Decision Making for Implementation of Nonpoint Pollution Measures in the Urban Coastal Zone

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Abstract

We have developed an optimization screening model for cost-effective prioritization of urban second-order stream subwatersheds for targeting nonpoint pollution reduction management practices in the Pennsylvania coastal zone drainage. The model is applied to Springfield Township in the suburban Philadelphia region. Results show that top priority should be given to treatment of any barren land in the less developed subwatersheds using on-site BMPs followed by similar sites on recreational fields, and then reductions in stream bank erosion should be targeted through BMPs installed on high intensity residential and commercial land uses in the more heavily developed subwatersheds.

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Introduction

The management of nonpoint pollution associated with stormwater runoff, leaking and overflowing sewers and septic systems and other nonpoint sources prevalent in urban and heavily developed suburban areas is a complex decision-making problem faced by watershed managers in regulatory agencies and municipalities. Watershed assessments and conservation plans generate lists of possible measures for reducing nonpoint pollution, but these lists are only the beginning of the difficult process of identifying and prioritizing projects to receive the limited moneys available from public and private sources. Ideally, top priority projects are those that achieve the necessary environmental improvements, such as water quality and habitat restoration, in the most cost-effective way.

The field of Management Science provides modeling tools that can be used to maximize the effectiveness of available funds for implementation of nonpoint pollution management practices. The purpose of our research is to create models to guide decision makers towards selection of cost effective implementation of nonpoint pollution management measures and practices and to calibrate the models for the specific set of circumstances (topographic, hydrologic, land use, etc.) that occur in an intensively developed municipality in the Philadelphia suburbs (Springfield Township, Delaware County) that is experiencing urban nonpoint pollution problems. Springfield is drained by two third-order stream watersheds, Crum Creek and Darby Creek, in the Delaware Estuary drainage (HUC 02040202).

This report covers the first phase of our research. We have developed a watershed-based screening tool that is used to rank second-order stream subwatersheds for implementation of management practices. We have evaluated different categories of models (for nonpoint pollutant loading, BMP cost and performance, and subwatershed-level optimization) based on accuracy of prediction, data requirements, and computational efficiency. We then selected an existing nonpoint loading model (AVGWLF) and created our own optimization model (NPSOPT – for NonPoint Screening Optimization) which generates screening-level prioritization of subwatersheds. Finally, we have demonstrated the application of the models in the urban coastal zone drainage.

The second phase of our research will incorporate more site specific considerations and multiple, conflicting objectives to more precisely focus the search for a small number of projects to recommend for progression to the design phase.

***Data from Watershed Assessme*nts**

Figure 1 shows the extent of the Crum Creek and Darby Creek Watersheds, with Springfield Township outlined in red with its area approximately equally distributed across both watersheds. The City of Philadelphia, just to the east, also drains into the Darby Creek Watershed through the Cobbs Creek Tributary. Four recent studies are available for these two watersheds that provide general observations, detailed data, and recommendations for management of nonpoint pollution in the lower reaches of these streams where urban stormwater runoff has degraded and impaired in-stream habitat and downstream water quality (Schnabel Engineering, Inc., 2001; McGarity, 2001; Cahill Associates, 2002; and Natural Lands Trust, 2005). These studies have identified the problems and have helped to strengthen and provide direction for local watershed associations. For example, the Crum Creek Watershed Partnership was formed in 2000 and has already sponsored water quality improvement projects recommended by the Lower Crum Assessment (McGarity, 2001) including a natural wetland restoration, a stormwater wetland retrofit, and a storm sewer inlet labeling program with funding from Pennsylvania's Growing Greener program (McGarity, 2004).

Most of the stream segments on the lower Crum and Darby Creeks are listed among the Federal Clean Water Act's Section 303D impaired waters based on biological assessments. The main branches of these streams flow into the Delaware Estuary in close proximity to one another near the Philadelphia International Airport. The primary causes for the impairments, identified by assessment studies, are nonpoint pollutant loads, stream bank erosion, thermal modification, and low base flow, and the primary cause is development for mainly residential and commercial uses. Impervious cover is in the range 30% to 75% in the different municipalities within the lower reaches of both watersheds, with Springfield Township falling in the lower end of that range. Crum Creek is also affected by a major withdrawal just upstream of Springfield by Aqua Pennsylvania, a privately owned water utility, which has a withdrawal permit that does not require conservation flow-by during low flow. There are no major point source discharges of wastewater in the lower reaches of either watershed because all of the municipalities are served by separate sanitary sewers that feed into the regional Southwest Philadelphia Treatment Plant. However, GIS data do indicate some private septic systems are still operating. Fecal coliform levels in tributaries commonly spike during storm events, in part because of wash off of animal waste, but also, because of frequent leaks and occasional overflows from the sanitary sewers.

A significant physiographic feature is the dividing line between the piedmont and coastal plain provinces which runs transverse to the main branches of the two creeks and which passes through Springfield from east to west. Thus, there is a significant change in elevation moving from north (330 ft) to the south (115 ft). This drop of more than 200 feet, with much of the drop occurring in steep slopes along second-order tributaries, results in high velocity runoff and corresponding high rates of soil and stream bank erosion.

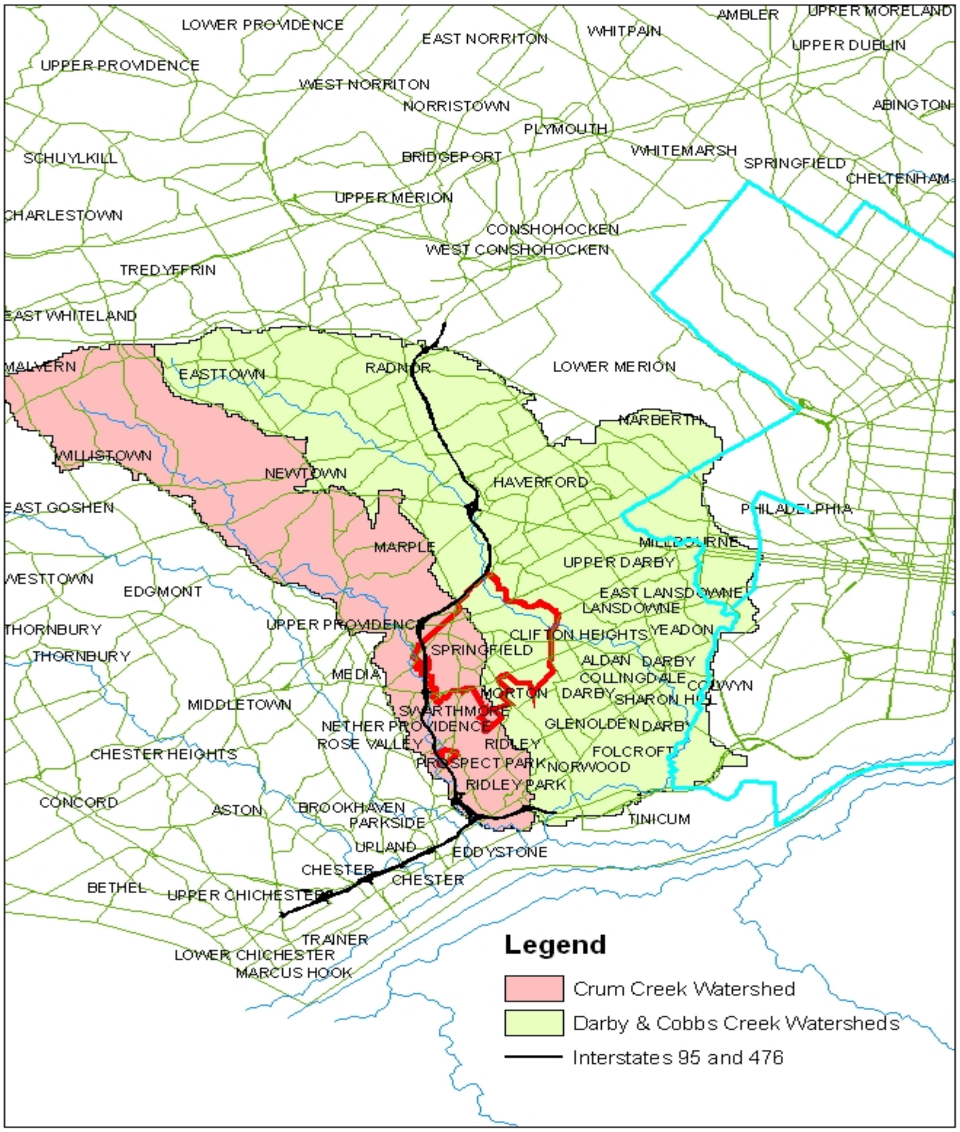

Figure 1. Springfield Township is located in the Philadelphia suburbs. Its urban runoff drains into the Crum and Darby Creeks which flow into the Delaware Estuary below Philadelphia and above Chester City

The eight main subwatersheds that drain Springfield Township were delineated, as shown on the map in Figure 2. Three subwatersheds drain into Crum Creek (Lownes Run, Whiskey Run, and Little Crum Creek) while five subwatersheds drain into Darby Creek (Darby Unnamed Tributaries 1 and 2, Levis Run, Muckinipattis Creek, and Stony Creek). The boundary lines of Springfield are also shown. Many segments of the first-order streams actually run underground in storm sewers. Figure 3 shows a map of percent impervious cover along with the same boundaries and streams as in Figure 2. Table 1 shows land areas in acres and land use characteristics for the Springfield portion of each of the subwatersheds. Surfaces of higher impervious percentages in Springfield primarily correspond to commercial districts along major roads and, to a lesser extent, high intensity residential development.

The recently completed River Conservation Plans for both watersheds echo the concerns raised in the monitoring and modeling studies regarding nonpoint pollution problems created by stormwater runoff. They go on to recommend goals for improved watershed management in the future. The Darby Creek plan (Cahill Associates, 2002) establishes ten goals, most of which relate directly to the reduction of nonpoint pollutants such as creating riparian buffers, improved stormwater management, watershed-based planning, public education, and better management of activities such as lawn fertilizer application, animal waste, and hazardous waste disposal. Darby Creek is also prone to destructive flooding, so flood control concerns are also elevated.

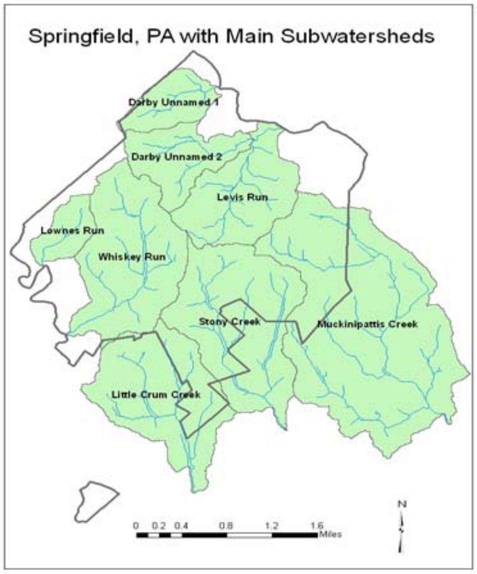

Figure 2. The eight main second-order stream subwatersheds draining Springfield that were delineated using BASINS (USEPA) and USGS digital elevation data, followed by nonpoint pollutant modeling by AVGWLF (Penn State) and, finally, prioritization for cost effective management practices by our optimization model (Swarthmore College) in this study. The boundary line of Springfield is shown as a thick gray line. Subwatershed boundaries are shown as thin gray lines. First and second order streams are shown in blue.

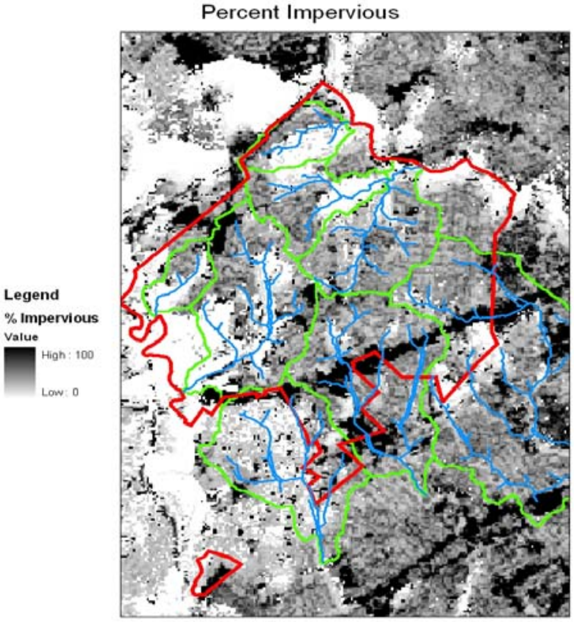

Figure 3. Impervious surfaces in Springfield correspond to commercial districts along major roads and, to a lesser extent, high intensity residential development. 100% impervious areas are solid black while the mostly pervious wooded lands and fields are white. **Source:** Pennsylvania Spatial Data Access (PASDA) web site link http://www.pasda.psu.edu/summary.cgi/isa_pa/pa2000isaa_se.xml which contains results from Thematic Mapper data using algorithms developed by Dr. Toby Carlson.

Table 1. Size and land use characteristics of the eight main subwatersheds in Springfield. Total acreage in each subwatershed is shown as well as the amount of that acreage that is impervious. Also, total acreage is broken down into five different land use categories. Impervious acreage occurs in all land use categories, but mainly in the Commercial and Residential categories.

Name	Area (Acres)	Percent Impervious	Impervious (Acres)	Commercial (Acres)	Residential (Acres)	Barren (Acres)	Recreational (Acres)	Forest (Acres)
Darby Unnamed Tributary #1	205.1	20.8%	42.66	4.9	123.6	9.9	49.40	17.3
Darby Unnamed Tributary #2	331.1	22.4%	74.17	0	232.3	7.4	17.30	74.1
Levis Run	523.9	29.1%	152.45	0	479.4	0	9.80	34.7
Little Crum Creek	182.9	39.4%	72.06	22.2	143.3	0	9.80	7.6
Lownes Run	145.8	22.9%	33.39	0	93.9	7.4	14.80	29.7
Muckinipattis Creek	420.1	33.8%	141.99	89.0	281.7	2.5	7.40	39.5
Stony Creek	578.2	43.5%	251.52	222.4	343.5	0	2.50	9.8
Whiskey Run	783.3	28.7%	224.81	93.9	469.5	9.9	96.40	113.6
Total	**3170.4**	**31.3%**	**993.05**	**432.4**	**2167.2**	**37.10**	**207.40**	**326.3**

Sources: Impervious surface data layers from Pennsylvania Spatial Data Access (PASDA) web site link http://www.pasda.psu.edu/summary.cgi/isa_pa/pa2000isaa_se.xml which contains results from Thematic Mapper data using algorithms developed by Dr. Toby Carlson. Land use data obtained from default land use data layers distributed with AVGWLF version 5.0, with Row Crop and Hay/Pasture categories changed to Recreational, as described in text.

Review and Selection of Nonpoint Pollution Loading Models

The search for high priority sites for implementation of nonpoint pollution management practices should be informed by scientifically sound estimates of pollutant loadings caused by different sources within the management area. Computer models are frequently used to generate loading estimates. Models for calculating nonpoint pollutant loading fall into three categories depending on their complexity: (1) simplified models based primarily on land use designations and imperviousness, (2) moderately detailed simulations based on empirical loading functions, and (3) highly detailed simulations requiring large amount of site-specific data. These categories of models differ primarily in the amount of location-specific data required to specify the parameters and on the amount of computation required to produce results.

The accuracy of computer model estimates of pollutant loadings depends on the validity of the underlying mathematical formulas used inside the model that express theories of pollutant generation and transport and the accuracy of the numeric values for the model parameters used to run the model when it is applied to a specific watershed. Inadequacies in either area can lead to inaccurate results, and all three categories of models above can be affected by such problems.

In our review of nonpoint pollution modeling for application to screening nonpoint source management in the urban coastal zone, we have concluded that the second-order stream subwatershed represents an appropriate level of aggregation, and categories of land use within each subwatershed can provide the basis for management units on which to specify the performance of management practices for reducing nonpoint pollution. We have also concluded that the resources typically available for a screening-level analysis will limit the choice of models to those in the simplified or moderately detailed categories.

We have selected the moderately detailed AVGWLF model for calculating annual pollutant loadings associated with second-order stream subwatersheds (Evans, 2004). Recent refinements made by Penn State University to AVGWLF make this choice attractive from an accuracy standpoint and feasible from a data requirements and model implementation standpoint. The model was originally developed at Cornell University and implemented in the BASIC language (Haith, 1987). An important feature of the current release of AVGWLF is its ability to calculate estimates of stream bank erosion separately from runoff erosion (Evans, 2003). This aspect enables us to separate the two components of total suspended solids in our calculation of management practice effectiveness. We judged AVGWLF to be a fairly accurate model that could be adapted for use with our nonpoint screening optimization model (NPSOPT) with a reasonable amount of effort.

After second-order stream delineations were obtained, the AVGWLF was run on each of the eight subwatersheds. Our research design anticipated the need for calibration of the pollutant loading model based on field observations of land use and water quality data. During the summer of 2004, a team of Swarthmore College students were trained in proper stormwater sampling protocols and laboratory procedures for measuring volumetric flow rates, suspended solids, and nutrients (nitrogen and phosphorous). Several rain events in early July were used as training exercises, and on July 23, a significant rain event was monitored with 19 samples collected with the aid of an auto-sampler.

Rough comparisons of model output and field data were made by computing annual average concentrations of nonpoint pollutants in the second-order streams inferred by the model by dividing the annual pollutant loadings by the annual volumes of streamflow. These modeled concentrations were compared with measured concentrations and the event mean concentrations. Comparisons for total suspended solids (TSS) and dissolved nitrogen (DN - measured as nitrate nitrogen in our laboratory) are fairly good suggesting that the modeled results for these two pollutants are adequate. Overall, these results suggest that incorporating AVGWLF loading results into the screening model will produce acceptable rankings based on either sediment loading reductions or nitrogen loading reductions.

Models for BMP Sizing, Performance, and Cost

Prioritization of subwatersheds for management practices also requires models for the performance, cost and extent of application within each subwatershed of management practices (BMPs). Thus, it is necessary to augment the AVGWLF model with a model that estimates the amount of pollutant that can be removed at the subwatershed level as well as the costs associated with the management practices that are typically used to achieve pollutant reductions.

In recent years, there have been many studies of nonpoint pollution BMP cost and pollutant removal efficiency. Most of these studies provide data or cost functions that are useful for estimating the costs of individual components of a project such as piping and tanks (Heaney, et al., 2002) or for site specific costs of a complete BMP installation (Brown and Schueler, 1997). The Center for Watershed Protection (CWP, 2004) maintains an online Stormwater Manager's Resource Center (SMRC, 2004) which provides “Fact Sheets” containing up-to-date information and practical guidance on specific stormwater management practices, including, in many cases, cost and performance data. Site specific costs vary over an extremely wide range.

One of the more comprehensive studies of BMP cost and effectiveness in urban settings was recently conducted by the USEPA's National Risk Management Research Laboratory (Muthukrishnan, et al. 2004). This study documents the difficulties in defining and measuring parameters that indicate the effectiveness and cost of structural and nonstructural BMPs. The needs for ongoing monitoring and better documentation of costs are expressed. However, valuable guidance is provided that is helpful in modeling the BMP decision process in urban areas. Optimum and appropriate placement of BMPs within a watershed is identified as a new "hot button" issue in stormwater management, and the need is expressed for optimization modeling studies of BMP placement decisions in watersheds. Moreover, the study favors an integrated approach employing "multiple layers of structural and nonstructural BMPs … used in unison" to achieve the greatest benefit to the watershed (Muthukrishnan, et al. 2004, p. 1-9).

Our review of the literature points to the challenge of modeling for cost effective BMP decision-making at the watershed or subwatershed level. Modelers must reconcile the differences in scale between the site-specific BMP cost and performance data and the much larger scale at which nonpoint pollution loading models are applied (i.e. second-order stream subwatersheds). Moreover, a screening model analysis must, by definition, deal with the "big picture" and can not incorporate the fine level of detail necessary to quantify specific sites within a subwatershed. Environmental models of this type usually incorporate cost functions that show marginal costs of pollutant removal moving towards higher levels as the overall pollutant removal percentage increases towards a limit defined by available treatment technology .

The model we have developed for BMP performance and cost applies to an entire subwatershed, but it treats each land use within the subwatershed separately. Site specific BMP costs are extrapolated to a subwatershed using a nonlinear model that can represent the wide range of marginal costs that are likely to occur over the subwatershed. A fundamental assumption in the model is that the integrated approach, described by Muthudrishnan, et al., above, involving cost effective selection and placement of nonstructural and structural BMPs is employed by watershed managers. Top priority for funding is given to projects that achieve the most nonpoint pollution reduction for each level of resources devoted. These are projects that have the lowest available marginal cost per unit of pollutant removed, and are quite likely to be nonstructural BMPs, at first, followed by structural BMPs applied to sites in the subwatershed where land costs are lowest and economies of scale are most likely to be achieved, followed by more expensive structural BMPs in the less favorable sites, and, finally, and only if absolutely necessary to achieve the desired pollutant reductions, the very expensive structural BMPs in the least favorable sites.

Optimization Screening Model to Prioritize Subwatersheds for BMP Implementation Projects

The mathematical derivation of the Optimization Screening Model (NPSOPT) is provided in detail in the project report (McGarity, 2005). It has been run to generate results for Springfield Township and to demonstrate its potential for application in other municipalities and watersheds. Our nonpoint pollution modeling results indicate that sediment is the primary nonpoint pollutant of concern in Springfield.

Figure 4 plots the total resources devoted to nonpoint pollution removal over all eight subwatersheds in the township versus reductions in sediment pollution over the range from 10 tons to 300 tons of total reduction. Our optimization model results for urban retrofit BMPs in Springfield compare well with results generated by Yu, et al. for optimal placement of generally less expensive dry ponds in a rural subwatershed of Ivy Creek in Virginia. Note, however, that our model selects inexpensive management practices such as grass swales for barren and recreational land uses for the first 100 tons of TSS removal followed by the more expensive management practices for the next 200 tons of TSS removal such as bioretention cells which are necessary for retrofit application on residential and commercial land uses. Both models demonstrate increasing marginal costs at the subwatershed-level, which contrasts with site-specific project costs that often experience economies of scale. Our model assumes that economies of scale exist at first, but become increasingly difficult to obtain as the total treated land area increases. This “site saturation effect” is particularly strong in the urban retrofit context. Resources are expressed as present value of costs for installation and maintenance. Data for Yu’s model were extracted (Yu, et al., 2003, p. 16), with costs converted to present value.

Priorities among land uses are summarized in the pie charts shown in Figure 5 for four different levels of TSS reduction total. At lower levels of sediment removal, the optimization model selects sites for which cost effective sediment removal can be obtained on-site directly from land runoff erosion control in the barren and recreational land uses. However, as the requirement for total sediment removal increases, the solutions shift towards those that reduce stream bank erosion through runoff reduction from impervious surfaces in the residential and commercial land uses.

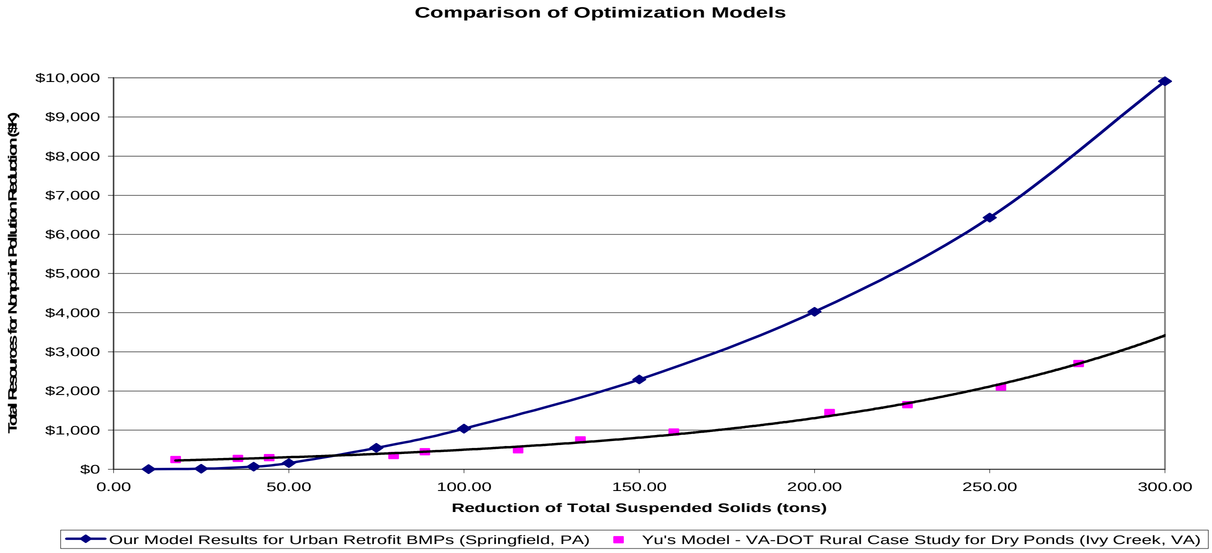

Figure 4. total resources (vertical axis, $1000) devoted to nonpoint pollution removal using urban retrofit BMPs over all eight subwatersheds of Springfield Township over the entire range (horizontal axis) from 10 tons to 300 tons of sediment reduction. Comparisons are shown with the subwatershed BMP placement optimization of Yu, et al. for the less expensive case of detention ponds to control agricultural nonpoint pollution. Total land areas drained are similar: 3170 acres in Springfield and 2900 acres at Ivy Creek.

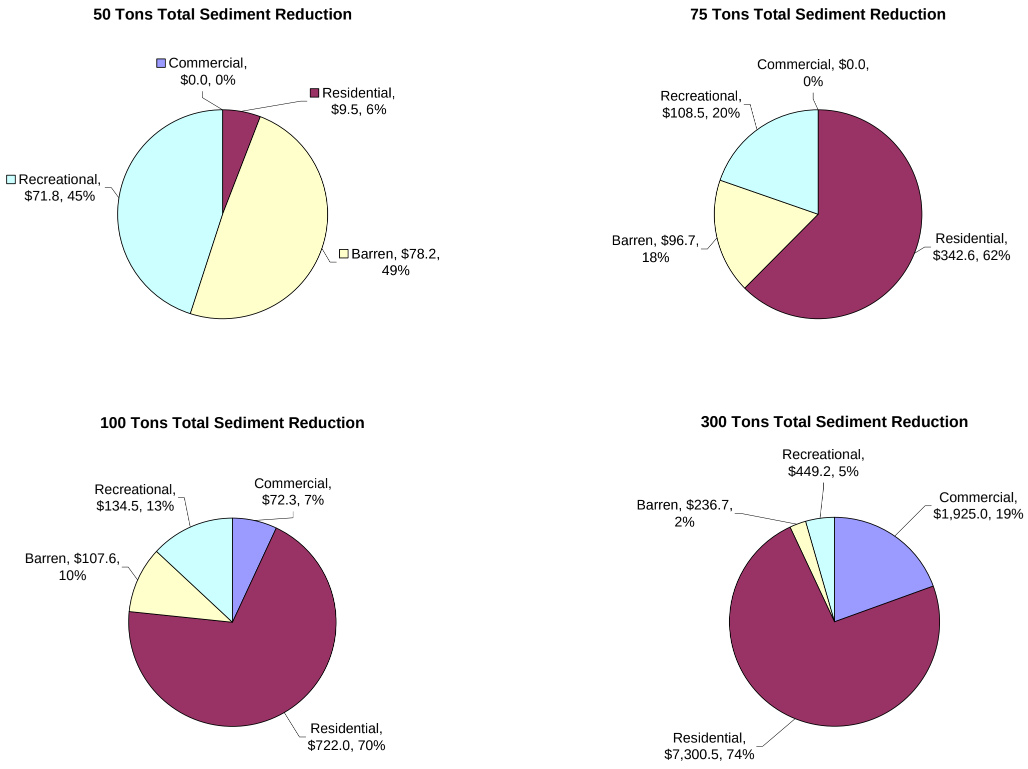

Figure 5. Priorities for TSS reduction by land use for four different levels of total sediment reduction: 50, 75, 100, and 300 tons. Costs are in units of $1000.

Conclusions

This study has identified the primary stormwater management problems in Springfield Township through a review of watershed assessment studies performed for the two major watersheds (Crum Creek and Darby Creek) that drain the township. We have selected a suitable nonpoint pollution model for calculating annual nonpoint pollution loads in the urban coastal zone (AVGWLF) and we have validated its results using field measurements for sediment and nitrogen, but not for phosphorous, which may be underestimated by the model, possibly because leaking sanitary sewers have not yet been implemented in the model. We have developed a model for subwatershed-level BMP cost and performance and incorporated the model into a nonlinear constrained optimization formulation.

The optimization screening model has been solved for a range of total sediment reductions and the results provide guidance for decision makers who need to prioritize subwatersheds and land uses to narrow the search for cost effective sites for implementation of nonpoint pollution management practices. The results of this model will provide helpful guidance for the next phase of our research which will engage municipal decision makers to a greater extent in a multiobjective modeling framework.

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