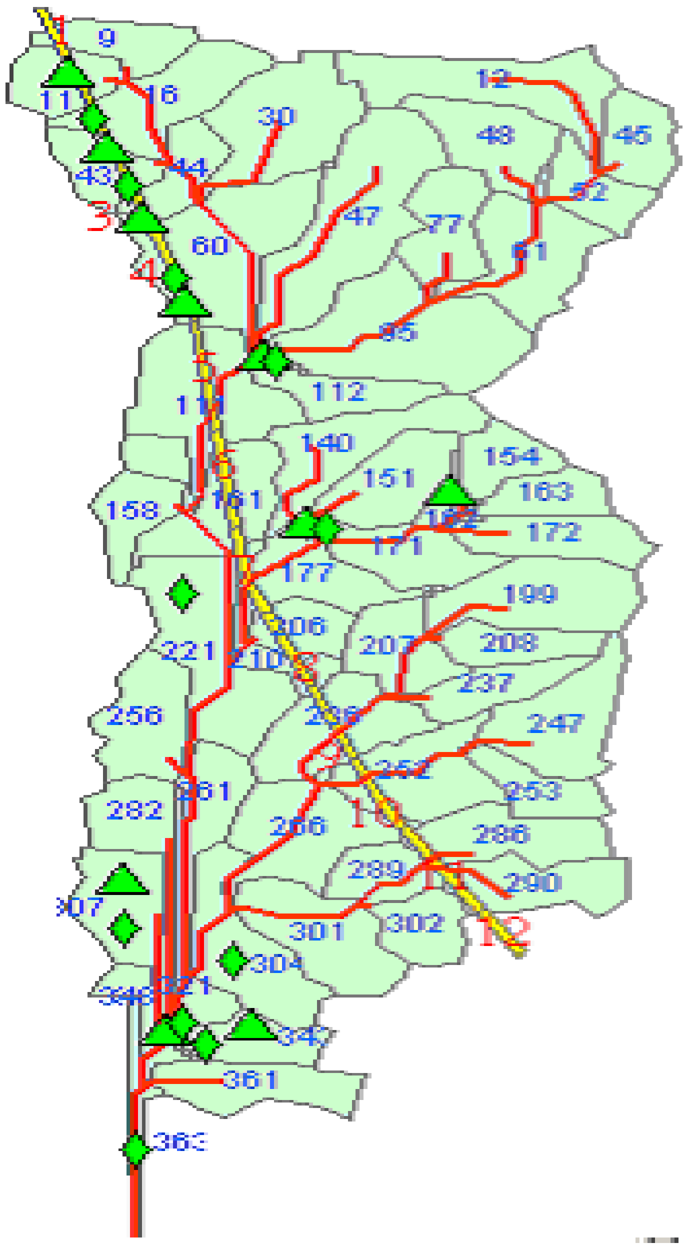


Figure 13. BMP placement for removal efficiency of 50% under Scenario 3.

Under Scenario 3, BMPs can be built anywhere in the watershed, either along the highway or in any sub-watershed. This strategy allows the maximum flexibility in placing BMPs in the watershed and, therefore, should lead to the cost-effective, or optimal, placement of BMPs. A comparison of the total BMP implementation cost for Scenarios 1 through 3 confirmed the expectation.

The implications of the results from the Rt. 288 case study described are as follows:

- For a specific water quality requirement (e.g., a 40% watershed sediment load reduction goal for a drinking water reservoir), the cost-effective solution is to place BMPs at critical locations in the watershed. Usually such critical areas are those with higher than average pollutant loads, or those in the vicinity of the water body in question (i.e., a drinking water reservoir).

- For VDOT, the linear placement of BMPs that it has applied for many years may not be the cost-effective strategy. Although the current regulatory requirements call for on-site treatment, for the watershed as a whole, the best strategy would be for VDOT to work with other stakeholders to develop an optimal placement scheme. In so doing, VDOT can save its BMP construction and maintenance costs while also helping to achieve water quality goals for the watershed.

- The USEPA should revamp its nonpoint pollution control and stormwater management regulations to allow stakeholders in a watershed to devise a best strategy in terms of pollutant removal and the associated costs so that the financial burden on the stakeholders will be minimized and the water bodies in a watershed adequately protected.

FINDINGS AND CONCLUSIONS

1. A holistic methodology for determining the cost-effective placement and configuration of stormwater BMPs for VDOT was developed. The methodology involves the coupling of a comprehensive watershed simulation model with an optimization technique. Specifically, the methodology developed in the study consists of three interacting functional components; a watershed simulation model, a BMP simulation module (the impoundment routine), and an optimization model.

2. The watershed simulation model (AnnAGNPS or WinVAST) was used to simulate the hydrology and water quality of a test watershed, and also to track the significant sources of pollution and thereby identify the critical areas. The impoundment module embedded in the AnnAGNPS model was revised to allow the simulation of sediment accumulation and resuspension. The revision enables the model to evaluate the long-term performance of stormwater ponds. Such evaluations will provide the necessary information for devising pond maintenance schedules.

3. The scatter search optimization model (OCL) was linked both to the watershed model and to the embedded BMP simulation model, and served as the evaluator to provide information on the feasibility of alternative solutions. The OCL helped determine the cost-effective BMP implementation plan. In the present study, the optimization analysis focused on the placement and sizing of the BMPs.

4. The scaling effect on watershed simulations was examined. It was found that the higher the resolution (i.e., dividing the watershed into a large number of sub-watersheds), the higher the attenuation effect on peak flows. This is due to the larger storage capacity associated with more channels for higher resolution cases.

5. A new impoundment module was developed based on the original subroutine available in AnnAGNPS, which can take into account sediment accumulation and resuspension. The sediment accumulation effect was simulated by updating the pond geometric parameter according to the amount of sediment trapped in the pond. For sediment resuspension, a simplified zero-dimensional method relating the magnitude of sediment resuspension to the inflow rate was developed.

6. Three BMP placement scenarios were examined; namely, the on-site, the sub-watershed (or sub-regional), and the watershed (or regional) level placement. The optimization program, coupled with the watershed model with embedded BMP simulators was used to find the least-cost BMP scenario. The results for a hypothetical watershed show a general trend. When the water quality goal is made more stringent, the optimal strategy consists of ponds. The optimal strategy for the least stringent water quality goal consists of ponds being constructed at the watershed level. As the water quality goal is made more stringent, ponds are constructed at the sub-watershed level. Finally, as the water quality goal is made even more stringent, ponds are constructed on-site as long as spaces are available for pond construction at all the potential sites.

7. The amount of sediment accumulated in the BMPs can affect the overall cost of operating the watershed BMP system. It was found that when the maintenance cost was tied with the amount of sediment accumulation, the overall system cost would be lower.

8. A highway application case study was made using the VDOT Rt. 288 Project in Chesterfield County, Virginia. The results showed that the current VDOT BMP placement approach (i.e., on-site treatment of stormwater runoff from highways), might not be cost-effective in terms of protecting the water quality at the watershed level. The results indicated that if VDOT works with other stakeholders in a watershed to develop a BMP placement strategy for the entire watershed, the cost-effective strategy would involve a fewer number of BMPs.

9. The results of the Rt. 288 case study further showed that as the water quality requirement becomes higher, more BMPs would be required, but the additional BMPs

tend to be needed near the outlet of the watershed and not at locations in upstream areas.

10. The methodology developed in the present study can be expanded in scope to include more types of BMPs, and to allow additional innovative BMP placement scenarios so that a decision support system for VDOT stormwater management can be realized.

RECOMMENDATIONS

1. It is recommended that the Location & Design Division (L&D) of VDOT consider a proactive approach in planning its stormwater BMP implementation strategy. Results from the present study show that the best strategy would be for VDOT to work with other stakeholders such as regulators, pollutant dischargers, citizen groups, etc., to develop an optimal placement scheme. In so doing VDOT may be able to reduce its BMP construction and maintenance costs while also helping to achieve water quality goals for the watershed.

2. As the largest construction entity in Virginia, VDOT can play a significant role in the formulation of a watershed pollution control strategy, such as the TMDL initiative. It is recommended that the L&D Division of VDOT discuss its stormwater management plans with localities, interested groups and regulatory agencies in order to devise the cost-effective plan for all parties.

3. BMP maintenance is costly. It is suggested that the L&D Division of VDOT consider sediment accumulation and resuspension over the life of BMPs in the planning and design process. The methodology developed in the present study, for example, could be used for such purposes.

4. It is recommended that the L&D Division of VDOT consider applying the optimization methodology developed in the present study in planning its BMP placement strategies. VDOT could consider expanding the methodology in scope to include more types of BMPs, and to allow additional innovative BMP placement scenarios so that a decision support system for VDOT stormwater management can be realized.

5. It is suggested that the L&D Division of VDOT consider the establishment of a long-term monitoring program for selected BMPs. The data collected under such a program would be immensely valuable in assessing BMP long-term performance and maintenance needs.

REFERENCES

Bingner, R., Darden, B., Herring, F., and Garbrecht, E. TOPAGNPS 1.20, U.S. Department of Agriculture-Agricultural Research Service, Washington, DC, 1998.

Driscoll, E.D. Analysis of Detention Basins in EPA NURP Program. Paper presented at the Conference on Stormwater Detention Facilities Planning, Design, Operation and Maintenance. New England College, Henniker, N. H., 1982.

Earles, T.A. Mitigated Wetlands for the Treatment of Stormwater Runoff: Monitoring and Management. Ph.D. Dissertation. Department of Civil Engineering, University of Virginia, Charlottesville, VA, 1999.

Glover, F., and Laguna, M. Fundamentals of Scatter Search and Path Relinking. *Control and Cybernetic*, Vol. 29, No. 3, 2000, pp. 653-684, 2000.

Glover, F.M., Laguna, M., and Marti, R. Scatter Search. In: *Theory and Applications of Evolutionary Computation: Recent Trends*. Edited by A. Ghosh and S. Tsutsui, Springer Verlag Publisher, 2000.

Huber, W.C. et al. *Stormwater Management Model User's Manual Version II*, EPA 670/2-77-17, USEPA, Cincinnati, OH, 1975.

Kao, J-J, and Tsai C-H. Multiobjective Zone TP Reduction Analysis for an Off-stream Reservoir, *J. of Water Resources Planning and Management*, Vol. 123, No. 4, 1987, pp. 208-215.

Langan, T., and Yu, S.L. Controlling Highway Runoff in Water-Supply Reservoir Watersheds. Final Report, Virginia Transportation Research Council, Charlottesville, VA, 22903, 1999.

Liao, H.H., and Tim, U.S. An Interactive Modeling Environment for Nonpoint Source Pollution Control. *Journal of the American Water Resources Association,* Vol. 33, No. 3, 1997, pp. 591-603.

Loganathan, G.V., Delleur, J.W., and Segarra, R.I. Planning Detention Storage for Stormwater Management, *J. of Water Resources Planning and Management*, Vol. 111, 1985, pp. 382-398.

Loganathan, G.V., Watkins, E.W., and Fibler, D.F. Sizing Stormwater Detention Basins for Pollutant Removal, *J. Environmental Engineering*, Vol. 120, 1994, pp. 1380-1399.

Manguerra H.B. and Engel B.A. Hydrologic Parameterization of Watersheds for Runoff Prediction Using SWAT, *J. of American Water Resources Association*, Vol. 34, No.5, 1998, pp. 1149-1162.

Northern Virginia Planning District Commission. *Evaluation of Regional BMPs in the Occoquan Watershed*, NVPDC, 7535 Little River Turnpike, Suite 100, Annandale, VA 22003, 1990.

Novotny, V., Chesters, G. *Handbook of Nonpoint Source Pollution and Management*, VNR, New York, 1981.

Schueler, T. R. *Controlling Urban Runoff*, Department of Environmental Programs. Metropolitan Washington Council of Governments, Washington, DC., 1987.

Segarra-Garcia, R., Loganathan, G. V. Storm-water Detention Storage Design under Random Pollutant Loading, *J. of Water Resources Planning and Management*, Vol. 118, 1992, pp. 475-491.

Stopinski, M., and Yu, S.L., Field Testing of Ultra-Urban Best Management Practices. Final Report, Virginia Transportation Research Council, Charlottesville, VA, 2000.

Tilley, David R., Brown, Mark T. Wetland Networks for Stormwater Management in Subtropical Urban Watersheds, *Ecological Engineering*, Vol. 10, 1998, pp. 131-158.

Tisdale, T.S., R. J. Kaighn, Jr., and S. L. Yu. *The VirginiA STorm Model for Stormwater Management, v6.0 User's Guide*, Dept. of Civil Engineering, University of Virginia, Charlottesville, VA, 1996.

USEPA. *Methodology for Analysis of Detention Basins for Control of Urban Runoff Quality*, EPA 440/5-87-001, Washington, DC, 1996.

Wu, Yin. *A 2-D Reservoir/Pond Model*, Ph.D. Dissertation, Department of Civil Engineering, University of Virginia, Charlottesville, VA, 1992.

Yu, S. L. *Stormwater Management for Transportation Facilities*, Transportation Research Board, National Research Council, Washington, DC, 1993.

Yu, S. L., Fitch, G. M., and Earles, T. A. Constructed Wetlands for Stormwater Management, Virginia Transportation Research Council Report 98-R35, Charlottesville, VA, 1998.

Yu, S. L., and Field, R. Derived distribution approach to detention pond design, *Proc. of the Sixth IAHR International Symposium on Stochastic Hydraulics*, Taipei, 1992, p. 607.

Zhen, Xiaoyue, and Yu, S.L., BMP Placement at the Watershed Scale. Paper presented at the ASCE Water Resources Planning and Management Annual Conference, Reno, NV, 2001.

Zhen, Xiaoyue. Development of a BMP Placement Strategy at the Watershed Scale. Ph.D. Dissertation, Department of Civil Engineering, University of Virginia, Charlottesville, VA, 2002.