Pennsylvania Coastal Zone Management Program

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

By

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EXECUTIVE SUMMARY

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 barren land uses in the less developed subwatersheds using on-site BMPs followed by similar sites on golf courses and 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.

PURPOSE OF STUDY

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 through the results contained in this report.

The second phase of our research, to be completed in March, 2006, will incorporate more site specific considerations and multiple, conflicting objectives to select a small number of projects to recommend for progression to the design phase.

METHODOLOGY

Our project consists of four main work elements which comprise our methodology:

1. Extract relevant data from existing watershed assessments on the two main third-order watersheds (Crum Creek and Darby Creek) that drain runoff from Springfield into the Delaware Estuary to gain familiarity with the nonpoint pollution problems and management measures that have been recommended for this area of the urban coastal zone;
2. Review nonpoint pollution loading models and literature on key urban nonpoint pollutant factors used in the models, and effectiveness (pollutant removal efficiency and cost) of management practices (BMP's) available to reduce pollutant loadings;
3. Construct an optimization screening model that can incorporate the results from the previous two work elements to determine the subwatersheds and the land use categories within those subwatersheds where nonpoint pollutant load reductions can be achieved in the most cost effective manner;
4. Use the screening model to generate results for Springfield that can be used to identify the high priority subwatersheds and land uses where the greatest effort should be directed towards controlling nonpoint pollutants.

RESULTS

We describe here the accomplishments related to each work element.

1. Data from Watershed Assessments

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.

Monitoring of physical and chemical water quality parameters in the Crum Creek watershed at stormwater outfalls show high loadings of suspended sediment, nutrients (nitrogen and phosphorous), fecal coliform, and two metals, copper and zinc [McGarity, 2001]. Nonpoint pollutant loads in Crum Creek have also been modeled using the AVGWLF model [Schnabel Engineering, 2001]. This study showed excessive sediment, nitrogen, and phosphorous loadings in the lower watershed, although the authors suggest that these loadings are probably overestimated because of misclassification (by the GIS layers distributed with AVGWLF) of many acres as cropland in this heavily urbanized area. (Note: our study, which also uses AVGWLF, confirms the misclassification and makes adjustments in the input data to the model aimed at improving its accuracy.)

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.

The Appendix to this report contains several photos that illustrate the nonpoint pollution and erosion problems of second-order streams in Springfield Township.

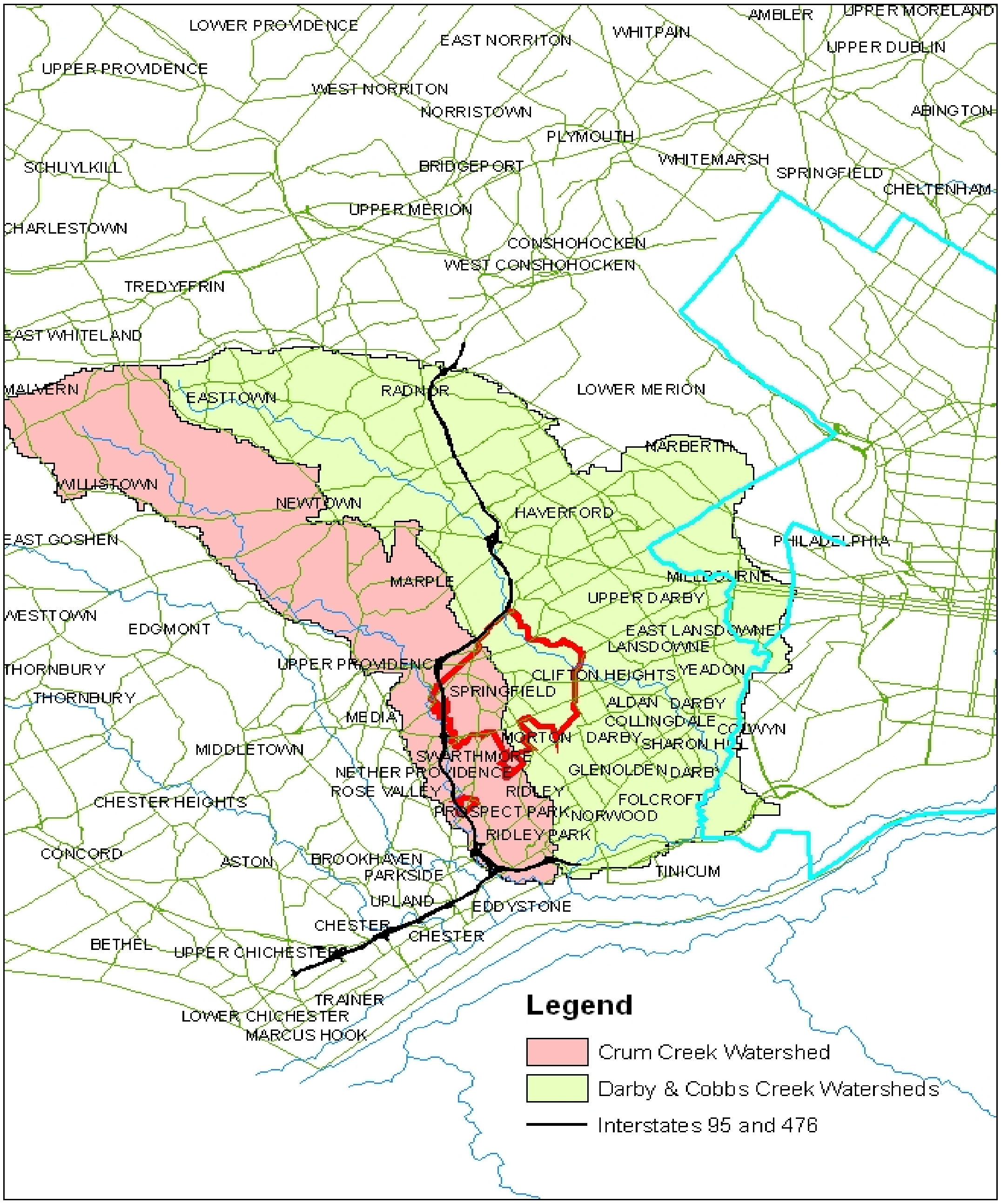


Figure 1. Springfield Township is located in the Philadelphia suburbs. Its urban runoff drains into the Crum and Darby Creeks which flow into the Delaware Estuary below Philadelphia and above Chester City

2. Subwatershed Models for Nonpoint Pollution Loading and BMP Cost & Performance

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 two things: (1) the validity of the underlying mathematical formulas used inside the model that express theories of pollutant generation and transport and (2) 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.

Simplified models are often based on statistical methods such as linear regression to relate loadings to a few parameters that are fairly easy to obtain. They usually ignore characteristics such as topography, soil types, and distribution of precipitation events, and are frequently applied using parameters that are derived from averages taken from a wide range of different locations. Examples of simplified models are those that rely primarily on unit loading rates called transport coefficients, which express pollutant loadings in mass of pollutant per unit area per unit time in units such as pounds per acre per year, for each land use category or as event mean concentrations in the runoff from different land uses. The EPA "Simple Method," [Schueler, 1987] which is implemented in the PLOAD model distributed by EPA with the BASINS suite of models, uses this method [USEPA, 2004a].

The highly detailed simulations employ the most advanced theory available on mechanisms of pollutant generation and transport, and require highly site specific data to characterize these mechanisms. But if the proper data are not available or can not be obtained at a reasonable cost, then the output of such models could be highly inaccurate if they are applied using generic parameters, and the principle of "garbage-in-garbage-out" would certainly apply. Examples of models in this category are SWMM [USEPA, 2004b] which is a dynamic hydrologic and hydraulic simulation model using small time steps that can route stormwater through a storm sewer system, and HSPF, distributed with the BASINS suite of models [USEPA, 2004a] which can simulate watershed hydrology and water quality for both conventional and toxic organic pollutants, including sediment-chemical interactions. Models in this category were not considered for use in the screening optimization model because of their requirements for substantial site specific data.

Models in the moderately detailed category represent a compromise between the two extremes, containing approximate, empirically derived mathematical formulas to represent pollutant generation and transport over an entire subwatershed with little consideration given to the exact location of specific sites within a subwatershed. This aspect of these models makes it easier to obtain the data necessary to run them because the parameters (such as acres of land in various land use categories and soil types, and average topographical features such as slope) are aggregated over an entire subwatershed. Data of this type can be derived from GIS data layers that are becoming available, increasingly, from public domain sources on the internet. However, these models are also vulnerable to the same potential pitfalls that limit the applicability of the other two categories, i.e. oversimplification of fundamental physical processes, on the one hand, and inaccuracies in the data required to calculate model parameters, on the other hand. When monitoring data from the study area or a similar location are available, though, the empirical coefficients in these models can be adjusted or "tuned" so as to calibrate them and enhance their accuracy.

Examples of models in the moderately detailed category are AGNPS [USGS, 2004] a distributed parameter model for agricultural runoff, and GWLF [Haith, et al, 1987, 1992], a combined lumped parameter and distributed parameter model that has been used for both agricultural and urban applications. AGNPS has been coupled with a GIS interface to derive input parameters and has been used in two different studies that demonstrate the suitability moderately detailed models to be used for BMP decision support and optimization [Yoon, 1998] and [Yu, et al., 2003]. Yoon demonstrates a "what-if" scenario based approach in which the user interacts with the simulation model to evaluate specific BMP implementation scenarios, and has applied the method to a 24,000 acre agricultural watershed in Minnesota. Yu, et al. have coupled a version of AGNPS called AnnAGNPS to a commercially available optimizer using a scatter search method to find optimal or near-optimal solutions. They have used the model to study the optimal BMP placement at three different spatial levels: on-site, sub-regional, and regional, and their results can be adapted for comparison with other BMP optimization models, as shown below. We have chosen to use GWLF with a Geographic Information System (GIS) interface developed by Penn State University called AVGWLF [Evans, et al., 2002, 2003, 2004], and reasons for our model selection are discussed below.

All three categories of models are useful in different contexts. The primary challenge is to select the model that provides sufficient accuracy for its intended use while considering limitations on modeling resources available, such as location specific data and technical expertise necessary to run the model and display the results. The context of the current study is screening-level analysis that can be used by watershed managers to prioritize the search for sites where nonpoint pollutant management practices can be implemented. The purpose of a screening model is to narrow down the search from an impossibly large number of options to a reasonable number of high priority locations (that pass through the "screen") where specific project sites can be found.

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. A higher level of detail may be required for the more site-specific analysis required by the multiobjective decision model being developed in the second phase of our research.

We have selected the moderately detailed AVGWLF model for calculating annual pollutant loadings associated with second-order stream subwatersheds. 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, 1992). The GIS interface was implemented at Penn State University in the AVENUE scripting language, and the entire package is presently being distributed at as AVGWLF version 5.0. This distribution includes an ArcView 3.2 interface with data layers for Pennsylvania suitable for application of the model to third-order stream watersheds and larger second-order stream subwatersheds. (Note: the default level of subwatershed delineation was not adequate for our application in Springfield, and additional delineation was required, as described below.)

An important feature of the current release of AVGWLF is its ability to calculate estimates of stream bank erosion separately from runoff erosion. This aspect enables us to separate the two components of total suspended solids in our calculation of management practice effectiveness. Also, the model has default parameters built in that were determined through calibration and validation studies on several watersheds in Pennsylvania, including the Neshaminy Creek watershed which is also in suburban Philadelphia and drains out of the Piedmont and onto the Coastal Plain. AVGWLF has been used for TMDL studies on the Neshaminy Creek and also on nearby Wissahickon Creek. Thus, 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 as described in the next section.

Modeling Nonpoint Pollutant Loadings and Verification using Field Data. The current distribution of AVGWLF (version 5.0) provides a subwatershed GIS coverage for Pennsylvania that is highly delineated, but not at a level sufficient for prioritization of subwatershed within Springfield Township. It was necessary for us to obtain specialized tools for subwatershed and stream delineation at a finer level. We evaluated delineation tools in the public domain including two tools associated with the U.S. Army Corps of Engineers Hydrologic Engineering Center (HEC) models, GEOHMS [U.S. Army Corps of Engineers, 2000] and HEC-PrePro [Olivera, 1998], and we also evaluated the U.S. EPA's BASINS suite of models [USEPA, 2004a]. We found the delineation tools provided with the BASINS suite to be the easiest to integrate with our nonpoint pollution modeling. We applied the BASINS delineation tool using digital elevation datasets (DEM) from the U.S. Geological Survey with a grid raster resolution of 10 meters [USGS, 2003] to produce the results that follow.

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. Table 1 shows land areas in acres and land use characteristics for the Springfield portion of each of the subwatersheds. Figure 3 shows an aerial photograph of the area with the Township boundary, the subwatershed boundaries, and the first and second order streams superimposed. Many segments of the first-order streams actually run underground in storm sewers. Figure 4 shows a map of percent impervious cover along with the same boundaries and streams as in Figure 3. 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 main commercial strips are along Baltimore Pike which cuts across the southern part of the Township, U.S. Route 1 and Pennsylvania Route 320 in the northwest, and Pennsylvania Route 420 running down the center from north to south along the divide between the Crum Creek and Darby Creek Watersheds.

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. Forest and Recreational categories have much lower percentages of impervious acreage.

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.

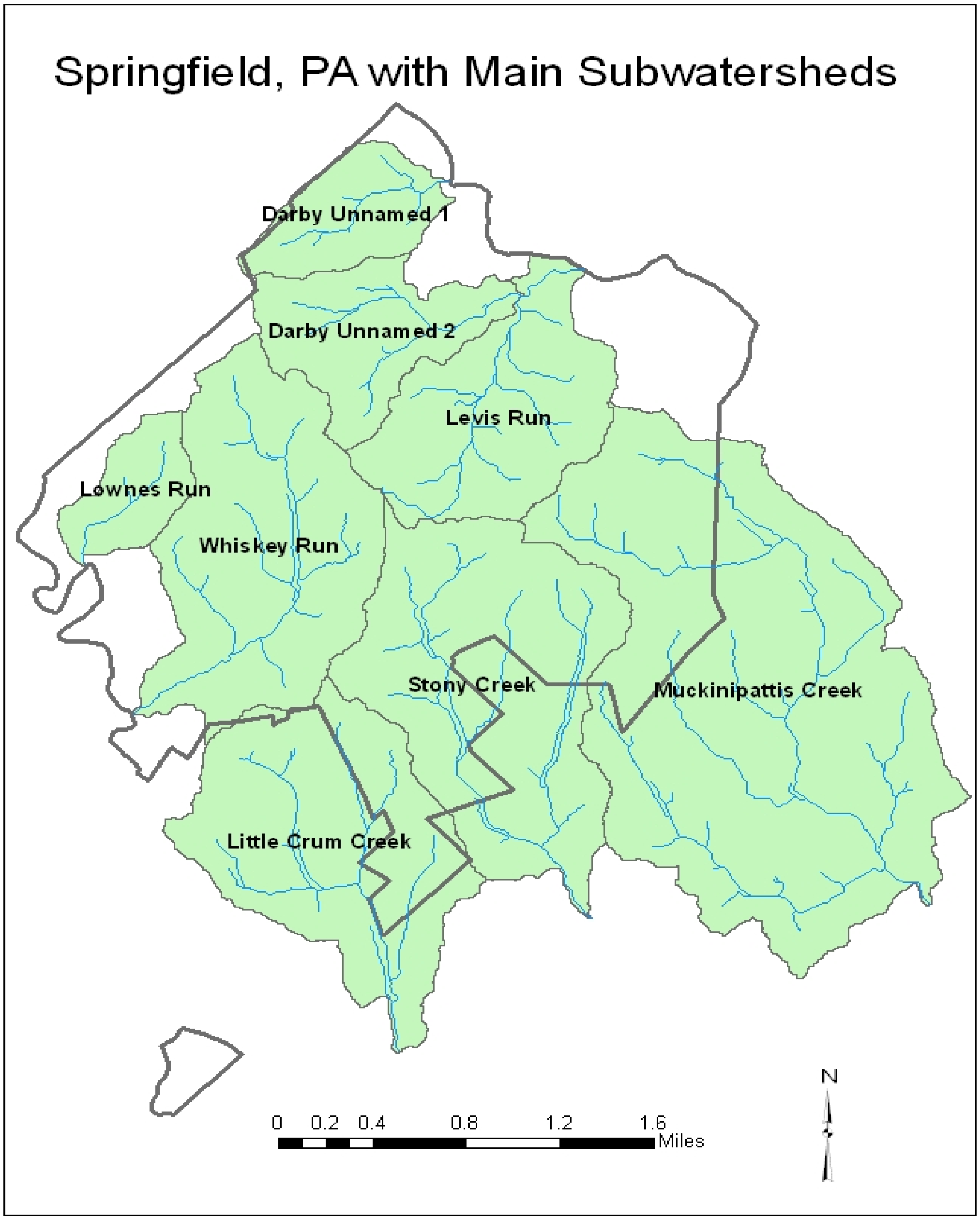


Figure 2. The eight main second-order stream subwatersheds draining Springfield that were delineated using BASINS (USEPA) and USGS digital elevation data, followed by nonpoint pollutant modeling by AVGWLF (Penn State) and, finally, prioritization for cost effective management practices by our optimization 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. Many of the first-order streams flow underground in storm sewers.

Subwatersheds with Aerial Photograph

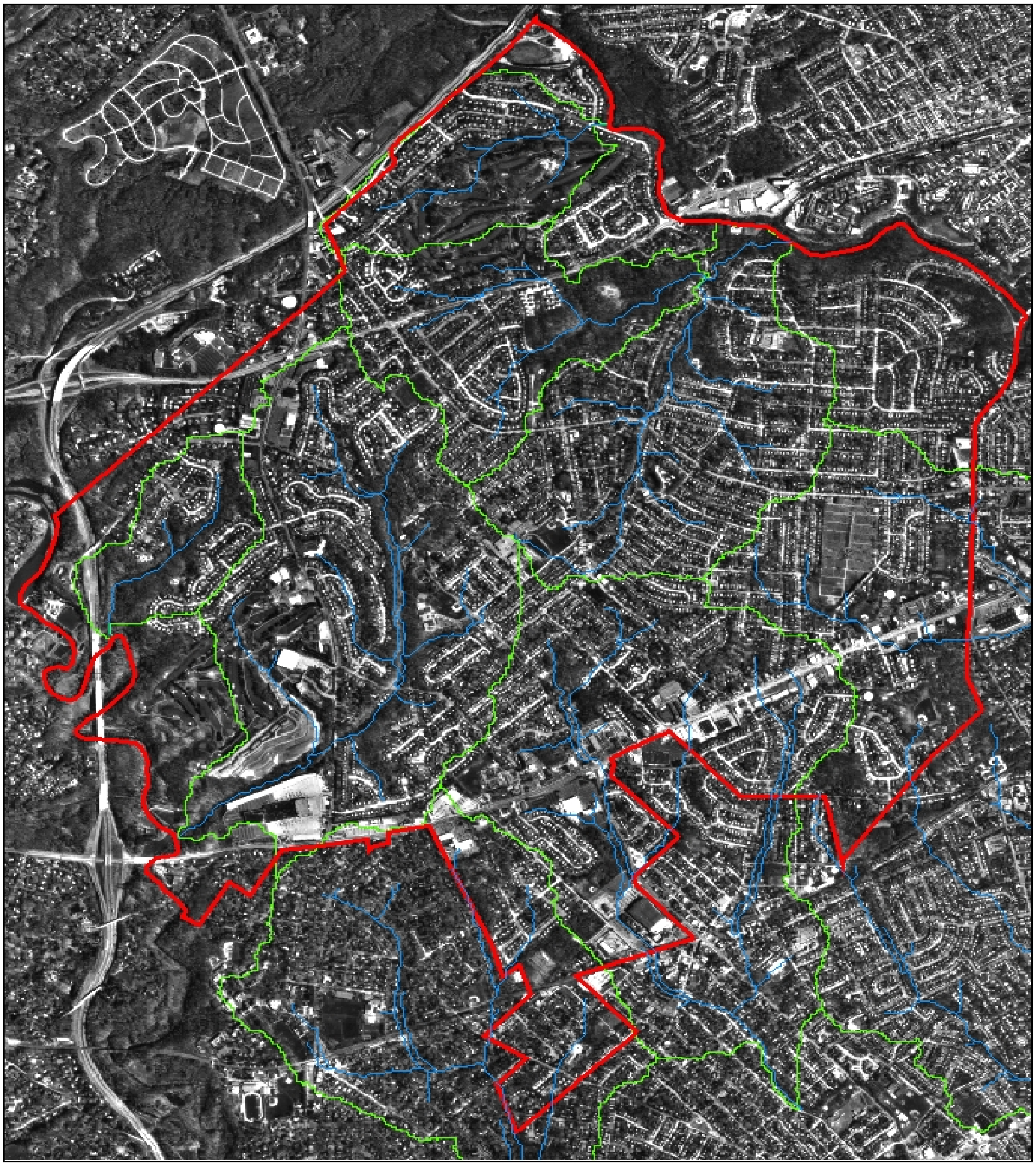


Figure 3. Aerial photography reveals intensive commercial and residential development, Interstate Highway 476 and two golf courses on the west and north perimeter, additional recreational fields and some forested area remaining along the streams. The boundary line of Springfield Township is shown in red, subwatershed boundaries are shown in green, and the first and second order streams are shown in blue.

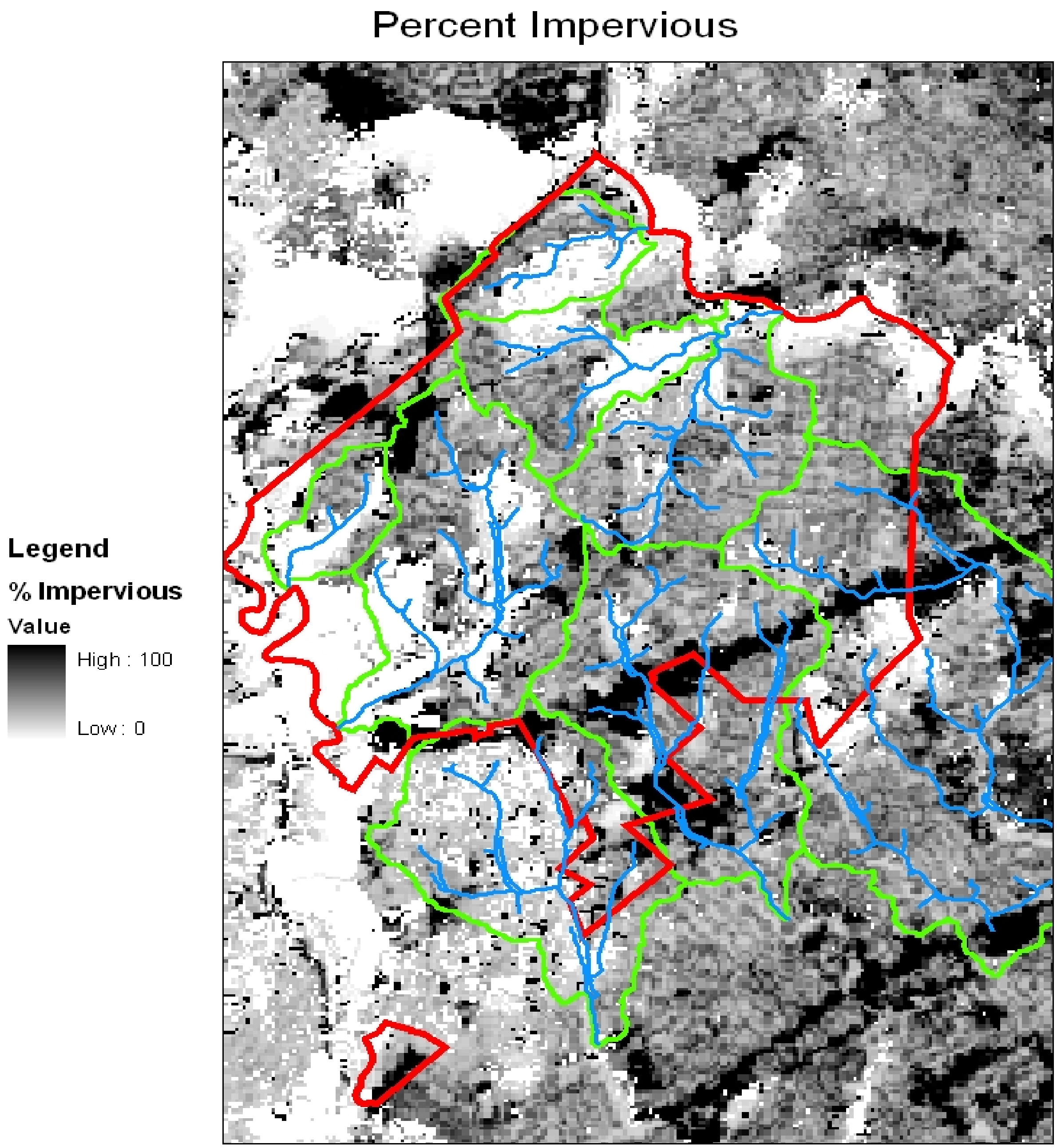


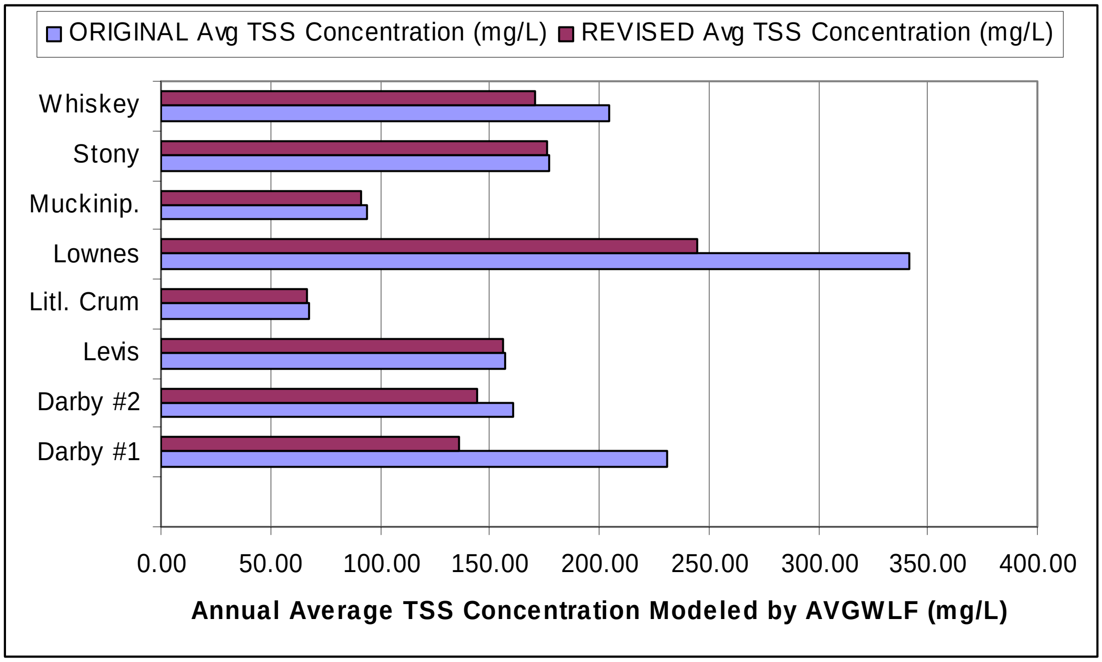
Figure 4. Impervious surfaces in Springfield correspond to commercial districts along major roads and, to a lesser extent, high intensity residential development. 100% impervious areas are solid black while the mostly pervious wooded lands and fields are white. **Source:** Impervious surface data layers 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.

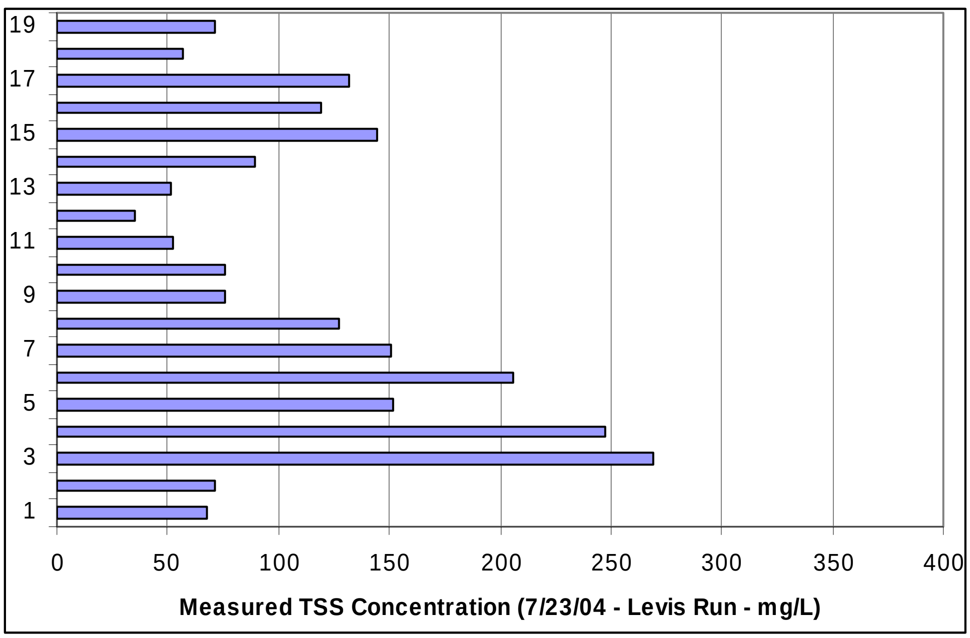
After the desired second-order stream delineations were obtained, the AVGWLF was run on each of the eight subwatersheds. Concerns about the accuracy of the results arose immediately when the model output screens showed significant numbers of acres classified as “row crops” and “pasture/hay.” There are no farms or grazing lands in Springfield Township. Close examination of the default land use GIS layers revealed misclassification of recreational land uses as agricultural land uses.

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 by the project director and environmental lab manager 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 ISCO auto-sampler loaned to the project by Aqua Pennsylvania. The sampling site was at a storm sewer outfall that carries about 70 % of the runoff from the Levis Run subwatershed. The samples were analyzed in our environmental laboratory using standard procedures and QA/QC procedures for stormwater sampling which were reviewed and approved for our lab by the U.S. Environmental Protection in 2000 as part of our Lower Crum Creek Assessment study funded by Section 319 (Federal Clean Water Act) funds [McGarity, et al., 2000]. The data were logged and analyzed for use in model verification, as shown below.

The AVGWLF land use data layer is based on the U.S. Federal Government’s Multi-Resolution Land Characterization (MRLC) database project [Evans, et al., 2004] which also corresponds with the U.S. Geological Survey’s NLCD database which can be accessed through the USEPA’s BASINS suite of models [USEPA, 2004a]. The various land use categories are assigned two-digit codes from nine different general categories. The general category “80: Herbaceous Planted/Cultivated contains five specific categories: 81: pasture/hay, 82: row crops, 83: small grains, 84: fallow, and 85: urban/recreational grasses. The current distribution of AVGWLF categorizes all such land uses as either 81 or 82. We know that there is no agriculture in Springfield Township. These categories were assigned to areas that we know, through field verification, to be golf courses and ball fields, so we refer to all land uses in this general category as “Recreational.” Misclassification of many acres as category 82, especially in subwatersheds having steep slopes, led to excessively large estimates of sediment and nutrient loading. Thus, we edited the “Transport” files generated by models GIS module before running the GWLF simulation module. We changed the pollutant runoff parameters for land classified as type 82 to be the same as the parameters for type 81 because we consider the pasture/hay category to have runoff characteristics that are closer to the actual land use, which is category 85, urban/recreational grasses. The model does not presently contain parameters for category 85, so the closest available category, 81, was chosen.

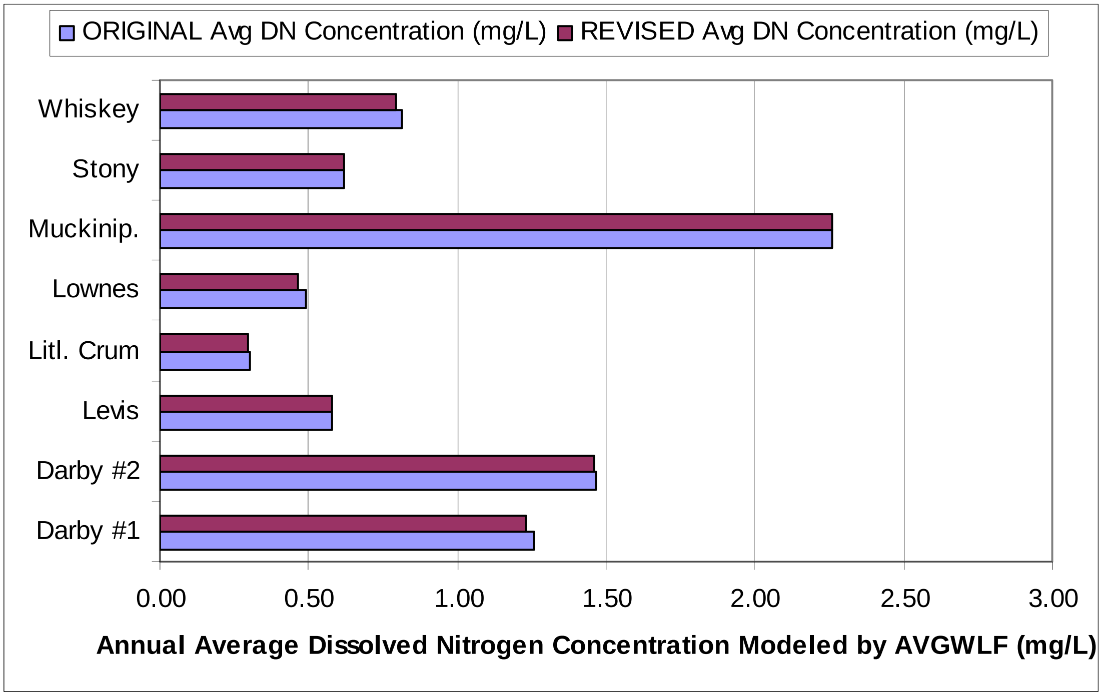
Rough comparisons of model output and field data can be made by computing annual average concentrations of nonpoint pollutants in the second-order streams inferred by the model by dividing the annual pollutant loadings by the annual volumes of streamflow. These modeled concentrations are compared with measured concentrations and the event mean concentration for total suspended solids and dissolved nitrogen in Figures 5 and 6. Two sets of modeled concentrations are shown, the values generated by the original model runs, and the revised results generated by the model when the land use misclassifications were corrected.

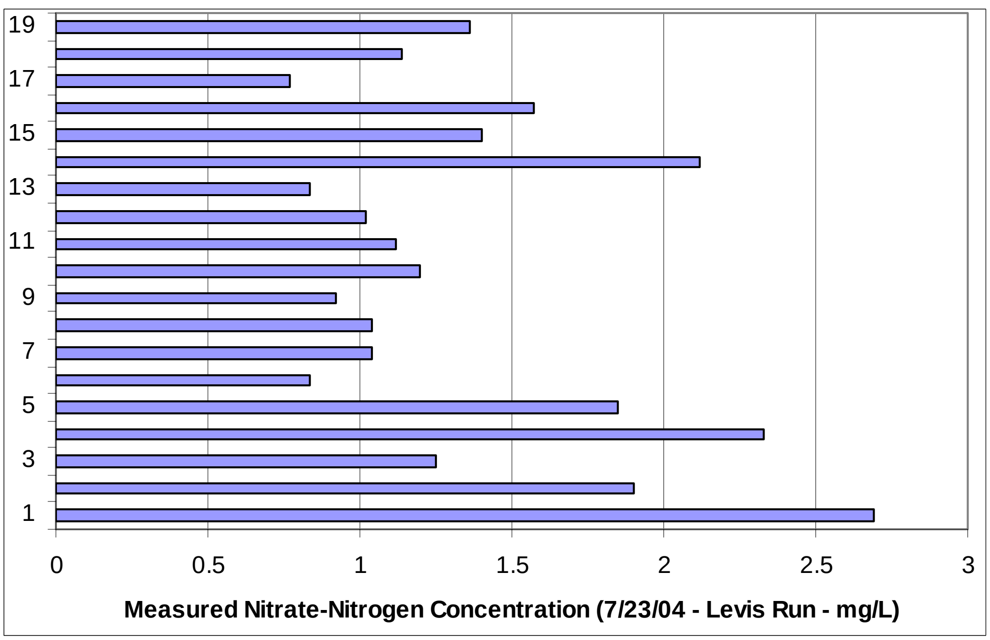




Measured Flow-Weighted Event Mean Concentration = 75.64 mg/L

Figure 5. Upper graph: Inferred concentrations of Total Suspended Solids (mg/L) from AVGWLF comparing original model runs having significant acreage misclassified as "row crops" in the Unnamed Darby Tributary #1, Lownes Run, and Whiskey Run subwatersheds with corrected runs; Lower graph: nineteen samples taken by autosampler measured for TSS (mg/L) on Levis Run at a point draining 70% of the subwatershed during a rain event on July 23, 2004.





Flow Weighted Event Mean Concentration = 1.24 mg/L

Figure 6. Upper graph: Inferred concentrations of Dissolved Nitrogen (mg/L) from AVGWLF (original and revised: differences are less significant than for TSS because of high groundwater dissolved nitrogen concentrations) Lower graph: nineteen samples taken by autosampler measured for Nitrate Nitrogen (mg/L) on Levis Run at a point draining 70% of the subwatershed during a rain event on July 23, 2004.

The rain event on July 23, 2004 consisted of a total of 0.45 inches of rain, as measured at a recording rain gage installed at the Township Hall located in the Levis Run subwatershed. The rain began soon after 2:00 PM and ended around 6:00 PM, and it occurred in two pulses with a slack period between.

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. The modeled TSS results for the revised land use classifications produce results that have better agreement with our field measurements. The modeled DN results show little change between the original and revised model runs because so much of the dissolved nitrogen is from high nitrogen concentrations in the groundwater which is unaffected by land use in the model. The groundwater nitrogen concentrations are taken from a separate GIS data layer that indicates high nitrogen concentrations in the Springfield's groundwater. 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.

Dissolved phosphorous concentrations inferred from the model do not compare well with our measured results of phosphate ion during the July 23, 2004 rain event. Our measured event mean concentration for phosphate was 0.6 mg/L whereas the inferred concentrations from the model range from a low of 0.01 mg/L to a high of 0.03 mg/L. One likely explanation for the discrepancy is the strong possibility that the stormwater discharged from this outfall on Levis Run contained some portion of sanitary waste from an overflowing or leaking sanitary sewer upstream. This kind of pollutant source is not modeled by default in AVGWLF, but it could be added manually as an extra point source. Another explanation is that the method we are using to compare long-term model results with short-term monitoring data is particularly problematic in the case of Phosphorous because a large fraction of Phosphorous loading occurs during storm events (Evans, 2005), and our monitoring efforts have focused mainly on storm events. Further investigation of these results and possible adjustments to the AVGWLF model are being pursued to resolve the discrepancy so that AVGWLF loading results can be used in the screening model to produce rankings based on phosphorous loadings.

All of the screening model results produced for this report are driven by reductions in sediment loading, and the nutrient loading reductions that accompany the sediment reductions are calculated and reported. The AVGWLF modeling results for nonpoint pollutant loadings before reductions from implementation of management practices are shown in tables 2, 3, and 4. These results are used in the current study as the starting point for the screening model. They are based on running the GWLF model for a ten-year period using data from 1982 through 1991, the most recent period having weather data applicable to all eight subwatersheds. GWLF performs its calculations within each subwatershed by analyzing each land use separately. It displays results for pollutant loadings in runoff by land use category and for pollutant loadings in stream bank erosion for the entire subwatershed, based on total stream length.

Table 2. Average annual sediment loading results showing the totals and the separate contributions from land soil erosion and stream bank erosion

Subwatershed Name	Land Soil Erosion (Tons)	Land Soil Erosion Transported to Runoff Sediment (Tons)	Stream Bank Erosion Sediment (Tons)	Total Sediment in Stream: Runoff Sediment Plus Stream Bank Sediment (Tons)
Darby Unnamed Tributary #1	123.87	24.44	19.58	44
Darby Unnamed Tributary #2	157	30.82	44.08	74.9
Levis Run	40.5	7.89	115.30	123.2
Little Crum Creek	17.4	3.43	18.68	22.1
Lownes Run	248.1	48.87	9.85	58.7
Muckinipattis Creek	41.4	8.13	60.17	68.3
Stony Creek	57.9	11.32	198.99	210.3
Whiskey Run	202.4	39.28	187.27	226.4
Total	**888.57**	**174.18**	**653.92**	**827.9**

Table 3. Average annual nitrogen loading results showing the totals and the separate contributions from ground water, land soil erosion, and stream bank erosion. Note the very high groundwater contributions, especially in the southern subwatersheds that lie in the coastal zone physiographic region.

Subwatershed Name	Dissolved Nitrogen in Stream (Pounds)	Total Nitrogen from Groundwater (Pounds)	Total Nitrogen from Stream Bank Erosion (Pounds)	Total Nitrogen from Runoff (Pounds)	Total Nitrogen in Stream (Pounds)
Darby Unnamed Tributary #1	796.72	737.89	1.96	174.98	914.83
Darby Unnamed Tributary #2	1512.4	1315.67	4.41	314.93	1635.01
Levis Run	909.31	776.16	11.53	146.70	934.39
Little Crum Creek	196.92	154.02	1.87	45.48	201.37
Lownes Run	223.09	139.27	0.98	337.57	477.82
Muckinipattis Creek	3395.53	3308.82	6.02	105.23	3420.07
Stony Creek	1479.6	1351.60	19.90	183.99	1555.49
Whiskey Run	2105.66	1691.52	18.73	544.58	2254.81
Total	**10619.23**	**9474.95**	**65.40**	**1853.46**	**11393.79**

Table 4. Average annual phosphorous loading results showing the totals and the separate contributions from ground water, land soil erosion, and stream bank erosion. Our field data suggest that these values may underestimate actual loadings in these subwatersheds.

Subwatershed Name	Dissolved Phosphorous (Pounds)	Total Phosphorous from Groundwater (Pounds)	Total Phosphorous from Stream Bank Erosion (Pounds)	Total Phosphorous from Runoff (Pounds)	Total Phosphorous in Stream (Pounds)
Darby Unnamed Tributary #1	16.23	11.21	0.86	13.30	25.37
Darby Unnamed Tributary #2	25.10	18.77	1.94	15.25	35.96
Levis Run	22.47	19.98	5.07	4.25	29.30
Little Crum Creek	8.78	6.27	0.82	2.81	9.90
Lownes Run	8.23	5.95	0.43	20.17	26.55
Muckinipattis Creek	35.17	34.13	2.65	2.92	39.70
Stony Creek	29.66	29.50	8.76	6.55	44.80
Whiskey Run	48.24	36.57	8.24	23.86	68.66
Total	**193.88**	**162.38**	**28.77**	**89.11**	**280.24**

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 [ReVelle, et al. 1967; Ellis, et al., 1985; McGarity, 1997].

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.

Our BMP performance/cost model uses a nonlinear function to represent the range of marginal pollutant removal costs that are likely to be experienced over a subwatershed. In its most fundamental form, the function expresses the fraction of land area in a subwatershed that would be treated for runoff control and pollutant removal at various levels of resources devoted, measured in dollars. Equation (1), below shows the mathematical form of the model:

$$f = \frac{x}{(C^{1/2} + x)} \qquad (1)$$

where:
f = fraction of land area treated by BMPs
x = resources devoted to BMPs ($1000)
$C^{1/2}$ = resources required to treat one-half of the land area ($1000)

Mathematically, equation (1) is known as a "saturation function" and it is widely used to model physical phenomena that exhibit declining response to increasing resources as a system becomes saturated through the action of a limiting factor. In this case, the limiting factor is available sites and options for BMP implementation in the urban context. Models similar to this one are often used in technology assessment studies, such as a recently completed market penetration study for new energy efficiency technologies [Moore, et al. 2005].

Equation (1) is used to calculate reductions in annual nonpoint pollution by multiplying f by the annual pollutant loading and by factors that influence the pollutant removal efficiency, as shown in Equations (2) and (3), below.

$$R = f\, R^{\max} \qquad (2)$$

where:
R = annual reduction in pollutant loading (tons – sediment, or pounds – nutrients)
$R^{\max}$ = annual reduction in pollutant loading if 100% of land area is treated

$$R^{\max} = f_T \eta_{BMP} L \qquad (3)$$

where:
f_T = fraction of total annual runoff that is treatable (90% for 1-inch design storm precipitation)
η_{BMP} = estimated annual pollutant removal efficiency for treatable runoff
L = annual pollutant loading for each land use (tons – sediment, or pounds – nutrients)

As stated earlier, the nonlinear BMP cost/performance model assumes watershed managers apply a cost effective, integrated approach in the selection site specific management practices for each land use within each subwatershed. Data on actual cases of watershed-based urban stormwater runoff management are not available in a form that enables us to directly calibrate and validate the model with field data. However, some recent studies have applied optimization modeling to site-specific BMP placement within small watersheds to produce results that are indicative of watershed-level BMP costs and performance in an optimally managed watershed.

The Virginia Department of Transportation (VADOT) recently funded the development of a model for optimal detention pond placement, and, as a case study, the model was applied to sediment loading reduction in a 2900 acre subwatershed of Ivy Creek in Albemarle County, Virginia [Yu, et al., 2003]. The eight subwatersheds in our study drain a total of 3170 acres of Springfield Township, so the total land areas are similar. However, the dominant land use in the VADOT study is rural agriculture, and the types of BMPs used, i.e. detention ponds, have limited application in the urban retrofit context. However, many of the same considerations arise in both urban and rural contexts such as cost effective placement of BMPs so as to capture economies of scale, when available, and thereby minimize the total cost of achieving the desired total reduction in sediment loading. Thus, we believe that the results of this study are useful for validating the general form of the nonlinear model.

Figure 7 shows a plot of data derived from the VADOT study and a fit of our nonlinear model to the data. We determined values for $R^{\max}$ and $C^{1/2}$ by transforming (inverting) the data and fitting a straight line to the transformed data. The curve fitting procedure produced a value for $R^{\max}$ of 435 tons of sediment reduction and a value for $C^{1/2}$ of $1.58 million, which is the present value of capital and maintenance costs for removing one-half of $R^{\max}$ (i.e. 217 tons of sediment). The solid line in Figure 7 results from applying Equations (1) and (2) with these parameters, and the data points marked by diamonds are results from the VADOT study. The excellent fit suggests that our nonlinear model for watershed-base BMP cost and performance is capable of accurately representing optimal BMP placement strategies *if* it can be calibrated for the specific circumstances existing in a subwatershed. Our procedure for calibrating the model for urban retrofit BMPs is described below and is used to generate the results in this study. Our results indicate, as expected, significantly higher costs associated with urban retrofit BMPs compared to detention ponds in a rural context (as shown in Figure 9).

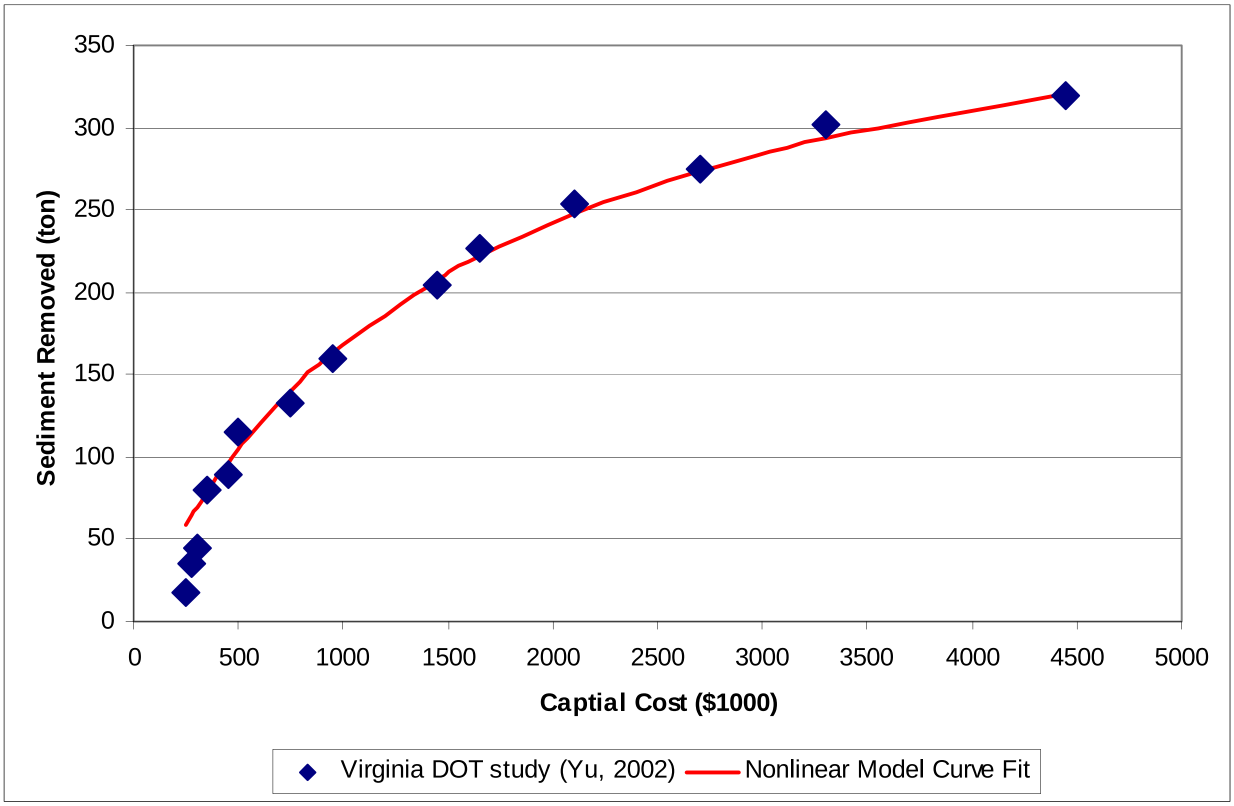


Figure 7. Results from subwatershed-level BMP optimization by Yu, et al., 2003 are used to demonstrate the suitability of our nonlinear BMP cost/performance model to characterize optimal BMP placement when calibration data are available.

Our procedure for calibrating the BMP cost/performance model for each subwatershed and each land use within a subwatershed is essentially a one-point calibration based on site specific cost estimates for the type of BMP that would be chosen for implementation in each land use at the point where around one-half or the maximum pollutant removal ($R^{\max}$) is achieved. We call this the "median BMP" because it represents the technology that would most likely be required to achieve the middle-ranges of pollutant removal after the less expensive options such as pollution prevention and nonstructural BMPs have been exhausted. Obviously, some judgment is required to identify the type of BMP that would be necessary to, in a sense, "push out the envelope" beyond 50% of potential pollutant reductions. Our choices for the median BMP for each land use in Springfield Township are shown in Table 5. BMPs for the forested land use category were not considered in this study.

Table 5. "Median BMPs" selected for calibrating the BMP Cost/Performance model in Springfield Township

Land Use	**Median BMP**
Commercial	Bioretention
Residential	Bioretention
Barren	Grass Swale
Recreational	Grass Swale

In order to calibrate the subwatershed-level model using site-specific BMP costs, we calculated the cost per unit treatment volume using formulas for BMP costs as a function of the "water quality volume." We estimated the typical water quality treatment volume based on a design storm rainfall depth and a typical area treated by the median BMP. Cost formulas were adapted from those given in the fact sheets published by the Stormwater Manager's Resource Center [SMRC, 2004], and they include economies of scale when they exist at the site level. The design storm for water quality BMPs in Southeastern Pennsylvania was chosen to be the 1-inch rainfall, which generates 90% of all runoff in this region [Clar, 2005]. We used the "Simple Method" [Schueler, 1987] to calculate the runoff volume associated with the design storm as recommended by the Maryland Stormwater Design Manual's Unified Stormwater Sizing Criteria [MDE, 2000]. The maximum area served per installation of the median BMP was specified as 5 acres for all four land uses.

The end result of the site-specific calculations, described above, is a cost per unit of land area treated which also is the slope of an alternate form of the nonlinear model (Equation 1 based on land area) at the calibration point. Equation (1) was differentiated using elementary calculus to obtain a formula for $C^{1/2}$ as a function of the calibration point slope. Then, numeric values of $C^{1/2}$ were generated for each subwatershed and land use in Springfield by matching the slope of the nonlinear model at the calibration point with the marginal cost of the median BMP. The calculated values of $C^{1/2}$ used in this study and the associated acreages are shown in Table 6 for each subwatershed and land use.

Table 7 shows the values for R^{max} obtained by applying Equation (3) with parameter values explained here. As mentioned previously, we used the 1-inch rainfall event as the basis for determining the water quality BMP volume, and in Southeastern Pennsylvania, 90% of all rain events produce one inch or less of rainfall over a 24-hour period. Thus, we set $f_T = 0.90$. The choice of values for annual BMP efficiency for each pollutant (sediment, nitrogen, and phosphorous) is complicated by the wide range of values reported in the literature for these values caused by the difficulties in measuring and in actually *defining* what is meant by BMP efficiency in different situations. Most BMP monitoring studies have been conducted for short periods of time and rarely for more than one year. Given the high cost of monitoring and the difficulty of collecting samples during storm events, it is not surprising that BMP efficiencies are difficult to nail down. In this study, we have chosen conservative estimates of BMP efficiencies for use in calculating R^{max}. We expect that the high clay content and corresponding small particle size of soils in Springfield make it very difficult to obtain sediment removal efficiencies of 80% that are often reported in the literature. Thus, we have used a sediment (TSS) removal efficiency (η_{BMP}) of 60% for sediment. For total nitrogen (TN), we have used η_{BMP} = 25%, and for total phosphorous (TP), we have used η_{BMP} =40%.

Table 6. Costs (present values) associated with treating one-half of the area in each land use ($C^{1/2}$) for each subwatershed, derived by matching the slope of the nonlinear model at the calibration point with the marginal cost of the "median BMP".

	Commercial		Residential		Barren		Recreational	
Subwatershed Name	Area (acres)	$C^{1/2}$ (\$1000)	Area (acres)	$C^{1/2}$ (\$1000)	Area (acres)	$C^{1/2}$ ((\$1000)	Area (acres)	$C^{1/2}$ (\$1000)
Darby Unnamed Tributary #1	4.9	$22	123.6	$261	9.9	$4	49.4	$23
Darby Unnamed Tributary #2	0		232.3	$488	7.4	$3	17.3	$9
Levis Run	0		479.4	$1,025	0		9.8	$11
Little Crum Creek	22.2	$83	143.3	$288	0		9.8	$11
Lownes Run	0		93.9	$202	7.4	$4	14.8	$12
Muckinipattis Creek	89.0	$355	281.7	$713	2.5	$2	7.4	$9
Stony Creek	222.4	$853	343.5	$832	0		2.5	$3
Whiskey Run	93.9	$372	469.5	$1,126	9.9	$5	96.4	$52

Table 7. R^{max} values for sediment and nitrogen for each land use in each subwatershed, showing the nonpoint pollution reduction achieved if all of the land area in the category is treated, obtained by applying Equation (3) for BMP efficiencies η_{BMP} and treatable fractions f_T as listed in the text.

	Commercial R^{max}		Residential R^{max}		Barren R^{max}		Recreational R^{max}	
Subwatershed Name	Sediment (tons)	Nitrogen (pounds)	Sediment (tons)	Nitrogen (pounds)	Sediment (tons)	Nitrogen (pounds)	Sediment (tons)	Nitrogen (pounds)
Darby Unnamed Tributary #1	0.05	0.002	2.92	0.52	8.64	28.19	1.57	10.42
Darby Unnamed Tributary #2	0	0	6.91	2.27	9.29	28.17	0.38	3.22
Levis Run	0	0	4.21	2.86	0	0	0.11	1.44
Little Crum Creek	0.16	0.07	1.62	0.36	0	0	0.05	5.58
Lownes Run	0	0	3.73	0.45	21.49	58.46	1.13	4.55
Muckinipattis Creek	0.70	1.31	3.02	1.22	0.54	2.95	0.11	1.26
Stony Creek	2.21	10.67	3.83	1.89	0	0	0.01	0.36
Whiskey Run	2.00	4.03	12.37	8.28	4.16	16.92	2.54	19.06
TOTALS:	**5.1**	**16.1**	**38.6**	**17.8**	**44.1**	**134.7**	**5.9**	**45.9**

We now display sample results for the nonlinear BMP cost/performance model. Figure 8 shows contrasting results for two different subwatersheds and land uses in our Springfield, Pennsylvania study. These results for runoff erosion do not show the whole picture, because associated reductions in stream bank erosion are not included. However, the widely different costs (horizontal axis) associated with similar sediment removals (right vertical axis) suggest strongly that maximum cost effectiveness will be achieved by assigning a higher priority to treating the barren sites in Lownes Run than to treating the residential sites in Whiskey Run. The results of the optimization model runs shown in Section 4, below, confirm this conclusion.

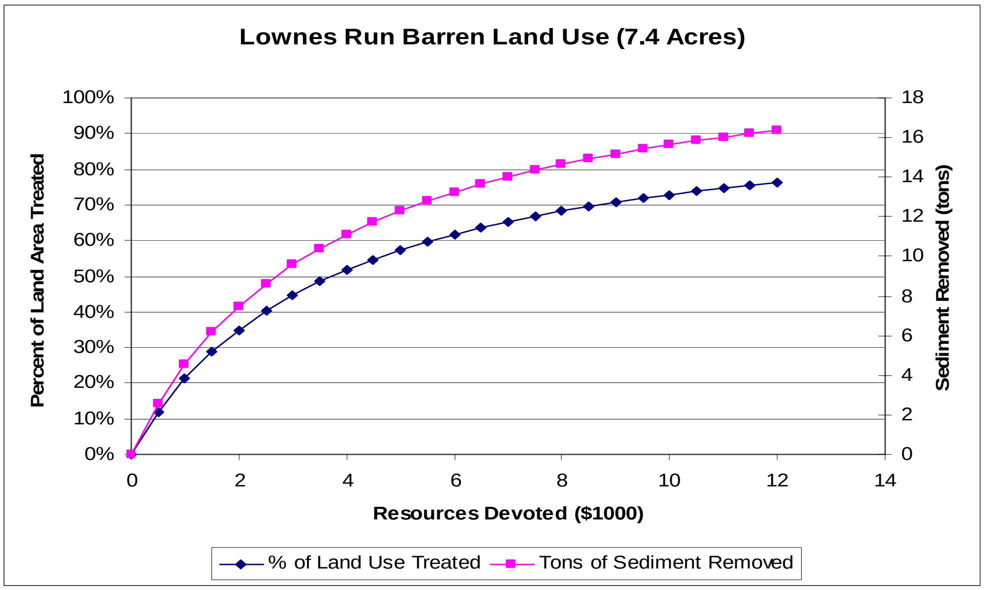


Figure 8. Contrasting results for runoff sediment removal for different land uses in two subwatersheds showing plots of f (Equation 1, left axis) and R (Equation 2, right axis) versus x (horizontal axis). The subwatershed-level BMP cost/performance model was calibrated using the parameter values shown in Tables 6 and 7. Note: these results show only reductions of sediment carried by runoff from land erosion and do not include reduced stream bank erosion benefits, which are calculated in the optimization model for the entire subwatershed and not separately by land use category.

Reduction of Stream Bank Erosion. Most types of stormwater management practices reduce runoff volume flow rates as well as nonpoint pollutants. High flow rates associated with impervious surfaces are responsible for stream bank erosion and increased frequency of bank-full events. Our field observations confirm that stream bank erosion is a severe problem in Springfield, especially on second-order streams. The Appendix to this report shows photos of three sites in Springfield where bank erosion is caused by frequent bank-full events. Thus, it is necessary for the model to include the benefits of flow rate reduction associated with implementation of BMPs in each subwatershed. These benefits are especially significant in the more heavily developed subwatersheds having greater amounts of impervious surface.

Stream bank erosion is calculated in AVGWLF using a lateral erosion rate formula adapted by Evans, et al., 2003 from empirical formulas developed by Van Sickle and Beschta, 1983, and Lemke, 1991. Equation (4) shows the lateral erosion rate (LER) which multiplies the total stream length in the subwatershed to obtain total erosion.

$$\text{LER} = aQ^b \tag{4}$$

where:

Q = mean monthly stream flow rate in m^3/s

a = empirical coefficient obtained by linear regression from several subwatershed specific parameters affecting stream bank erosion as shown in Evans et al., 2003

b = 0.6

In our model, we calculate reductions in annual stream bank erosion by assuming that virtually all stream bank erosion in our urban context occurs during storm events, and that storm flow rates are reduced by BMPs by the fraction f^{ALL}, the fraction of total subwatershed land area (all land uses) treated by BMPs. The relationship between erosion reduction and f^{ALL} is developed below. From Equation (4), we obtain an expression for erosion reduction as a function of the ratio of the revised flow to the original flow by assuming that the installation of BMPs in the subwatershed does not change the coefficient a (which means that it cancels out of the ratio):

$$R^B = L^B\left[1-\left(\frac{Q_{revised}}{Q_{original}}\right)^b\right] \tag{5a}$$

$$Q_{revised} = Q_{original}\left(1- f_T f^{ALL}\right) \tag{5b}$$

where:

R^B = reduction in nonpoint pollution associated with stream bank erosion reduction (tons or pounds)

L^B = original nonpoint pollution load attributed to stream bank erosion

$Q_{original}$ = original flow rate in stream before installation of BMPs (m^3/s)
$Q_{revised}$ = revised flow rate in streams after installation of BMPs (m^3/s)
f^{ALL} = fraction of land area treated over all land uses in the subwatershed

Substituting (5b) into (5a) we obtain:

$$R^B = L^B[1-(1- f_T f^{ALL})^b] \qquad (6)$$

which incorporates the assumptions that the runoff from the untreated land areas is unaffected, the runoff from the design storm is retained by BMPs installed on the treated land area, and that the fraction (1- f_T) of the original runoff from the treated areas will still contribute to streamflow during storm events that exceed the design storm.

3. Formulation of the Optimization Screening Model

We have now developed all of the elements necessary to state the formulation of the optimization screening model for prioritizing subwatersheds and land uses within the subwatersheds. Our approach to maximizing the cost effectiveness of achieving nonpoint pollution reduction is to specify a desired pollution reduction for the Springfield portions of all eight subwatersheds and then minimize the total cost of achieving the specified level of reduction. We call the model NPSOPT for NonPoint Screening OPTimization.

The mathematical formulation of the model is facilitated by the use of sets that contain indices for the subwatersheds and the land uses. Let SW represent the set of subwatersheds (Darby Unnamed 1, Darby Unnamed 2, Levis Run, etc.) and LU represent the set of land uses (Commercial, Residential, Barren, and Recreational).

Now, we can define the "decision variables" whose values in the optimal solution are used to establish priorities. We also define the "objective function" which calculates the total resources devoted to nonpoint pollution management over the entire township by simply summing the decision variables over all subwatersheds and land uses.

Decision Variables:

x_{ij} = resources devoted to nonpoint pollution reduction by structural and nonstructural BMPs in subwatershed i for land use j , $i \in SW,\ j \in LU$

Objective Function:

$$\textbf{Minimize} \sum_{(i \in SW,\ j \in LU)} x_{ij} \qquad (7)$$

The BMP cost/performance model equations in Equations 1-6 are now incorporated into the optimization screening model as a set of “definitional constraints” which apply simultaneously to all subwatersheds and land uses. .

Definitional Constraints:

$$f_{ij} = \frac{x_{ij}}{(C_{ij}^{1/2} + x_{ij})} \quad , \qquad i \in SW,\ j \in LU \qquad (8)$$

$$R_{ij}^{SR} = f_{ij} R_{ij}^{\max,SR} \quad , \qquad i \in SW,\ j \in LU \qquad (9)$$

$$R_{ij}^{NR} = f_{ij} R_{ij}^{\max,NR} \quad , \qquad i \in SW,\ j \in LU \qquad (10)$$

$$R_{ij}^{PR} = f_{ij} R_{ij}^{\max,PR} \quad , \qquad i \in SW,\ j \in LU \qquad (11)$$

where: SR refers to sediment in runoff, NR refers to total nitrogen in runoff, and PR refers to phosphorous in runoff,

$$f_i^{ALL} = \left(\frac{1}{A_i^{ALL}}\right) \sum_{j \in LU} f_{ij} A_{ij}\ , \qquad i \in SW \qquad (12)$$

where: A_{ij} = land area in subwatershed i having land use j , $i \in SW,\ j \in LU$
A_i^{ALL} = land area in subwatershed i (all land uses) $i \in SW$

$$R_i^{SB} = L_i^{SB}[1-\left(1- f_T f^{ALL}\right)^b],\ i \in SW \qquad (13)$$

$$R_i^{NB} = L_i^{NB}[1-\left(1- f_T f^{ALL}\right)^b], \qquad i \in SW \qquad (14)$$

$$R_i^{PB} = L_i^{PB}[1-\left(1- f_T f^{ALL}\right)^b], \qquad i \in SW \qquad (15)$$

where: SB refers to sediment from bank erosion, NB refers to total nitrogen from bank erosion, and PB refers to phosphorous from bank erosion.

Now, we add constraints to accomplish the desired reductions in nonpoint pollution loadings for each of the three types of pollutants, sediment (TSS), nitrogen (TN) and phosphorous (TP).

Nonpoint Pollution Reduction Constraints:

$$\sum_{(i \in SW,\ j \in LU)} R_{ij}^{SR} + \sum_{i \in SW} R_i^{SB} \geq R_{\min}^{S} \qquad \text{(TSS)} \qquad (16)$$

$$\sum_{(i \in SW,\ j \in LU)} R_{ij}^{NR} + \sum_{i \in SW} R_i^{NB} \geq R_{\min}^{N} \qquad \text{(TN)} \qquad (17)$$

$$\sum_{(i \in SW,\ j \in LU)} R_{ij}^{PR} + \sum_{i \in SW} R_i^{PB} \geq R_{\min}^{P} \qquad \text{(TP)} \qquad (18)$$

where: $R_{\min}^{S}$ $R_{\min}^{N}$ $R_{\min}^{P}$ are the desired reductions in sediment, nitrogen, and phosphorous loadings, respectively, and all solutions to the model will assure that loading reductions of *at least* these amounts occur..

The left sides of these inequalities calculates the total pollutant loadings over the entire township for sediment (16), nitrogen (17), and phosphorous (18) and the right side sets the total removals required, in tons (for sediment) or pounds (for nutrients). Typically, only one of these three constraints will be binding (left side equaling right side) in the optimal solution, and the pollutant associated with that constraint is the one that has the most influence on the results.

Finally, the model requires that bounds be set on certain variables to assure only feasible solutions are considered:

Bounds on Variables:

$$x_{ij} \geq 0 \qquad i \in SW,\ j \in LU \qquad (19)$$

$$0 \leq f_{ij} \leq 1 \qquad i \in SW,\ j \in LU \qquad (20)$$

Solvers for the Optimization Model. The optimization screening model was developed using the Microsoft Excel program which was useful as a development test bed but not practical for production runs of the model. The solver built into Excel is capable of solving the nonlinear optimization problem, but it sometimes experienced glitches that caused it to fail to find any feasible solution.

A more stable platform for solving the model is the AMPL modeling language which couples to several different optimization solvers [Fourer, et al., 2002]. We experienced excellent results with AMPL and the MINOS nonlinear solver using the “student edition” of the software, which is available for download at no charge. Application of our model to a larger watershed could require the full version of AMPL which must be purchased.

4. Use of the Optimization Screening Model to Prioritize Subwatersheds for BMP Implementation Projects

The NPSOPT model 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. Thus, $R^S_{\min}$, the desired reductions in total sediment (runoff sediment plus stream bank erosion) were specified in all runs of the model. Each model run was performed for an increasing level of $R^S_{\min}$, ranging from a low of 10 tons of sediment reduction to a high of 300 tons of sediment reduction. The level of resources (i.e. the values of the decision variables in units of $1000) optimally allocated to each land use in each subwatershed for each level of $R^S_{\min}$ is an indicator of the priority that should be assigned to each area in the search for specific BMP sites.

Total Costs versus Total Sediment Reduction. Figure 9 plots the objective function, i.e. total resources devoted to nonpoint pollution removal over all eight subwatersheds in the township, versus $R^S_{\min}$ over the range from 10 tons to 300 tons. Our optimization model results for urban retrofit BMPs in Springfield compare well with results generated byYu, 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 from Yu, et al., Figure 7 on p. 16 of that reference, with costs converted to present value.

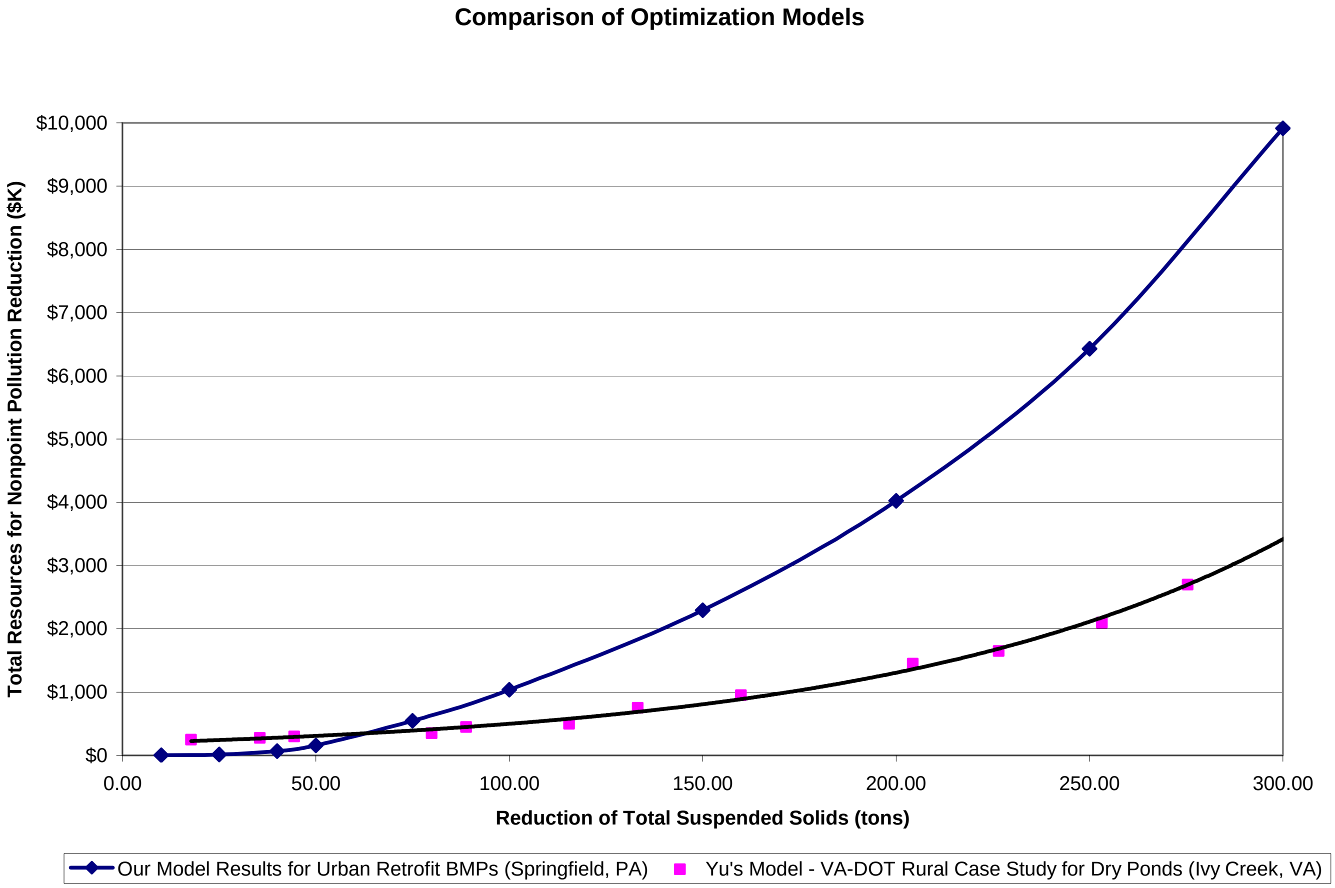


Figure 9. total resources devoted to nonpoint pollution removal using urban retrofit BMPs over all eight subwatersheds of Springfield Township, versus $R^S_{\min}$ over the entire range from 10 tons to 300 tons of sediment reduction. Comparisons are shown with the subwatershed BMP placement optimization 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.

Prioritization by Land Use. We now plot optimal values for the individual decision variables to show how the priorities shift as the total sediment reduction increases. The model first selects barren land use for TSS reduction (cost curve calibration based on grass swales). Figure 10 show priorities among the subwatersheds for the barren land use category. The subwatersheds having the greatest potential for cost effective nonpoint pollution reduction are those showing the greatest resources allocated by the optimization model. These results can be used to develop a priority ranking among the subwatersheds for implementation projects treating runoff from land designated as barren: (1) Lownes Run, (2) Darby Unnamed Tributary #1, (3) Darby Unnamed Tributary #2, (4) Whiskey Run, and (5) Muckinipattis Creek.

The model next selects recreational land use (Figure 11) for TSS reduction (cost curve calibration based on grass swales), and these results can be used to rank subwatersheds for implementation projects treating runoff from golf courses and athletic fields. The top ranked subwatersheds for targeting recreational land uses are Whiskey Run and Darby Unnamed Tributary #1, each of which contains a country club with a golf course.

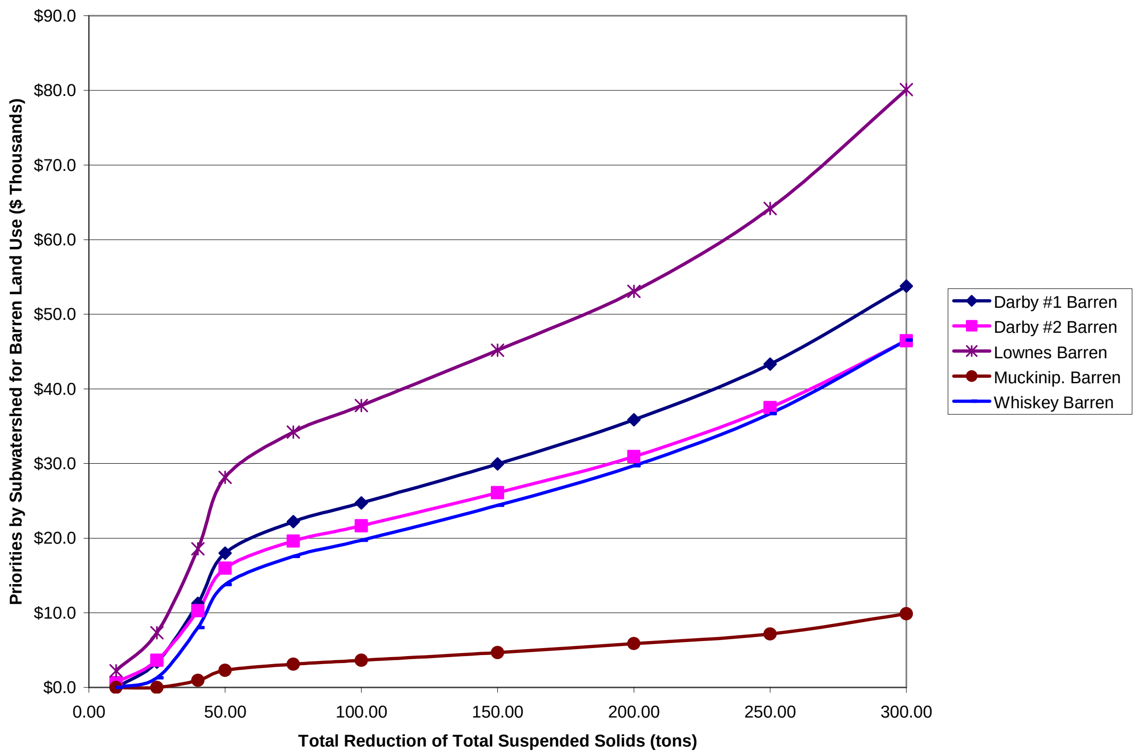


Figure 10. Barren land use priorities by subwatershed

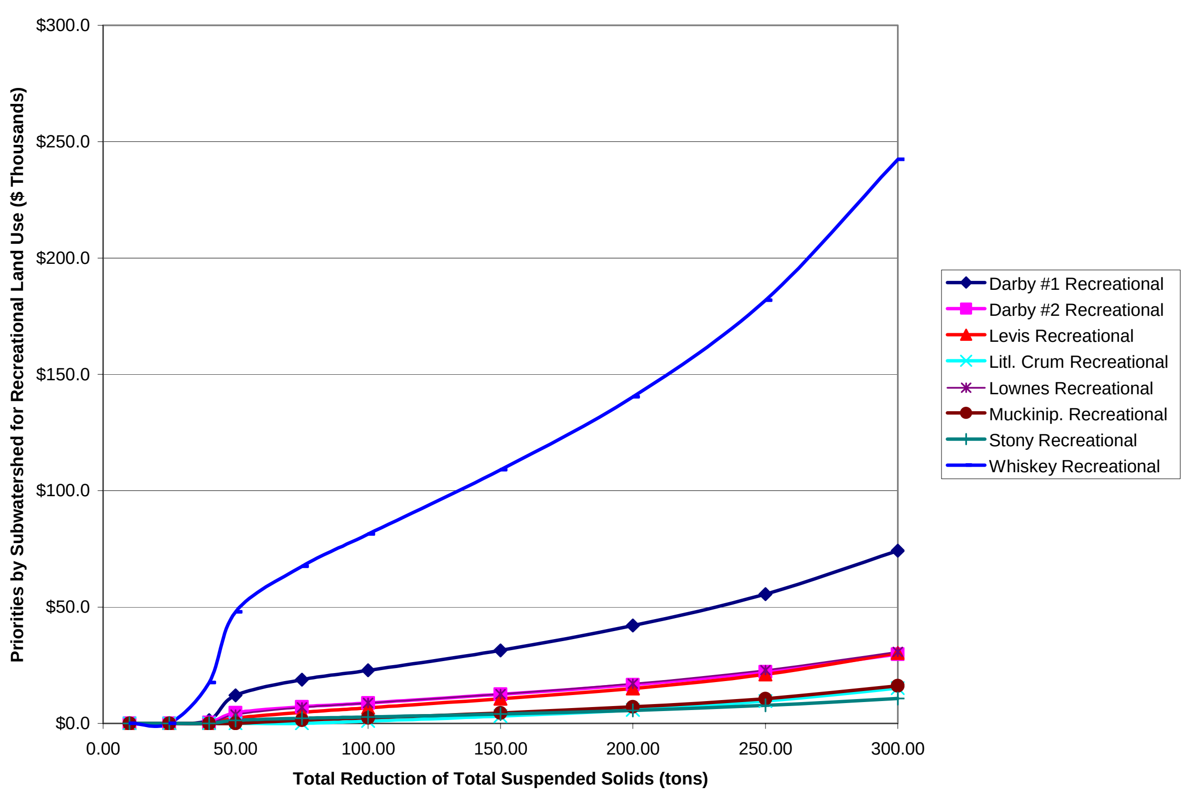


Figure 11. Recreational land use priorities by subwatershed

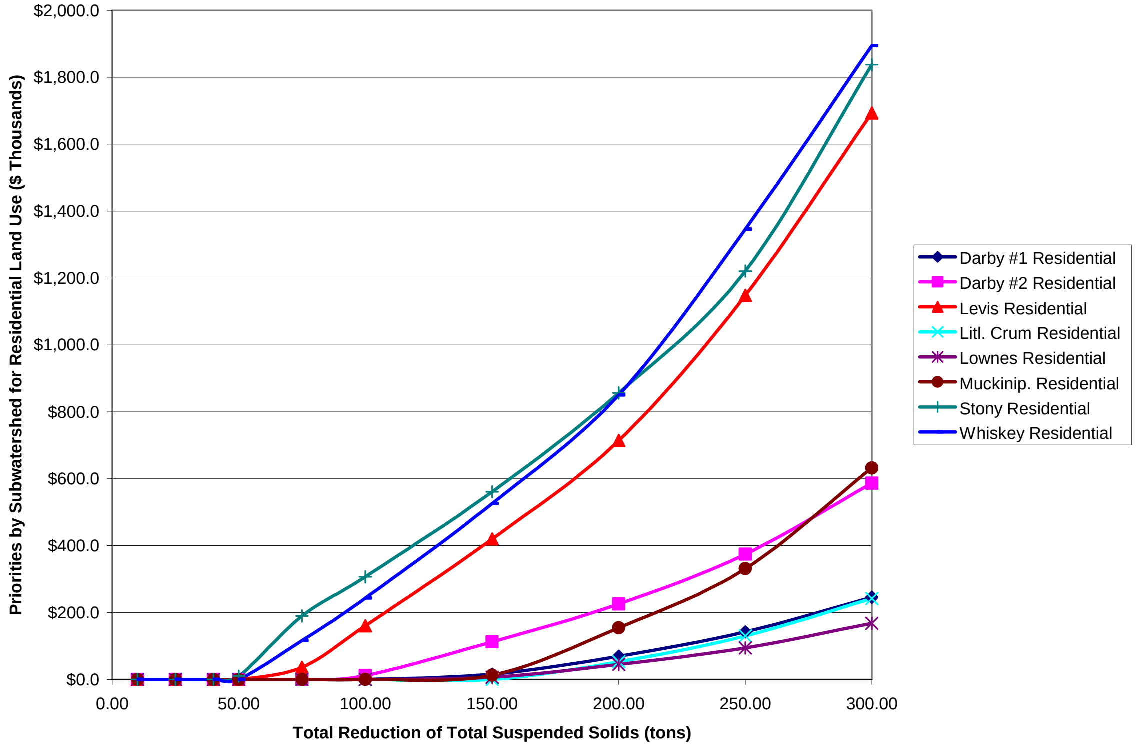


Figure 12. Residential land use priorities by subwatershed

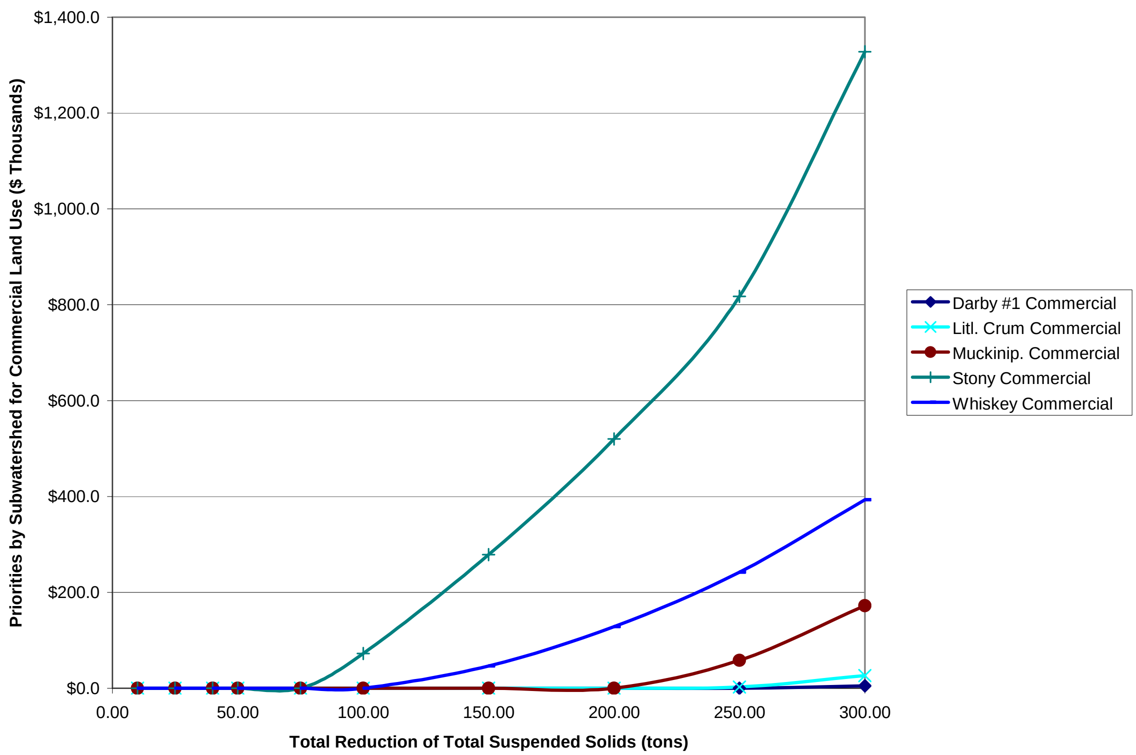


Figure13. Commercial land use priorities by subwatershed

Figure 12 reveals that TSS reductions of around 100 tons and greater require installation of more expensive retrofit management practices in residential areas (cost curve calibration based on bioretention cells), and these results can be used to rank subwatersheds for implementation of residential retrofit projects. The Stony Creek, Whiskey Run, and Levis Run subwatersheds have the greatest amount of land in high intensity residential use. The first-order streams are mostly covered and flowing in storm sewers, and the banks of the second-order streams are severely eroded. Most of the TSS reduction in this range is a result of reductions in stream bank erosion.

As total TSS reduction in Springfield is pushed up towards 300 tons, we see in Figure 13 that the heavily commercialized Stony Run, Whiskey Run, and Muckinipattis Creek subwatersheds are selected for retrofit management practices (cost curve calibration based on bioretention cells) as reductions in stream bank erosion are responsible for more that ¾ of the total TSS reduction (see Figure 15, below).

Priorities among land uses are summarized in the pie charts shown in Figure 14 for four different levels of total TSS reduction.

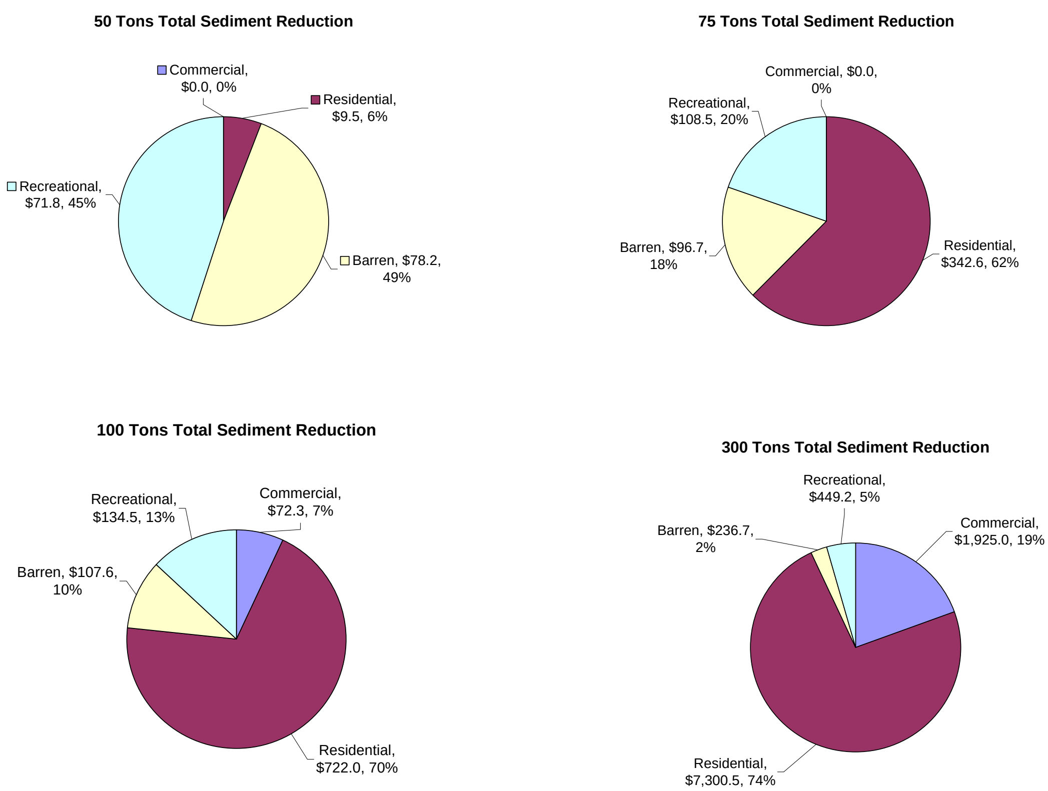


Figure 14. Priorities for TSS reduction by land use for four different levels of total sediment reduction: 50, 75, 100, and 300 tons.

Components of Nonpoint Pollution Removal. Figure 15 shows how the composition of the total sediment removal changes as the requirement for total sediment reduction increases. 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 16 shows details of how the individual components of nonpoint pollutant removal vary as a function of the total resources allocated. The upper graph shows the low range and the lower graph shows the entire range up to $10 million.

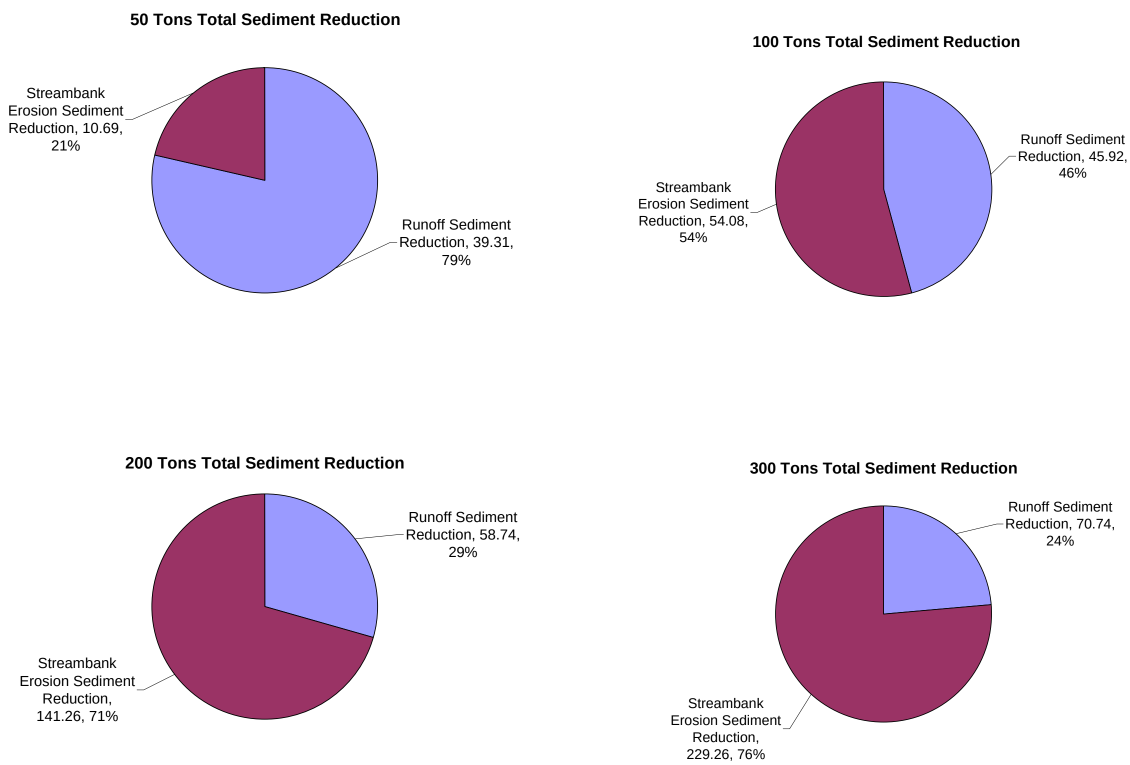


Figure 15. Sources of sediment reduction: changing relative amounts reduced from stream bank erosion and land runoff for four different levels of overall nonpoint pollution reduction

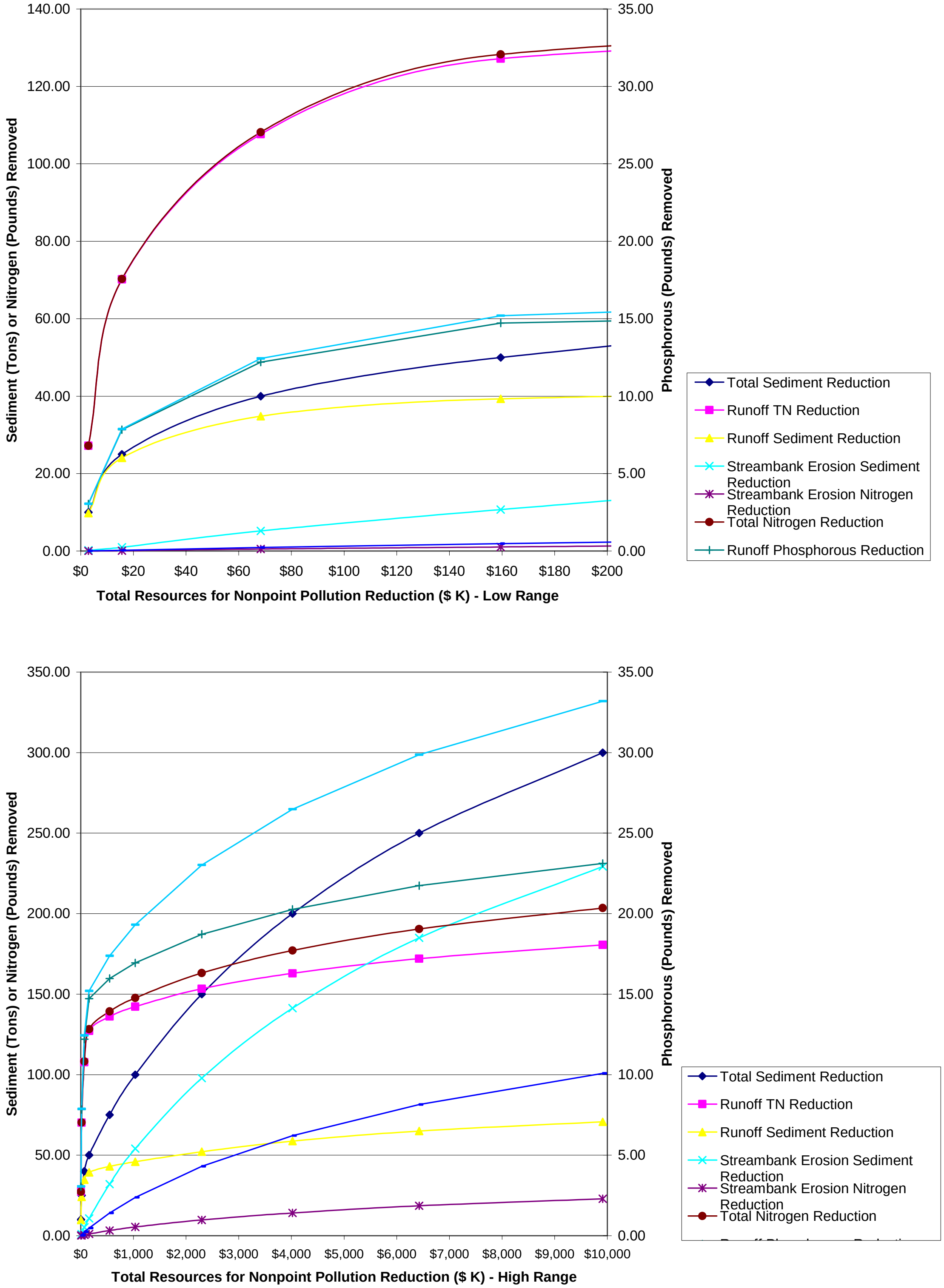


Figure 16. Pollutant reductions associated with optimal solutions for total resources in the low range: $0 - $200,000 and upper range: $0 - $10 million. Note: our field measurements suggest that the phosphorous loadings (right axis), and, therefore, the removal levels may be underestimated.

Prioritization by Total Resources Allocated. Finally, we show how the individual decision variables change as the total resources allocated increases, over three ranges: $0 - $75,000, $0 – $600,000, and $0 – $10 Million. This form of the data is likely to be of most interest to decision makers because it gives an idea of how various levels of funding might be allocated among projects in different subwatersheds and on different land uses as the total amount available for nonpoint pollution management is increased.

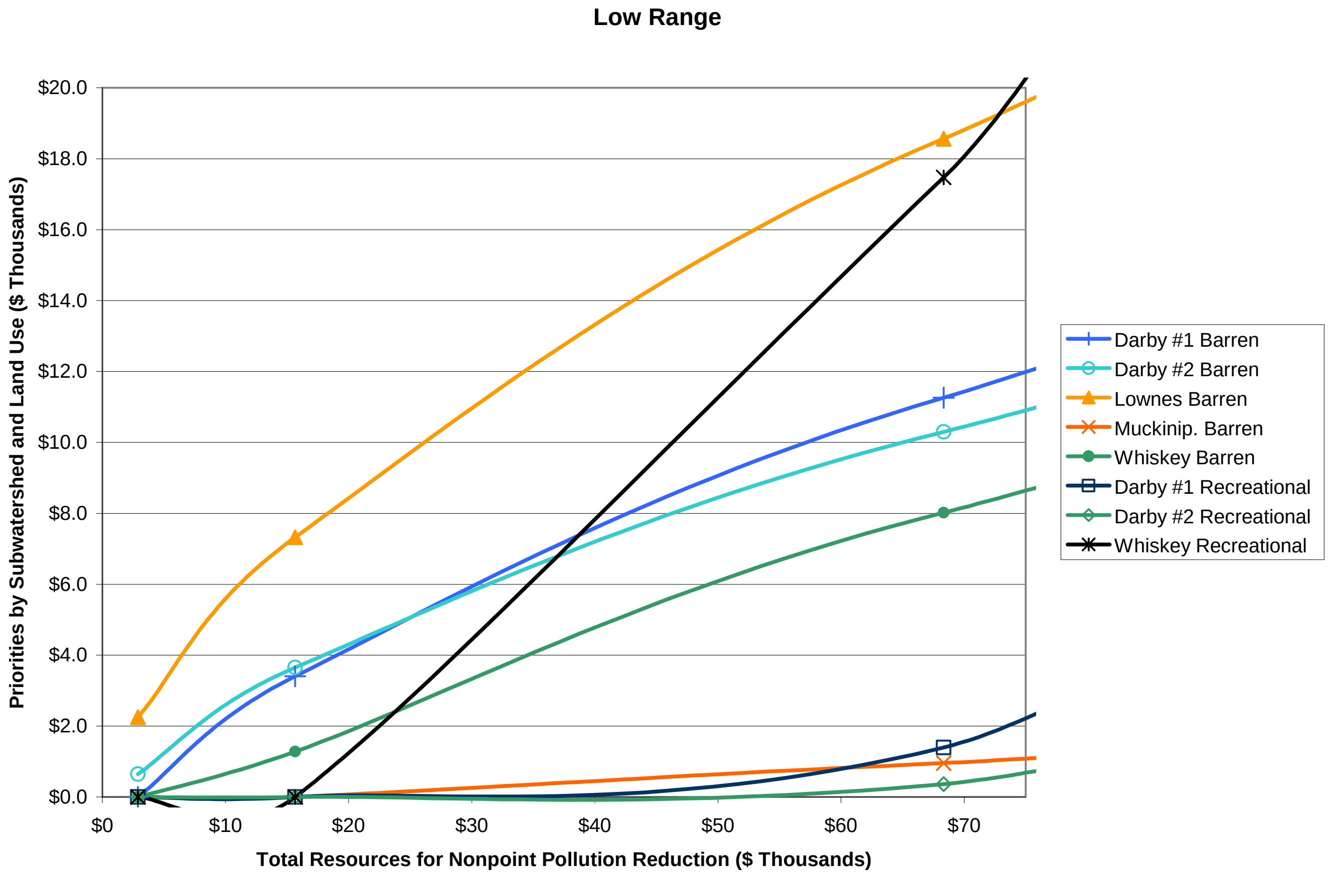


Figure 17. Priorities for the first $75K of Total Resources

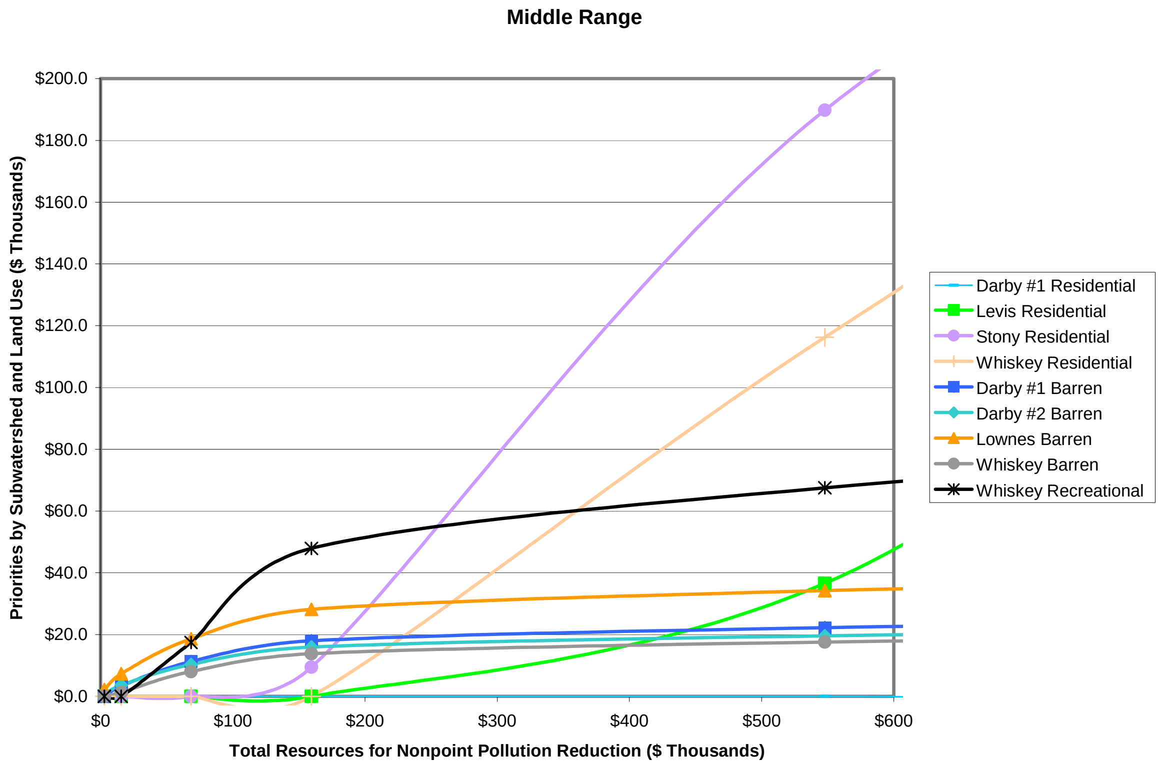


Figure 18. Priorities for the first $600K of total resources.

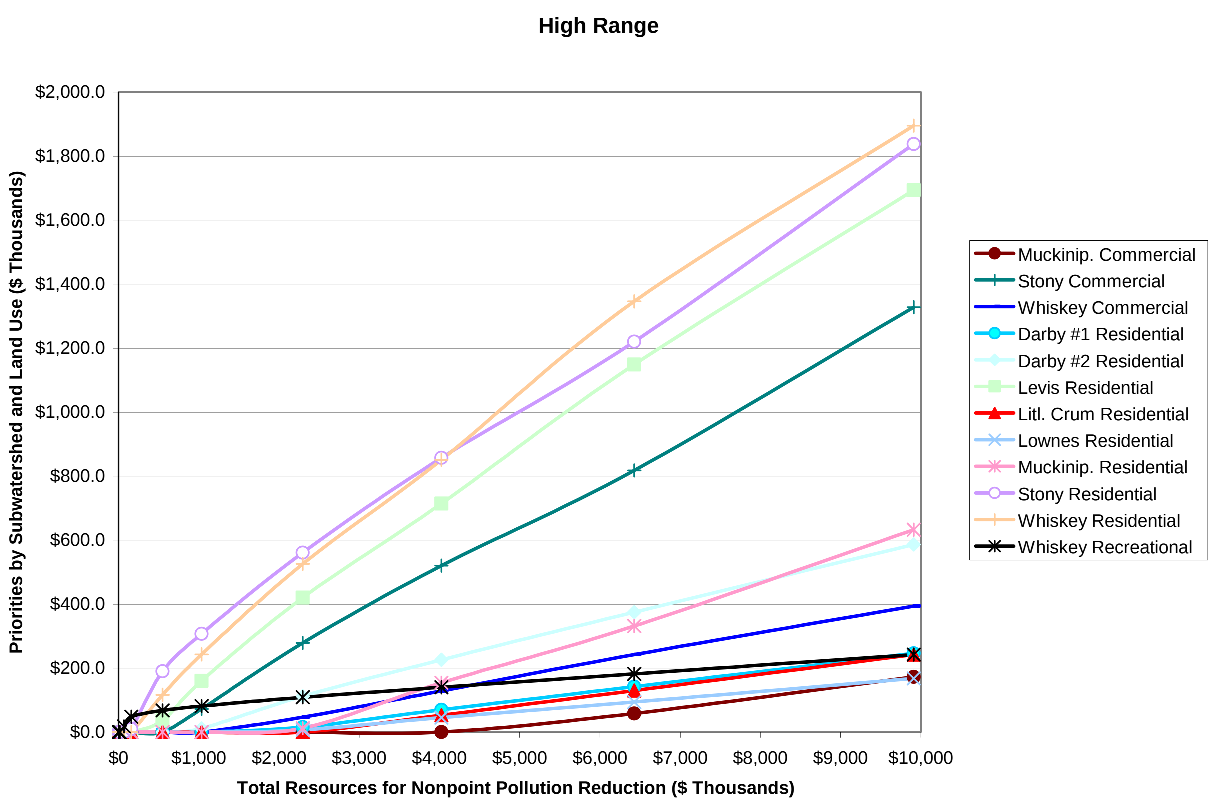


Figure 19. Priorities for the first $10 Million of Total Resources

RECOMMENDATIONS AND CONCLUSIONS

This project has successfully completed its four work elements as demonstrated in the Results section. We have 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 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. More site specific modeling and field monitoring of rain events will be conducted during the summer of 2005 to assist decision makers in the selection of sites to recommend for detailed BMP design studies, and, eventually, funding of BMP installations.

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APPENDIX: PHOTOGRAPHS

The photos in this section show scenes from second-order streams in Springfield Township, PA that illustrate the nonpoint pollution and streambank erosion problems referred to in this report. All of these photos are provided by Mr. Ken Rapp of the Springfield Township Environmental Advisory Council.

Figure A-1. Springfield Photo Site #1 showing that sanitary sewers commonly follow the stream valleys, making leaks of raw sewage into the stream a common occurrence during rain events, especially when sanitary sewers are infiltrated by stormwater runoff, causing them to surcharge.

Figure A-2. Springfield Photo Site #2 during low flow (upper) and high flow (lower) showing causes of severe bank erosion.

Figure A-3. Springfield Photo Site #3 during low flow (upper) and high flow (lower) showing causes of severe bank erosion.

Figure A-4. Springfield Photo Site #4 during low flow (upper) and high flow (lower) showing causes of severe bank erosion.