

**Screening Optimization Model for Watershed-Based Management of  
Urban Runoff Nonpoint Pollution**

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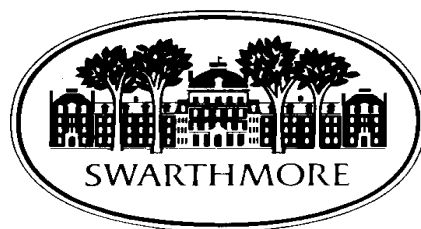
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# Screening Optimization Model for Watershed-Based Management of Urban Runoff Nonpoint Pollution

## ABSTRACT

This report presents background, results, and details by task on an EPA funded project to develop an optimization model for cost-effective prioritization of nonpoint pollution reduction management practices in urban areas. The project builds on a model originally developed for the Pennsylvania coastal zone drainage which has, in this project, been evaluated and adapted for more widespread use in urban areas. The project accomplished the following five tasks: (1) evaluation of the model for adaptation to multiple nonpoint loading models and development of a generalized user interface to accommodate data inputs from a variety of sources, (2) selection of graphical and geographic interfaces (GUI and GIS) for the model and development of software components to link with these user interfaces, (3) development of guidance for calibration of subwatershed-level pollutant-removal/cost functions including theoretical refinements of the methodology and development of a curve fitting technique named BMPFIT, (4) evaluation of alternative optimization software suitable for solving the model and development of software components, named NPSOPT, necessary to translate input data and cost parameters into input files for the solver, and (5) integration of tasks (1) through (4) to generate an enhanced model for distribution and widespread application in urban watersheds as the modeling system named StormWISE. Project results are being disseminated through release of the software code in the public domain, open source mode on the accompanying CDROM, on the web site <http://watershed.swarthmore.edu>, and through professional presentations including a peer reviewed paper at the national meeting of a professional society.

## INTRODUCTION

**Project Background.** 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 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.

This project applies optimization methods from the fields of Management Science and Operations Research to develop mathematical models and computer software tools for prioritizing projects that implement best management practices for storm water runoff in urban areas. The model, named StormWISE, for Storm Water Investment Strategy Evaluator, is designed to help watershed managers develop optimal strategies for targeting drainage areas and land use categories for nonpoint pollution reduction projects. In the model, data on BMP cost and pollutant removal efficiencies are combined with data on nonpoint pollutant loads, by subwatershed, to produce outputs that help users identify projects that can maximize the effectiveness of available funds. StormWISE is categorized as a “screening” model because it is designed for use at a high level, typically in the early stages of a watershed management planning process. It does not select specific sites for projects directly, but its output can substantially narrow the range of options with respect to project sites and BMP technologies.

The model also provides an objective way to choose among competing proposals for funding of BMP implementation projects that is based on sound scientific and economic modeling methodologies.

**Project Goals and Tasks.** This project builds on research conducted at Swarthmore College over the past ten years, including a Section 319 watershed assessment (McGarity, 2001), three implementation projects funded by Pennsylvania's Growing Greener program (McGarity, 2003), and two research projects funded by the federal Coastal Zone Nonpoint Pollution program (McGarity and Horna, 2005a, 2005b and 2005c). StormWISE was originally developed and calibrated for the specific set of circumstances (geographic, hydrologic, land use, etc.) existing in an intensively developed municipality in the Philadelphia suburbs (Springfield Township) that is experiencing urban nonpoint pollution problems. The primary goal of the project reported on here is to build on our experience applying StormWISE in suburban Philadelphia by extending the model for use by urban watershed managers in other areas of the country. The project was accomplished primarily during the 2005-06 academic year during my sabbatical leave with support from EPA and matching support from Swarthmore College, and included additional work with a student programming assistant during Summer, 2006.

Specific project tasks devised to accomplish the project goals include (1) evaluating the potential for use of the model with different nonpoint loading models, (2) selection of an appropriate Geographic Information System (GIS) interface for communicating results to decision makers, (3) development of a method for adapting the model's BMP cost functions to include multiple local cost factors, (4) examine options for the optimization solver software that is used to generate optimal solutions, and (5) integration of the model components into software that can be distributed to potential users of the StormWISE.

## **PROJECT RESULTS**

This section discusses the results of the project, including an overview of the methodology and results, and specific accomplishments related to each of the project tasks.

**Overview of Methodology and Results.** The methodology employed in this project to accomplish the five tasks consisted of refining the theoretical basis of the previously developed model so that it can be more widely applied, and, simultaneously, developing software modules to enable testing of theoretical refinements and to enable widespread use of the model by increasing the degree of automation in the process and by adding a user interface. This section describes the methodology and summarizes the results. Activities and accomplishments related to the specific tasks are detailed in the next section.

### **Model Theory**

Optimization techniques have been applied in the field of Water Resources since the 1960's (ReVelle, et al., 1967), but only recently to management of nonpoint pollutants in urban stormwater. Refinement of the theoretical basis of the StormWISE model was accomplished in this project through literature review and through making direct contact with other researchers in the fields of nonpoint pollution modeling and stormwater management. Programs and projects supported by EPA's Urban Watershed Management Research (UWMR) Branch of the National Risk Management Research Laboratory (NRMRL) were particularly relevant to this project. I met EPA technical staff and attended seminar presentations during several visits to the UWMR facilities in Edison, NJ during the project. Relevant research reports and presentations are listed in the Bibliography of this report, including Lai, et al. (2005, 2006), Pitt and Clark (2005), Traver (2006), and Hunt, et al. (2006). Contact with Fu-hsiung

(Dennis) Lai at EPA led to interaction with EPA contractors at Tetra Tech, Inc. working on an EPA funded optimization tool for BMP placement called SUSTAIN, who have helped to review progress on StormWISE.

In addition, I attended five conferences related directly to the project, four in the Philadelphia area and one national conference. Local conferences included (1) Pennsylvania Stormwater Management Symposium, Villanova University, October, 2005, (2) *Philadelphia Stream Summit*, Department of Earth and Environmental Science, University of Pennsylvania, January, 2006, (3) *Stormwater BMP Retrofits: Making them Work for You in the Darby and Cobbs Creek Watersheds*, Pennsylvania Environmental Conference, April, 2006, and (4) *Urban Watersheds Revitalization Conference*, Villanova University, May, 2006. The national conference was the American Water Resources Association specialty conference: *GIS and Water Resources*, Houston, TX, May, 2006 which included a full-day pre-conference workshop “BASINS/ArcView – SWAT.” These conferences contained presentations and resulted in professional contacts were particularly relevant to the accomplishment of tasks 1, 2 and 3.

The key theoretical component of the StormWISE screening model is the BMP performance-cost trade off function, which plots the amount of pollutant loading reduction achieved in a subwatershed-sized drainage area versus the level of resources devoted to implementation of management practices, expressed in units of thousands of dollars. The mathematical form of the function is that of a surface saturation phenomena in physical systems in which a limited number of surface sites are available, and the effectiveness of the driving forces that populate the sites diminishes as the fraction of sites already populated increases towards 100%. One example is the Langmuir adsorption equation (Langmuir, 1918) that is widely used to model equilibrium adsorption of gas or liquid molecules on surfaces in response to increasing partial pressure or concentration. When the equation is applied to the problem of populating potential sites for BMP projects, the driving force is the level of economic resources devoted to a drainage area and the response is the fraction of land area (and the associated stormwater runoff) that can be treated.

Other research on optimal placement of BMP's for watershed-based stormwater management has demonstrated the same behavior as that modeled by the Langmuir equation (see, for example, Yu, et al., 2002 and Lai, et al., 2005 and 2006). These studies show that site-specific models that generate optimal placement strategies for BMP's have solutions characterized by rapid increases in pollutant loading reduction in response to initial expenditures, as the least expensive projects at readily available sites and having economies of scale (the “low hanging fruit”) are implemented followed by diminishing cost effectiveness as the more expensive projects are taken on at the more problematic sites. This function is also used in technology assessment studies, such as a recently completed market penetration study for new energy efficiency technologies [Moore, et al. 2005].

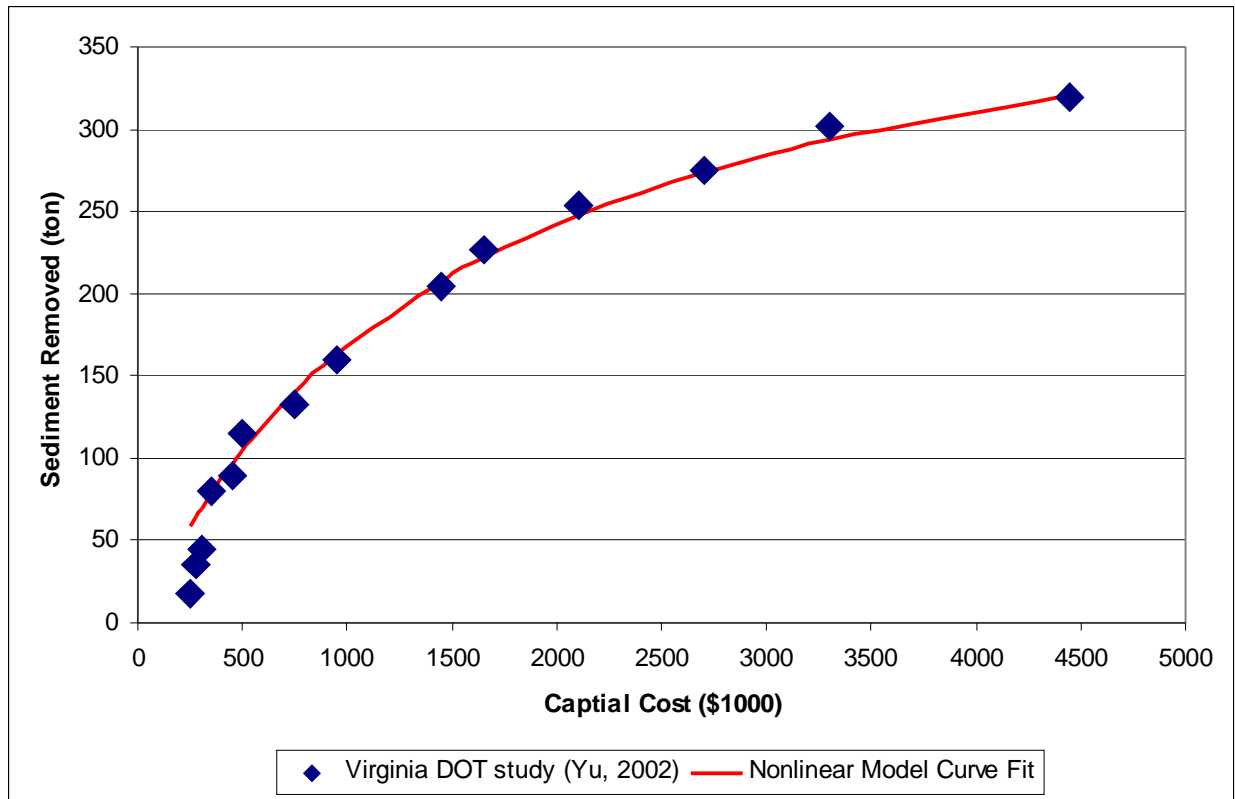


Figure 1. Langmuir surface saturation equation fit to data from results of an optimal BMP placement model developed by Yu, Zhen, and Zhai (2002) in a watershed-based study of BMP placement for minimization of cost. (Figure taken from McGarity and Horna, 2005.)

The Langmuir surface saturation equation applied to BMP performance and cost over a subwatershed-scale drainage area takes the form shown in Equation (1), below:

$$f = \frac{X}{(H + X)} \quad (1)$$

where:

$f$  = fraction of land area treated by BMPs

$X$  = resources devoted to BMPs (\$1000)

$H$  = “half-cost” – the resources required to treat one-half of the land area (\$1000)

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.

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

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

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

where:

$f_T$  = fraction of total annual runoff that is treatable (eg. 90% for 1-inch design storm precipitation)

$\eta_{BMP}$  = estimated annual pollutant removal efficiency for treatable runoff

$L$  = annual pollutant loading for each land use (tons – sediment, or pounds – nutrients)

The use of equations (1) – (3) to model optimal implementation of BMP's on the watershed scale was first proposed by McGarity and Horna (2005). Figure 1, above, taken from that study, shows how well these equations fit data from the site specific BMP placement optimization model developed by Yu, et al. (2002) for the Virginia Department of Transportation. We see that a simple set of analytical functions having two parameters,  $H$  and  $R^{\max}$ , can be used to represent the results of many thousand complex calculations involving detailed simulation models driven by an optimization engine (scatter search, in this case).

In previous applications of the screening model, a single-point calibration was used to obtain estimates of the parameter  $H$ . Site specific costs were used associated with the BMP technology that, according to judgment of watershed managers, would most likely be required at the point where runoff from *one-half* of the drainage area is being treated. The marginal cost of that technology was computed from published cost curves that account for economies of scale (see, for example Schuler, 1987).

In this project, the methodology described above is extended to enable multiple BMP technologies to be used for calibrating the performance-cost equation. If we let  $A$  represent the land area treated by BMP's within a drainage area  $A_d$ , then  $f$  in equation (1) is the ratio of these two areas. Substituting this ratio for  $f$  in equation (1), solving for  $X$ , and differentiating with respect to  $A$  gives the result below:

$$\frac{dX}{dA} = \frac{(H / A_d)}{(1-f)^2} = \frac{h}{(1-f)^2} \quad (4)$$

where:

$h$  = half cost per unit drainage area (\$/acre)

$\frac{dX}{dA}$  = marginal BMP cost, obtained from site specific data (\$/acre)

We can solve equation (4) for  $h$  to obtain:

$$h = \left( \frac{dX}{dA} \right) (1-f)^2 \quad (5)$$

Equation (5) shows that the half cost can be calibrated for any point on the pollutant removal versus cost curve. Our previous studies fixed  $f$  at 50% for this calibration, but we see that any value of  $f$  could be used.

A further extension of the methodology is to enable multiple values of  $f$  to be used simultaneously in a multipoint calibration. Consider  $m$  different BMP technologies, each having different marginal costs. Let  $y_i = \left( \frac{dX}{dA} \right)_i$  for  $i = 1, 2, \dots, m$  represent the marginal costs for each BMP technology, obtained from site specific data based on realistic experience with BMP implementation projects. Arrange the  $m$  different BMP technologies so that  $y_1$  has smallest cost,  $y_2$  is second smallest, etc. and  $y_m$  is the most expensive. Then, based on considerations of how applicable each BMP technology is in the geographic region where the model is applied and on the various land use categories where it can be applied, estimate the range of application for each BMP technology in terms of  $f$ . For example, one result of applying this method to a specific drainage area is that for commercial land uses, the least expensive BMP having marginal cost  $y_1$  can be applied to only 15% of the acreage, the second least expensive BMP having marginal cost  $y_2$  can be applied to the next 20%, and the third least expensive BMP having marginal cost  $y_3$  can be applied to the next 25%, where  $y_1 < y_2 < y_3$ .

A linear optimization model has been formulated to find the value of  $h$  which yields the best fit of a saturation function of the form of equation (1) to the data. This model is shown below:

$$\text{Minimize } \sum_{i=1}^m e_i^+ + e_i^-$$

Subject to:

$$\begin{aligned} y_i' &= \frac{h}{(1-f_i)^2} & i = 1, 2, \dots, m \\ -e_i^- &\leq y_i' - y_i \leq e_i^+ & i = 1, 2, \dots, m \\ 0 &\leq f_i - f_{i-1} \leq u_i & i = 1, 2, \dots, m \\ e_i^+, e_i^-, f_i &\geq 0 & i = 1, 2, \dots, m \end{aligned}$$

where  $u_i$  is the upper limit for the range of BMP  $i$  (0.15, 0.20, and 0.25 in the example above),  $y_i'$  is the marginal cost of BMP  $i$  estimated from the curve,  $y_i' - y_i$  is the deviation of the actual marginal cost for BMP  $i$  from its estimated value. This formulation minimizes the sum of the absolute deviations of the data from the curve. This curve fitting technique is recognized in the field of Robust Statistics to be superior to the more commonly used least-squares technique when the data are likely to contain outliers. BMP cost data typically vary over wide ranges, so this technique was chosen for the BMPFIT component of the StormWISE system.

I have received favorable reviews of the methodology used in this project from several of the other modelers with whom I have discussed the techniques during the course of this project. I expect to receive additional critique and suggestions for refinement of the model as the results of this project are disseminated through professional meetings and peer reviewed publications.

## Software Modules

The StormWISE software system consists of core modules and user interface modules. An overview of the functionality of these modules is given here. Details regarding their development are presented below in the discussion of specific tasks.

Core modules provide the basic functionality of the StormWISE system, which is to process an input file containing pollutant loading and BMP cost data and to create an input data file for the optimization solver. Core modules are written in the ANSI standard C++ language, and they make extensive use of the extremely efficient C++ standard template library. Core modules can be compiled into native machine language on any of the operating systems in widespread use, including Microsoft Windows, Mactintosh OS, and Linux. Public domain compilers such as GCC and MinGW are available at no cost that can be used to compile the core modules. StormWISE core modules are distributed in a folder named *corecode* on the accompanying CDROM.

A simple console based user interface is provided with the core modules to enable use of the model from the command line prompt. This interface program, called *npsopt\_wasoff*, for nonpoint source optimization – urban washoff version, can be easily modified by the user if desired. The input file format is documented in Appendix A. The format is designed for easy creation of input files using a standard text editor. The input modules that parse this file are designed to tolerate a significant range of variability in the order and style of data input tables. If all of the required data components are specified in the input file, then an output file is generated and the program terminates.

The output file from *npsopt\_wasoff* becomes the data input file for the AMPL optimization solver. The user also invokes the AMPL from the command line on the model file *npsopt.mod*, which contains code in the AMPL modeling language that defines the variables, objective function, and constraints of the nonlinear optimization model. AMPL software must be downloaded and installed on the computer. The free version of AMPL can solve problems having up to 300 variables and 300 constraints. This capability allows the user to test the StormWISE system of a wide range of different stormwater management problems. For example, if the user needs to manage only one pollutant at a time, such as sediment loading, then the free version of AMPL can accommodate five different land use categories covering 30 different subwatersheds. If three pollutants, such as sediment, nitrogen, and phosphorous, are managed simultaneously, then five land uses can be managed over 15 different subwatersheds. Many urban watersheds can easily be accommodated within these limits. With the commercial version of AMPL, the limitations are removed, and watersheds of virtually any size can be managed for an essentially unlimited number of pollutants and use categories.

A menu driven graphical/geographic user interface has been developed for StormWISE during this project which runs on the Microsoft “.NET” (pronounced dot Net) system. The .NET system is well supported by Microsoft Windows, and is beginning to be supported by public domain operating systems such as Linux. The .NET system uses a “common language runtime” (CLR) environment that enables creation of code libraries that can be easily accessed from any of the .NET languages, including Visual Basic, Visual C# (C-sharp), Visual C++, and Visual J# (Microsoft’s version of Java). Code developed in the .NET system is often called “managed,” and code developed by traditional compilers is called “unmanaged.” Visual C++ allows creation of programs that contain both managed and unmanaged code. This feature enables us to incorporate the unmanaged ANSI standard C++ core modules of the StormWISE system into a dynamic link library (DLL) that can be easily accessed by any of the .NET managed languages. The .Net system can be downloaded from Microsoft for free and installed on



computers running Microsoft Windows. The managed interface to the core modules is written in managed Visual C++ and is called *npsoptclr.dll* for “nonpoint source optimization common language runtime dynamic link library.”

Another reason for adopting the .NET system is the recent development of the public domain GIS system called MapWindow at Idaho State University (Michaelis and Ames, 2006). StormWISE uses MapWindow modules which can be downloaded from <http://www.mapwindow.com> and installed on the user’s computer for free and with no restrictions. The StormWISE interface to MapWindow enables the user to import the standard GIS format “shape” files used by pollutant load calculation models, such as AVGWLF and SWAT, to generate input data on runoff parameters. These GIS files can then be used to display the results of the optimization solver on a map using color ramp schemes that identify the drainage areas and land use categories that should receive high priority for BMP implementation projects. The MapWindow GIS interface was recently chosen for Version 4 of EPA’s BASINS watershed modeling system (Kittle, et al., 2006).

The StormWISE graphical interface also uses the data table display and editing capabilities of the .NET library to enable editing the input files in a data grid array. This capability facilitates the use of alternative pollutant load calculation models that do not have GIS interfaces, such as EPA’s SWIMM model and others. Input files can be edited in an interactive mode and multiple runs of the optimization solver can be accomplished in one session. If a GIS map file is not available, StormWISE can generate a simple pie diagram to display its prioritization results. The graphical interface invokes AMPL automatically when the “run” menu option is chosen, and it parses the AMPL output file to generate results for tabular and graphical displays on screen. These displays can also be sent to a printer. The graphical interface modules currently distributed with StormWISE are written in Visual Basic.

Finally, a utility program called *GWLF\_postprocessor* has been written to demonstrate the feasibility of an automated interface for StormWISE to a popular nonpoint pollutant load calculation model. This console-based program can read the output files from multiple runs of the model AVGWLF, which was developed at Penn State University (Evans, et al., 2002, 2003, 2004) is an implementation of the GWLF model developed at Cornell University (Haith and Shoemaker, 1987). AVGWLF is supported particularly well for use in Pennsylvania with an extensive GIS and nonpoint pollution runoff parameter database. *GWLF\_postprocessor* is a fairly simple program written in the ANSI standard C language. When AVGWLF is used for pollutant load calculations, *GWLF\_postprocessor* can automate the process of preparing input files for StormWISE. The source code of this program can also be used as a template for users who want to adapt it for use with other nonpoint pollutant load models.

### **Activities and Accomplishments by Task**

**Task 1.** Evaluation of the model for adaptation to multiple nonpoint loading models and development of a generalized user interface to accommodate data inputs from a variety of sources.

A standard interface for the optimization screening model was developed to replace the tedious manual procedure originally required to run the model for the earlier Springfield Township studies. Code was first prototyped in the “C” programming language to process input tables containing model parameters that can be created either by a person or by other software. Prototype code enabled development and testing of the standard interface file format consisting of four general data components: sets, one-dimensional tables, two-dimensional tables, and three dimensional tables. All of the necessary model input data can be expressed in these formats. The program parses the input in a flexible manner,

with only a few rigid requirements for the input, such as the required semicolon at the end of the data tables for each model component. The interface program generates files in the AMPL modeling language that are processed further by the optimization modules to generate results on optimal selection of BMP's for reducing nonpoint pollution in urban runoff. The prototype modules were converted to ANSI standard C++ to enable creation of the "core modules" and the dynamic link library that contains them. These modules are distributed in the folder named *corecode*.

The functionality of the core modules is accessed by two different methods, the console application *npsopt\_washoff* and the graphical interface application *StormWISE*. The *npsopt\_washoff* application can be compiled and linked to the core modules on any computer that has a standard C++ compiler. It accepts the name of the input file containing model data in the standard format, described above, and outputs data files for the AMPL optimization module. AMPL is then run by issuing another command from the console. The AMPL output file displays the results of the optimization, indicating optimal BMP investment levels by subwatershed and land use category. Details on the *StormWISE* graphical and GIS user interface are presented in the discussion of Task 2, below.

An additional console-based computer program, called *GWLF\_postprocessor* was written to process AVGWLF output files in comma-separated value (CSV) format containing NPS loading results for multiple drainage areas within a watershed. The output of this program is an input file which can be read immediately by either *npsopt\_washoff* or *StormWISE* with little or no editing by the user. The source code for this program is written in widely used ANSI standard C, and in a form that enables developers to adapt it to serve as a postprocessor for other pollutant loading models. Interfacing to an NPS loading model is primarily a task involving parsing the output files generated by the loading model to extract pollutant loadings and hydrologic parameters for each drainage area in the watershed (the front end) and processing that data to produce an input file in the format I have specified for NPSOPT (the back end). The back end written for the automated AVGWLF interface can be used with minimal changes. Interfacing to a different loading model involves writing a different front end to parse the output files from that model.

I also became familiar with other popular pollutant load calculation models. I attended seminars at EPA's Urban Watershed Management Branch in Edison, NJ where I met EPA staff involved in modeling who described applications of the EPA SWMM model. Also, I became familiar with the SWAT model through "hands-on" participation in a pre-conference workshop "BASINS/ArcView SWAT – a Tool for TMDL Development /Assessment" at the American Water Resources Association (AWRA) Spring Specialty Conference in Houston. These experiences informed the development of the input file format for *StormWISE* modules to facilitate manual preparation of model input from the output of these and other pollutant load calculation models.

**Barriers Encountered in Task 1.** Development of automated interfaces for multiple loading models became a low priority for this project as the wide range and intricacies of the many models presently in use became apparent. Thus, the decision was made to develop a graphical data entry interface for *StormWISE* (see Task 2, below) that enables users to manually input results from their favorite loading model. The automated interface for AVGWLF, *GWLF\_postprocessor*, is being distributed as an optional stand alone module in the widely used and standard C language so that users can adapt it, if they wish, to read the output of different pollutant loading models.

**Task 2.** Selection of graphical and geographic interfaces (GUI and GIS) for the model and development of software components to link with these user interfaces

Traditional “command line” and text file interfaces are widely used in the environmental modeling world, and the input format described above in Task 1 is designed to facilitate this type of use. But a user-friendly graphical interface is necessary to make the screening optimization model widely accessible to watershed managers. The following specifications were established in this project for the desired features in a user-friendly model interface including: (1) a geographical information system (GIS) for displaying drainage areas included in the analysis, (2) graphical and tabular presentation of the results of multiple optimization model runs at increasing pollutant removal levels, and (3) a set of graphical user interface modules to control the overall flow of information between the components of the model.

Development of a graphical user interface requires selection of an “application development framework” (ADF) based on a particular programming language and a suite of tools to speed the process of writing code for the user interface for a particular computing platform. There are multiple, competing ADF’s available, and selection of an ADF for a major project such as this one requires careful specification of requirements and consideration of how well the different ADF’s satisfy the requirements.

Graphical user interfaces tend to be highly operating system specific. Microsoft Windows is the most widely used operating system, so the selected ADF must certainly have the capability of generating GUI-based code for this system. Microsoft’s own ADF, Visual Studio, has tools for building GUI applications that generate non-standard code incorporating Microsoft’s CLI extensions to the C++ language for the Microsoft “.NET” system which runs primarily on Windows. At first, it appeared that incorporation of existing ANSI standard code into Visual Studio would be problematic. I investigated an alternative ADF called “Qt” from TrollTech, Inc. which provides an ANSI standard C++ library of GUI “widgets” for building the user interface as well as a graphical tool for building the components. It is a multiplatform ADF which can generate executable code on the Windows, Linux, and Macintosh operating systems. However, incorporation of geographical information system (GIS) modules into the Qt framework was not straightforward and subsequent discovery of the MapWindow GIS system for “.NET” led to the final choice of that system for the GUI components of StormWISE.

At the beginning of the project, I assumed that I would link my software modules to the proprietary ARCGIS™ interface because of its widespread popularity. However, I also wanted the software to be useful to watershed managers who do not have access to commercial GIS software. At the AWRA conference in Houston, I met Professor Dan Ames in the Department of Geosciences at Idaho State University who has led the development of an international effort to create public domain open source GIS software. This project has very recently produced a high quality package called MapWindow which comes with a library of GIS object creation and manipulation modules that can be incorporated into other software and redistributed without royalty fees. I decided to give priority to development of an interface for my modules to MapWindow because it provides the needed geographical display capability without burdening the user community with significant costs. MapWindow modules come with good documentation and example programs demonstrating their use that can serve as building blocks for other software. MapWindow is attracting a growing user community which will likely grow substantially as EPA’s BASINS watershed modeling system version 4.0 is released, since the new BASINS uses MapWindow as the GIS interface.

MapWindow must be implemented in the “managed .NET” programming environment. Since we selected the “.NET” interface for the StormWISE GUI (described above), our user interface is able to make extensive use of MapWindow. When StormWISE is operated in its GIS mode, a color scale is used to indicate the model results: optimal BMP/LID investment priorities for each subwatershed drainage area, broken down by landuse categories if desired. StormWISE can read the standard ESRI

“shapefile” format that is commonly used by nonpoint pollution loading models with a GIS interface. This format can also be created by watershed delineation programs such as ArcHydro (Maidment, 2002). If a “shapefile” is not available, which may be the case if the pollutant load model does not have a GIS interface, then StormWISE displays results as a pie-diagram, with each wedge of the pie showing optimal levels of investment by subwatershed and land use category.

**Barriers Encountered in Task 2.** Use of the .NET programming environment could limit use of the StormWISE GUI/GIS interface to computers running Microsoft Windows. However, there are efforts presently underway in the open source programming community to develop “.NET” programming support for other operating systems such as LINUX, and this could eventually enable use of the MapWindow-based interface on computers running LINUX.

Some potential users of StormWISE may not use a nonpoint pollution loading model that has a GIS interface. Thus, shape files may not be available for GIS display of StormWISE results. However, both a tabular output display and a pie diagram of results is included in StormWISE which presents all of the information contained in the GIS display. Future development of StormWISE could take advantage of plug-ins available for MapWindow that enable creation and editing of shapefiles, including delineation of subwatershed drainage areas, that enable creation of GIS displays for presentation of StormWISE results to decision makers when pollutant loading estimates are generated without the benefit of a GIS interface.

**Task 3.** Development of guidance for calibration of subwatershed-level pollutant- removal/cost functions including theoretical refinements of the methodology and development of a curve fitting technique.

Progress on this task was made through literature review and by establishing contacts with researchers and experts in the field of urban stormwater BMP’s including Dr. Dennis Lai of EPA’s Urban Watershed Management Branch, Professor Robert Traver of Villanova University’s Urban Stormwater Partnership, Dr. Barry Evans at Penn State University, and consultant Michael Clar of Ecosite, Inc. The web site of the Center for Watershed Protection (<http://www.cwp.org>) has descriptive material on a range of different best management practices, including site-specific cost functions and typical pollutant removal efficiencies (Schuler, 1987).

During the project period, I attended the following seminars, workshops, and conferences where presentations were viewed and contacts made enabling access to data on a wide variety of BMP/LID designs and demonstrations.

November 17, 2005: “Integration of Pollutant Source Reductions and Advanced Stormwater Treatment Technologies into Stormwater Control,” R. Pitt and S.E. Clark, U.S. EPA Urban Watershed Research Branch Seminar, Edison, N.J

April 5, 2006: “Stormwater BMP Retrofits: Making them work for you” – sponsored by the Pennsylvania Environmental Council and including urban retrofit BMP design concept studies performed by Cahill Associates, Inc. and Borton-Lawson Engineering, Inc. including designs for specific urban sites and rough cost estimates.

April 6, 2006: “Infiltration Volume Reduction BMP Monitoring Results,” full-day seminar by Robert Traver and graduate students, Villanova University, sponsored by U.S. EPA Urban Watershed Management Research Office, Edison, NJ, including a particularly relevant presentation on “Watershed-Scale Evaluation of a System of Storm Water Detention Basins by Clay Emerson.

April 20, 2006: “LID & BMP Case Studies,” full-day seminar by Bill Hunt and associates, North Carolina State University, sponsored by U.S. EPA Urban Watershed Management Research Office, Edison, NJ., including case study presentations on bioretention, green roofs, permeable pavement, and a stormwater wetland.

May 7, 2006: Workshop: BASINS/ArcView-SWAT 2005 – A Tool for TMDL Development & Assessment, led by Dr. Raghavan Srinivasan, Texas A&M University, including overview of model theory and hands-on case studies of the use of this widely-used nonpoint pollutant runoff model.

May 8-10, 2006: AWRA 2006 Spring Specialty Conference: GIS and Water Resources IV, Houston, Texas, program at <http://www.awra.org/meetings/Houston2006/index.html>.

May 19, 2006: Urban Watersheds Revitalization Conference: Renewing Urban Creeks and Neighborhoods, sponsored by the Urban Sustainability Forum and hosted by Villanova University, Department of Civil and Environmental Engineering, including presentations on award-winning stormwater BMP projects and including “Ultra Urban BMP’s,” Cost-Benefit Analysis of Kensington Green Program,” and a “Smart Growth Development Panel Discussion” – website <http://www.greentreks.org/pec/agenda.asp>

The main challenge of this task was the development of BMP cost functions for a large drainage area (subwatershed) of several hundred acres based on cost data drawn primarily from demonstration projects serving 1-20 acres. The approach taken in StormWISE is to break down each drainage area into land-use categories and to designate specific BMP technologies that are suitable for each land-use. Within a land-use, the specified BMP’s are applied in order of increasing cost subject to limits placed by the user on the total land area that can be served by each type of BMP. This method attempts to model the process generally recommended for cost-effective watershed management, i.e. pushing the low-cost, highly effective management measures (including nonstructural BMP’s) to their limit at those (probably limited) sites where they can be applied before moving to technologies associated with higher costs serving a similarly limited number of sites (Muthukrishnan, et al., 2004). The process continues until we are forced to consider the highest cost BMP’s for the most problematic sites in the drainage area. A smooth curve, having the mathematical form of a “saturation” function, is used to model the saturation of sites available for low-cost BMP’s and the increasing marginal costs that result when we are forced to choose the more expensive BMP’s as the fraction of the treated land area increases towards 100%. The best-fit curve of this type is fit to BMP cost data in the BMPFIT component of the StormWISE model by applying a robust curve-fitting method (the technique of minimum absolute deviations - MAD) in order to minimize the impact of outliers in data that have a wide range of variability. The mathematical formulation for this model is described above in the Model Theory section.

**Barriers Encountered in Task 3.** BMP cost and performance data are site specific and they vary over extremely wide ranges, making it difficult to extract cost parameters for optimization studies. A screening model operating at the subwatershed level requires more generalized data. The BMPFIT methodology requires that watershed managers combine site-specific data from actual installations with judgment, based on experience, regarding the applicability of various BMP technologies to the various land use categories that exist in the particular watershed being analyzed.

**Task 4.** Evaluation of alternative optimization software suitable for solving the model, and development of software components necessary to translate input data and cost parameters into input files for the solver

Two different optimization solvers were investigated for use with StormWISE components *BMPFIT* and *NPSOPT*: (1) Microsoft Excel’s built-in solver, and (2) the AMPL modeling language with the MINOS solver. Both of these solvers are part of commercial products, although Excel is

commonly available as a component of the Microsoft Office suite, and a version of AMPL is available for free. The current release of StormWISE uses both solvers to various extents.

The optimization model formulation for the NPSOPT component of StormWISE is a well-behaved nonlinear cost minimization that is solved for an increasing range of watershed-wide pollutant removal levels. AMPL and its solver MINOS are able to solve the NPSOPT problem in very little time on a personal computer in all cases that we have tested. AMPL is interfaced directly to the graphical StormWISE interface described above in Task 2. The free edition of AMPL will solve the optimization problem for moderately sized watersheds. There is no size limitation with the commercial version of AMPL.

The BMPFIT multipoint calibration model for subwatershed-scale BMP cost functions can be run either with the Excel solver or with AMPL, with identical results for similar inputs. An Excel spreadsheet is provided on the accompanying CDROM that can be used as a template for processing site-specific BMP cost data to obtain cost parameters for use in StormWISE. An advantage of the Excel template is the built-in graphical display of the curve fitting results and the potential for interactive use of the technique to obtain the final calibration. The template can be particularly useful for first-time users who are learning the technique. Experienced StormWISE users may prefer to use the AMPL version of BMPFIT which is better suited to automation. The AMPL version is distributed on the accompanying CDROM as a model file (*bmpfit.mod*), a command file (*bmpfit.run*), and two example data files for commercial land use (*bmpfit\_commercial.dat*) and residential land use (*bmpfit\_residential.dat*).

**Barriers Encountered in Task 4.** I spent some time searching for a purely public-domain solver that could be used without licensing issues and integrated more tightly with the other components of the model. The advantages of such a solver could be significant, including tighter integration of optimization modules with the core modules and unlimited watershed size without the requirement for commercial software. I did find a promising offering developed by Carl Laird at Carnegie-Mellon University called IPOPT for Interior Point OPTimizer (<https://projects.coin-or.org/Ipopt>), which is written in standard C++, as are the core modules of StormWISE. Integration of the StormWISE modules with this optimizer is probably feasible, but was a low priority given successful application of both Excel solver and AMPL, and is left for future development of StormWISE.

**Task 5.** Integration of tasks (1) through (4) to generate an enhanced model for distribution and widespread application in urban watersheds as the modeling system named StormWISE.

This task included the interfacing between the standard input format for NPSOPT and AMPL, as reported above, which integrated Tasks 1 and 4. Documentation of the standard input format for NPSOPT is provided in Appendix A of this report. Tasks 1, 2 and 4 were integrated through development of the object-oriented core modules and the “.NET” interface for these modules which led to rapid progress on development of the user interface having GUI and GIS components. Tasks 2 and 3 were integrated through development of the BMPFIT modules (Excel and AMPL) and modification of the NPSOPT interface file to accept the results of the multipoint calibration.

StormWISE software modules are included as source code on the CDROM that accompanies this report. Also included are executables for the Windows XP operating system with installation instructions.



**Barriers Encountered in Task 5.** Further integration of the software modules is possible and probably desirable. For example, the BMPFIT modules could be merged into the StormWISE graphical user interface, but for a merged version to have the same functionality as the Excel template, plotting capabilities should be added as well. On the other hand, the StormWISE system, as it is currently packaged, is separated into well defined components with distinct functions, and future efforts towards integration of the components will benefit from feedback from the initial group of users.

## **DISSEMINATION OF RESULTS**

As of the report date for this project, several opportunities have arisen for dissemination of the results. This report is posted on a Swarthmore College web site <http://watershed.swarthmore.edu> and the StormWISE software can be downloaded from that site.

The methodology used in the StormWISE system is innovative and very recently developed as part of this project. It will benefit from review, critique, and refinement. In July, 2006, EPA modeling expert Dennis Lai solicited a review of the screening optimization model methodology from optimization experts at Tetra Tech, Inc. who are working on the EPA funded SUSTAIN modeling system for optimal selection of BMP sites. My answers to four questions posed by Tetra Tech staff appear in Appendix B of this report.

In September, 2006, I was invited to participate in a panel of optimization experts assembled by Dennis Lai to advise Tetra Tech staff on the optimization methodology used in the SUSTAIN model project. The objective of the SUSTAIN system is to optimally place stormwater BMP's on a site-specific basis in a watershed (Lai, et al., 2005, 2006). During the workshop, I made a brief presentation on StormWISE including a live demonstration of the software. I believe that the screening optimization capability of StormWISE can be used as a "front end" for highly detailed, site-specific facility placement models such as SUSTAIN and the Prince Georges County BMPDSS model, also developed by Tetra Tech, Inc. The results of a high-level screening model can be used to prioritize subwatersheds and land use categories for selection of BMP sites that are subsequently analyzed in great detail by a site-specific model. The feedback I received from the assembled experts to the StormWISE screening optimization methodology was quite positive.

In November, 2006, I presented a refereed paper at the American Water Resources Association Annual Conference in Baltimore, MD. The paper, entitled "A Cost Minimization Model to Prioritize Urban Catchments for Stormwater BMP Implementation Projects," was in a session on "BMP Siting and Design," which was attended by about 75 persons. Several questions were fielded after the presentation, and contacts were made with potential users of StormWISE from different parts of the country. The slides from my powerpoint presentation are included on the accompanying CDROM.

Also in November, 2006, I was the featured speaker at the monthly meeting of the Philadelphia Metropolitan Section of the American Water Resources Association in downtown Philadelphia, where I presented a talk entitled "New Cost-Benefit Model for Storm Water Management Facilities," which was attended by faculty and students from local universities, consulting engineers, Pennsylvania Department of Environmental Protection staff, and EPA Region III staff. Following this talk, I have received additional invitations to speak on StormWISE and to meet with prospective users. The slides from my powerpoint presentation are included on the accompanying CDROM.

## CONCLUSIONS

This report is submitted to satisfy the final requirements of a successfully completed, EPA funded project to develop a screening optimization model for watershed-based management of urban runoff nonpoint pollution. The project's goals and specific tasks are reviewed. The results of the project are presented as a general overview of methodology and results followed by a discussion of the activities and accomplishments of each of the project's five tasks. The last section describes how the results of this project are already being disseminated among stormwater management professionals and potential users of the model. A complete Bibliography follows. Appendices are included that contain documentation on the software (Appendix A) as well as documentation on specific events where the results of this project have been disseminated (Appendix B).



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## APPENDIX - A

### StormWISE Software Documentation

#### 1. Contents of CDROM

##### A. Stormwise\_Distribution – executable programs and example data files

###### 1. BMPFIT –

a. AMPL run, model, and data files to implement multipoint cost calibration to obtain StormWISE parameter HALF\_COST\_PER\_AREA. This is a console program. At the command prompt, type

*ampl xxx.run*

where “xxx” stands for a land use category,

for example:

*ampl commercial.run*

to display results for commercial land use category to the screen.

BMP performance and cost data can be changed by editing the file *xxx.dat* for each different land use category.

b. BMPFIT.xls – a template file for Microsoft Excel which, when used with the Excel “solver” add-in, will perform a multi-point cost calibration to obtain StormWISE parameter HALF\_COST\_PER\_AREA and also plot the results.

2. GWLF\_postprocessor – a console program to read comma separated value (.csv) files containing output from the AVGWLFL pollutant load simulation model (sediment, nitrogen, and phosphorous loadings) and generate an input (.inp) file for use by StormWISE.

AVGWLF .csv files containing summary data have the form

PROJECT-XXXX*sum.csv*

where PROJECT is the name of the AVGWLFL project and

XXXX is a code for the drainage area generated by AVGWLFL.

After generating such an output file for each of the subwatershed drainage areas in your analysis, copy them into your StormWISE project folder and at the command prompt, type

*gwlf\_postprocessor PROJECT XXX1 XXX2 XXX3 ...*

where XXXx names each of the different drainage areas to include in the StormWISE analysis. An example of the use of this program is provided in the StormWISE\_Examples folder in the StormWISE directory, and is described further below. NOTE: the file BMP.inp must be present in the same directory when running GWLF\_postprocessor, which contains a portion of the StormWISE .inp file related to BMP technologies and costs. BMP.inp can be edited to change cost and performance assumptions for BMP technologies. The source code for GWLF\_postprocessor is in the “C” programming language, and it can be recompiled from the provided source code to run on almost any computing system. Also, this program can be modified by users with C programming experience to parse the output files of other nonpoint pollution loading simulation programs.

3. npsopt\_washoff – a console program with similar capabilities to the StormWISE graphical interface program. It can read StormWISE .inp files generated manually, by GWLF\_postprocessor, and also by the StormWISE graphical interface program, described below. The .inp files contain pollutant loading and cost data. The output is an AMPL “.dat”

file that is read by the optimization module in file `npsopt_washoff.mod`. The sequence of commands is as follows:

*Notepad PROJECT.inp*  
to create or edit a StormWISE input file,  
where

“PROJECT” is the name of the current project, which is usually the name of the larger watershed being analyzed.

After exiting notepad, type:

*npsopt\_washoff PROJECT.inp*

to generate the file `PROJECT.dat` which is read by AMPL when the command:

*AMPL PROJECT.run*

is typed at the console. The file `PROJECT.run` must be edited to contain the name of the correct data file, `PROJECT.dat`. An example from Swarthmore College’s Springfield project is provided in this folder. The AMPL output, containing optimal investment levels by land use category and subwatershed drainage area, is displayed to the screen by default. Output can be redirected to a file as follows:

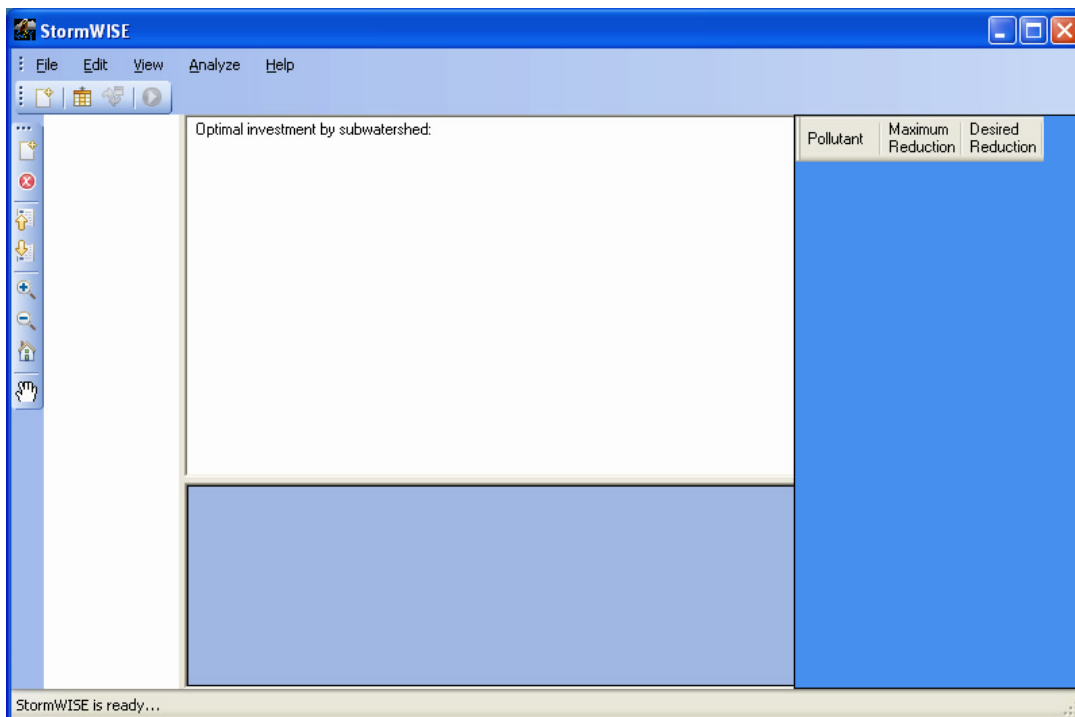
*AMPL PROJECT.run > PROJECT.txt.*

This file can be opened by Notepad and printed, if desired, or copied and pasted into a word processing document.

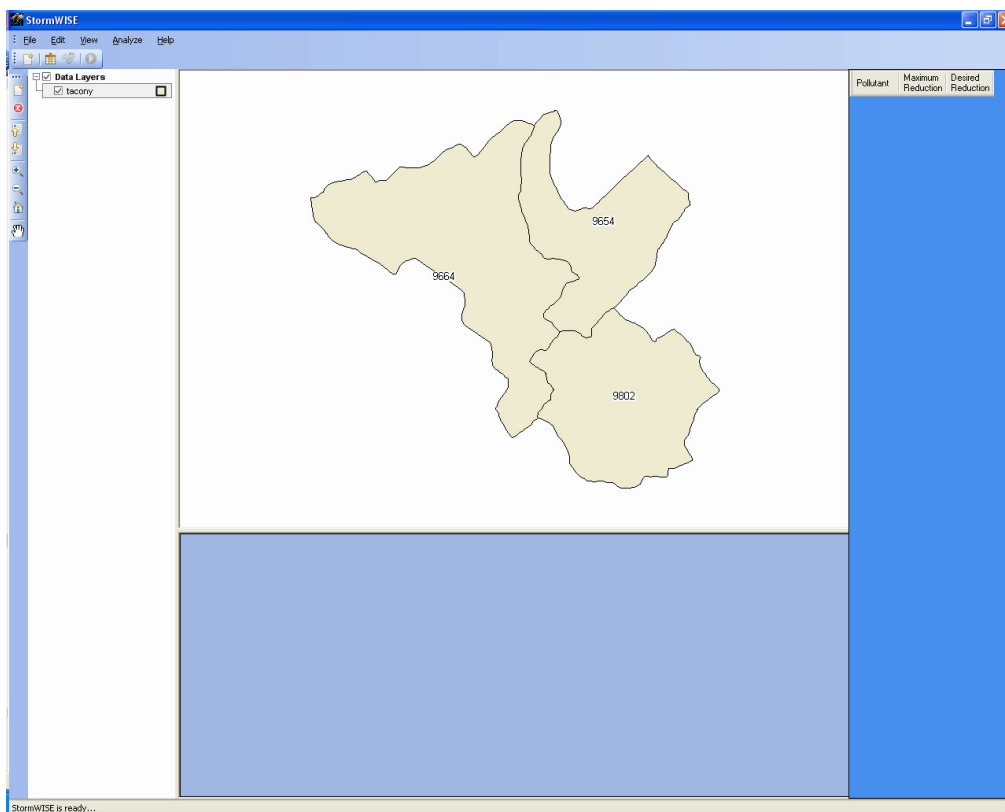
**4. StormWISE** – a graphical and GIS user interface program containing all of the functionality of `npsopt_washoff` with an easy to use interface and the option to display results on a map showing the subwatershed drainage areas. Editing of `.inp` files can be accomplished using data grid tables similar to a database or spreadsheet program. If GIS “shape” files are not available containing maps, a “pie” chart is automatically generated to display results graphically. A data grid table displays optimization model results in both cases. The user can easily modify assumptions and data such as the amount of pollutant reduction desired. Typically the user will generate a sequence of results, each for a different level of pollutant load reduction, and the cost implications of each selection will be displayed. The color-ramp output on the GIS map or the pie chart helps the user to quickly identify those subwatershed drainage areas that should be targeted to locate BMP implementation sites.

**NOTE:** StormWISE graphical and GIS interface requires that Microsoft “DotNET 2.0” be installed on the users computer. The DotNet modules may already be installed to support other software installed on the computer. Also required is the MapWindow public domain GIS interface. Users of the EPA modeling system BASINS 4.0 may already have MapWindow installed. Installation programs “DotNET Installer.exe” and “MapWinGIS Installer.exe” are included in the StormWISE folder. Before running StormWISE, the entire StormWISE folder should be copied to the user’s computer to a hard drive location such as drive C:\ for a permanent installation, or perhaps to the user’s desktop for simply testing capabilities of the software. Installing StormWISE itself does not require running a special installation program.

Start StormWISE by double clicking on the `StormWISE.exe` file in the StormWISE folder. A shortcut to this file can be placed on the desktop or on the Program menu, if desired. The user is greeted by the opening screen, shown below.



An array of menu options and tool bar shortcuts is provided along the top. Along the left is a tool strip for the GIS displays. Using File/Add GIS Layer, or clicking on the Add Layer tool allows the user to navigate to the location of a GIS “shape” file containing a map of the drainage areas. The three drainage analysis from the “Tacony” example is shown below.



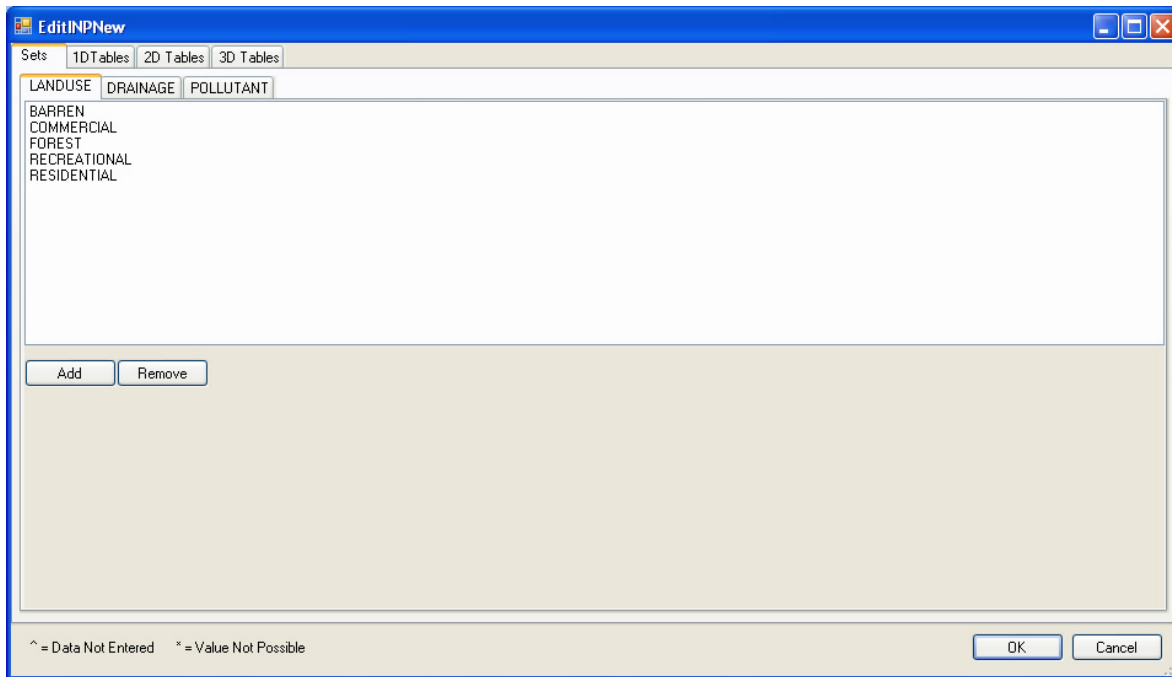
The GIS shape files are found in the folder Tacony\_GIS in the StormWISE\_Examples\Tacony folder.

Next, an input file is loaded. This file can be created manually using a text editor, or it can be generated automatically by GWLF\_postprocessor. Also, an empty input file, “empty.inp” is provided in the StormWISE\_Examples folder. If it is loaded, then the model data must be entered using the data grid table editing capabilities of StormWISE. The resulting input table can then be saved for future use. Data fields that have not yet been entered are indicated by the caret “^” character. StormWISE will not allow the user to solve the model until all data fields containing “^” have been replaced with valid numeric data.

Continuing with the Tacony example, “csv” files from an AVGWLF analysis of three subwatershed drainage areas (labeled 9654, 9664 and 9808) are supplied in the folder. These can be used with GWLF\_postprocessor to automatically generate an input file for StormWISE. Open up a command prompt (console) window and navigate to the Tacony folder. Enter:

```
gwlf_postprocessor tacony 9654 9664 9802
```

This will generate a file called “tacony.inp” which can be loaded by StormWISE using the menu sequence “FILE/Select INP file” (or by clicking on the select INP tool) and navigating to the Tacony folder. The data editing screen below appears:



The tabs on this screen show the four different model components of all StormWISE projects: Sets, 1DTables, 2DTables, and 3DTables. There are three different sets, LANDUSE, DRAINAGE, and POLLUTANT. LANDUSE contains the names of the landuse categories used in the current project. DRAINAGE contains the names of the subwatershed drainage areas, which are 9654, 9664, and 9802 in this case. POLLUTANT contains the names of the pollutants to be included in the analysis, in this case SEDIMENT, TOT\_N (total nitrogen) and TOT\_P (total phosphorous).

Clicking on the 1DTables tab shows subtabs for the two one-dimensional tables which contain numeric entries for the “TREATMENT\_FRACTION” and the “HALF\_COST\_PER\_AREA,” as shown below. The first is the fraction of the runoff that is captured by the water quality BMP, typically 90%. The second is the BMP cost per acre of drained area for each managed land use category. This “marginal cost” increases with the fraction of the entire acreage treated. The HALF\_COST\_PER\_AREA is the marginal cost at the point where half of the acreage in a particular land use category is managed by BMP’s. Estimates of this cost parameter are estimated from site-specific BMP cost data using the BMPFIT program, described earlier.

LANDUSE	Value
BARREN	0.9000
COMMERCIAL	0.9000
FOREST	0.9000
RECREATIONAL	0.9000
RESIDENTIAL	0.9000
*	

^ = Data Not Entered   \* = Value Not Possible

OK Cancel

Clicking on the 2DTables tab shows subtabs for two two-dimensional tables which contain numeric entries for BMP\_EFFICIENCY, as a fraction, by pollutant and land use category, and DRAINAGE\_LANDUSE\_AREA, which shows the land area, typically in acres, for each drainage area (as columns) and each land use category (as rows). Note that to exclude a particular land use category from consideration for BMP installation, simply enter zero for the BMP\_EFFICIENCY, as shown in the Tacony example, below.

^ = Data Not Entered \* = Value Not Possible

BMP_EFFICIENCY		DRAINAGE_LANDUSE_AREA				
		BARREN	COMMERCIAL	FOREST	RECREATIONAL	RESIDENTIAL
▶	SEDIMENT	0.6000	0.6000	0.0000	0.6000	0.6000
	TOT_N	0.4000	0.4000	0.0000	0.4000	0.4000
	TOT_P	0.2500	0.2500	0.0000	0.2500	0.2500
*						

Finally, clicking on the 3DTables tab shows a single three-dimensional table for POLLUTANT\_LOAD having a layer for each pollutant, and a two-dimensional table showing loadings, in appropriate pollutant loading units (such as Tons for sediment and Pounds for nutrients). The loadings, in Tons, for Sediment in the Tacony example are shown below. Note that when a particular land use does not exist in a subwatershed drainage area, a “\*” character indicates that the loading value is not possible.

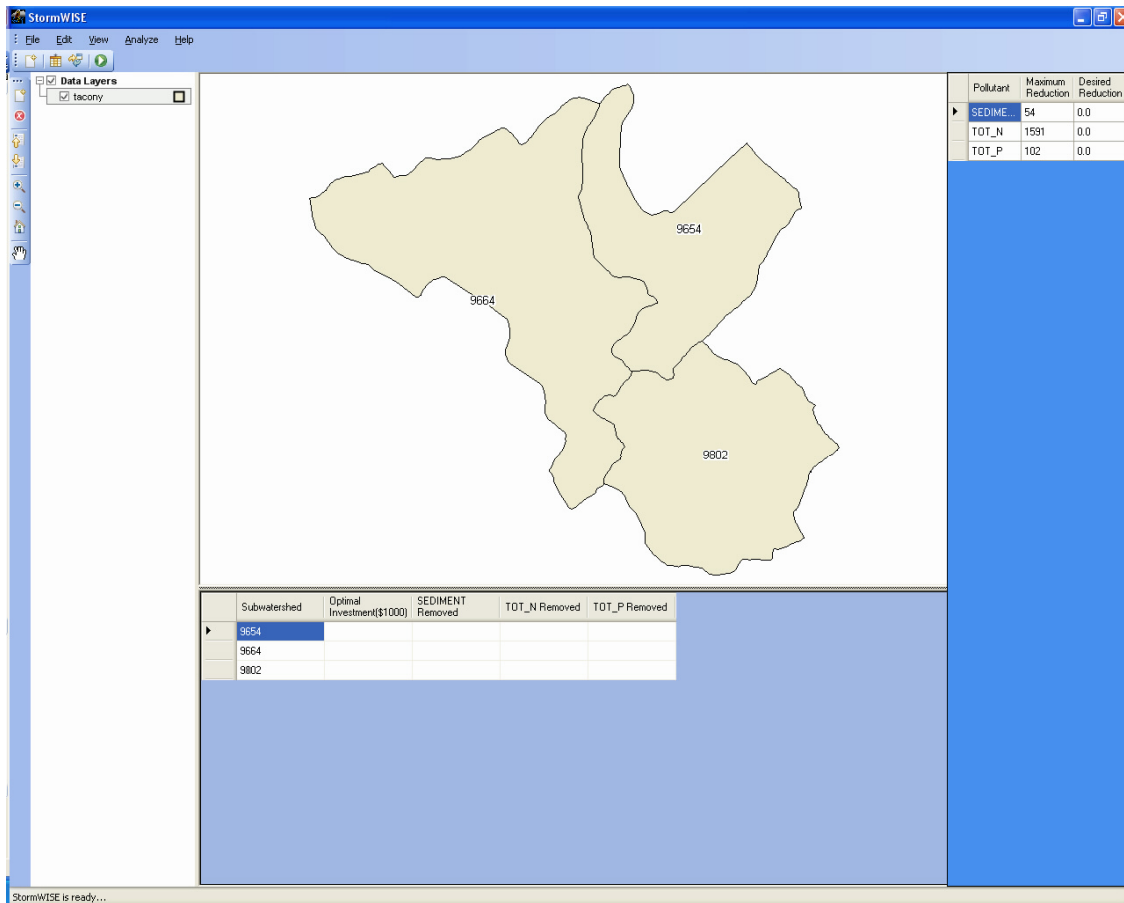
^ = Data Not Entered \* = Value Not Possible

POLLUTANT_LOAD				
SEDIMENT	TOT_N	TOT_P		
		9654	9664	9802
▶	BARREN	*	7.3200	1.0900
	COMMERCIAL	20.3700	34.7500	11.6800
	FOREST	0.0100	0.5600	0.0500
	RECREATIONAL	*	13.2884	5.5383
	RESIDENTIAL	0.7700	4.6700	0.6800
*				



All data fields can easily be changed by simply editing the numeric fields. But the user should NOT edit any of the name fields in this format. Changes to name fields must be made by clicking on the “Sets” tab, selecting the Set to be edited, and then clicking the “Add” button to create an additional landuse, drainage area, or pollutant, or by highlighting one of the existing names and clicking the “Remove” button to eliminate it from the model (be sure to highlight a name before clicking “Remove”). If a set name is added, then numeric data must be entered in all tables where that name appears in a row or a column.

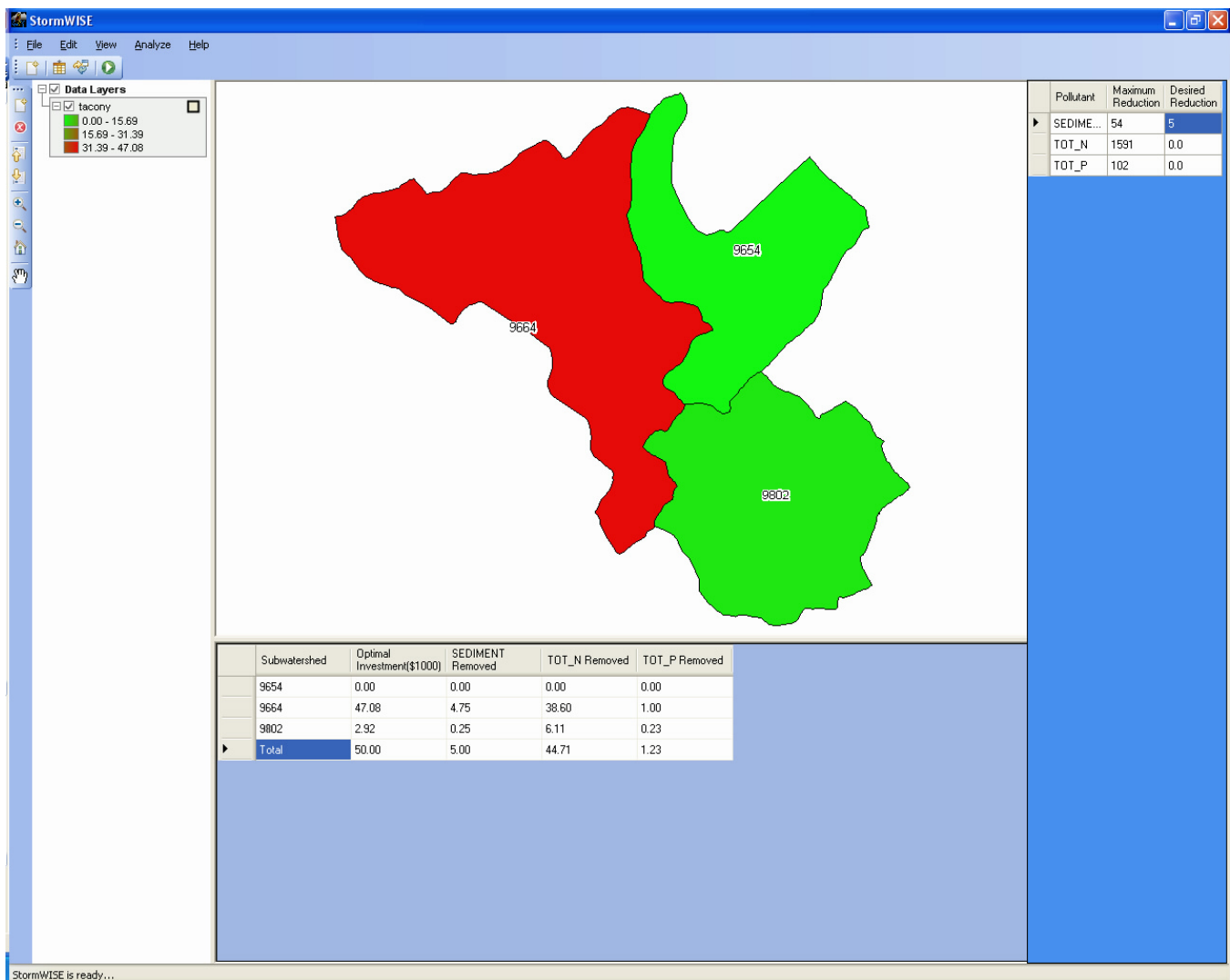
If all data fields are valid, then clicking the “OK” button in the lower right corner of the edit view will update the model with the data and return to the main screen, as shown below.



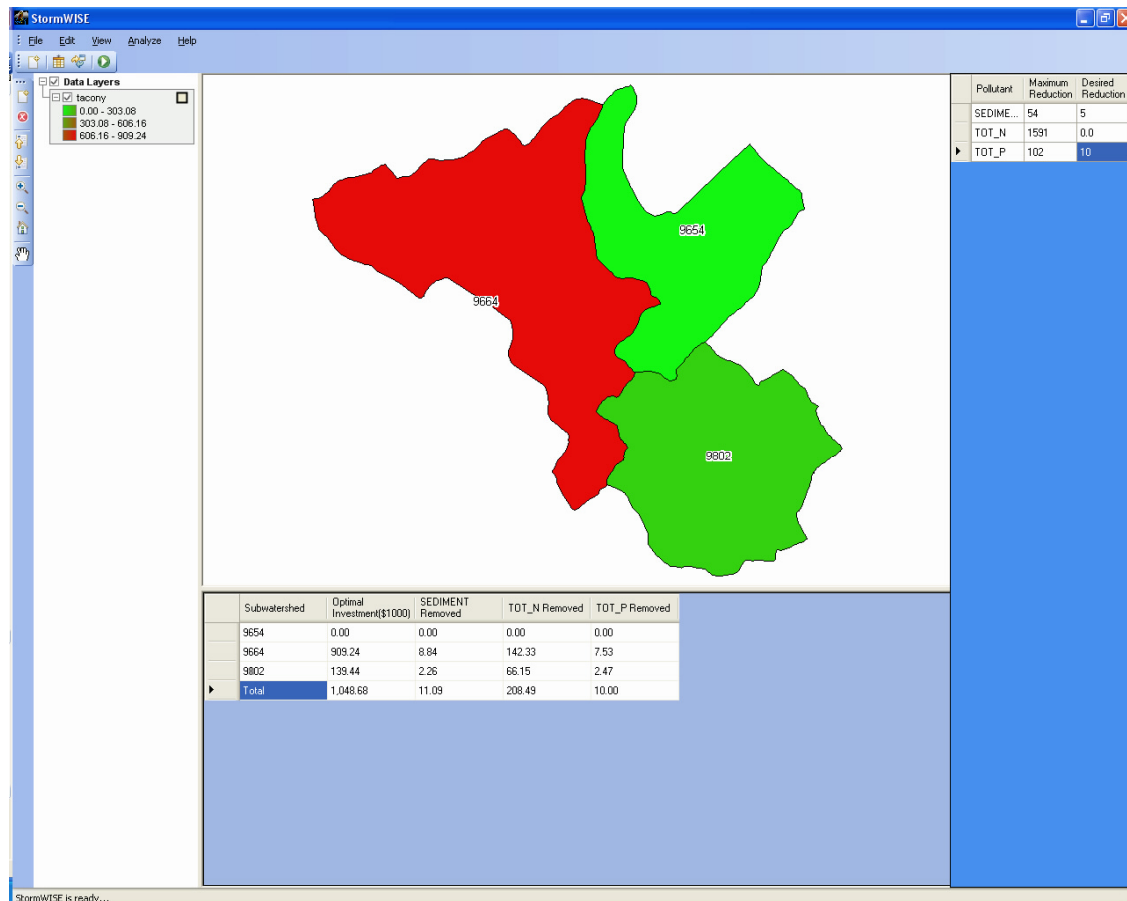
Two new tables have been added to the display: an empty table in the lower area which is prepared to receive the output of the optimization module, and a partially filled table in the upper right corner. This table invites the user to enter the pollutant reduction that is desired for the first run of the optimization screening model. If the model is run without editing this table, no pollutant reduction will occur, and no cost will be incurred. The maximum possible reduction is displayed. Entering any value larger than the maximum will also result in zero output.

The screen below shows the result when the user requests a reduction of 5 tons annually of sediment over the entire study area (i.e. from all three drainage areas). After entering a value of 5 in the “Desired Reduction” column, the user selects the menu option “Analyze/Run” or simply clicks the Run tool. The table now shows how much sediment reduction to pursue by installing BMP’s in each of the three drainage areas. The optimal investment levels (in \$1000 units) to

direct towards each drainage area are shown as well as the amounts of pollutant removal achieved by that investment. Note that although the user made no request regarding the amount of TOT\_N and TOT\_P to reduce, some reductions in these pollutants are achieved anyway because BMP's that remove sediment also typically remove nutrients. Also, note that the total cost of achieving these pollutant reductions is estimated to be \$50,000 and that most of it should be directed towards projects in drainage area 9664 and no projects should be pursued in drainage area 9654, if overall cost minimization is the only objective influencing the decision. In reality, the decisions regarding where to place BMP's depend on multi-objective considerations such as flood control, and other practical considerations. Thus, model results can not be interpreted strictly. On the other hand, these results can help watershed managers approach the very difficult problem of prioritizing projects in a way that achieves the greatest pollutant reduction for a certain level of investment. Another way of stating this result is that the model predicts that any alternative BMP investment strategy in this subwatershed would result in either a cost higher than \$50,000 to achieve the same 5 tons annually of sediment removal, or sediment removal of less than 5 tons for the same investment of \$50,000. Note that to display the color ramp on the left, the user must click on the legend at the "+" just left of "tacony."



Note that the solution above yields very little of the potential 102 pounds annually of phosphorous removal. If the user now enters the amount of 10 in the Desired Reduction column for TOTAL\_P, and runs the model again, the result is shown below.



More investments in BMP technology are required, both in subwatershed 9664 and 9802. Also, the amounts of SEDIMENT and TOT\_N removed also increase because the BMP's installed to remove phosphorous also typically remove sediment and nitrogen.

At this point, the user can save the model data in data file having the same or a different name. Also, the GIS map and the data tables can be printed out using the File/Print menu.

First-time users should open up one or more of the “.inp” files using a text editor, such as Notepad to view the format of this file. It is very similar to the format of the data grid view tables in the graphical interface. Users can manually edit these data fields, if desired. The format of the “.inp” files is not rigid regarding delimiters (other than the semicolon and braces), capitalization, and white space. However, please note that the semicolon “;” at the end of each block of data is mandatory. Deleting a semicolon or failing to use one when manually generating a “.inp” file will lead to unpredictable results. Also, all of the data components (sets, 1-d tables, 2-d tables, and the 3-d table) must be present in the file, with the titles properly spelled.

Two other example files are provided: “Empty,” described above, and “Springfield” which is based on Swarthmore College’s Springfield Township study performed for the Pennsylvania

Coastal Nonpoint Pollution Program, with a report available online at <http://watershed.swarthmore.edu>.

## **B. StormWISE Source Code**

All source code files are provided on the CDROM in the folder StormWISE\_Source which contains a subfolder “source\_090” indicating the current “pre-release” version 0.90 of the model. As soon as EPA’s review of the software is completed, final revisions will be made, and the software will be released as version 1.0.

Four folders within the folder “source\_090” contain Microsoft Visual Studio project files as well as the source code files. These are GWLF\_PostProcessor, npsopt\_washoff, npsoptclr, and StormWISE. An additional folder, “corecode” contains C++ source code files that are common to both the command line and graphical versions of the software.

GWLF\_PostProcessor is self contained code written in standard C. The source code files can be extracted and compiled by a C compiler on any computing system.

“npsopt\_washoff” is primarily a single “main.cpp” program written in standard C++. It calls functions in the “corecode” folder.

“corecode” contains modules “datablock.cpp” for structuring the input file data into blocks which are converted to sets, 1-D tables, 2-D tables, or 3-D tables by the “dataget.cpp” modules. The data structures are defined and implemented in “datacomponent.cpp”. Finally, “npsopt.cpp” provides routines for editing and assuring consistency of all data blocks. The core code is all written in standard C++, and it makes extensive use of the extremely efficient standard template library. It can also be compiled on any computing system supporting a C++ compiler, and can be made functional using “npsopt\_washoff” or another program written by future developers.

“npsoptclr” provides an interface for the core modules to the Microsoft “.NET” common language runtime (CLR) environment. It is written using Microsoft’s “managed extensions” of the C++ language which enable easy access to C++ code by other managed languages, including C# (C-sharp), Visual Basic, and J# (Microsoft’s implementation of the Java language). Microsoft’s Visual C++ 2005 software is used to compile these modules. “npsoptclr” functions as a “wrapper” for the core code modules to enable them to interact with “.NET” managed code. It’s output is a dynamic link library file, “NpsOptClr.dll” which must be present for the StormWISE program to function.

Finally, the StormWISE folder contains the code for the graphical/GIS interface. These modules are written in Microsoft Visual Basic and are compiled by Microsoft Visual Basic 2005, which is included along with Visual C++ 2005 in the suite Visual Studio 2005. Visual Basic was chosen primarily because the MapWindow GIS open source user community provides best support for programming the MapWindow environment through Visual Basic, and we were able to easily adapt modules that are distributed in the open source format for use in StormWISE. Also, the base of software developers with Visual Basic experience is

quite large, so the prospects are good that this code can be used beyond the scope of the current project through distribution in the open source community.

Future revisions and extensions of the StormWISE source code will be distributed through Swarthmore College's Watershed web site: <http://watershed.swarthmore.edu>.

## **APPENDIX - B**

### **Dissemination of Results**

- I.     **Questions on Screening Model Methodology:**  
by Tetra Tech, Inc. Staff with answers provided by A. E. McGarity, July, 2006.
- II.    **Abstract of paper presentation:**  
McGarity, A.E. “A Cost Minimization Model to Prioritize Urban Catchments for Stormwater BMP Implementation Projects,” American Water Resources Association National Meeting, Baltimore, MD, November 8, 2006.
- III.   **Abstract of invited lecture:**  
McGarity, A.E. “Cost-Benefit Model for Storm Water Management Facilities,” presentation to the Philadelphia Metropolitan Section of the American Water Resources Association, November 16, 2006.

## I. Questions on Screening Model Methodology:

by Tetra Tech, Inc. staff with answers provided by A. E. McGarity, July, 2006.

- Would a combination of various BMP types be considered as a possible solution for one land use in one subwatershed?

Yes. A fundamental and implicit assumption of the model is that watershed managers will select a combination of different BMP's costing different amounts. In fact, I assume that watershed managers will make OPTIMAL decisions in this regard. But since StormWISE is a "top-down" model rather than "bottom-up", the exact details of which BMP's are chosen for specific sites are not explicit in the model. In my Coastal Zone study, before I developed the multi-point "calibration" (BMPFIT - see below), I specified a single BMP to use as a single-point calibration at the mid-point of a nonlinear curve. I matched up the MARGINAL cost of a specified "median" BMP with the SLOPE of a nonlinear cost curve at the point where 50% of the land area for each land use is "treated". But that does not mean that I assumed only one BMP technology would be used exclusively for each land use. The mathematical form of the treatment cost function I'm using imposes a smoothly increasing marginal cost on each land use as the pollutant removal levels increase. The results from "bottom-up" optimizations that I have seen show the same kind of behavior, except, perhaps, for the "smoothness". Of course, in reality, BMP deployment is discrete and actual cost functions will look more like stair-steps. But StormWISE is a screening model with the goal of advising watershed managers about generalized stormwater management priorities such as where in the watershed they ought to spend their valuable time searching for cost-effective projects that are most likely to return the most bang (pollutant removal) for the buck (long-term capital investment). For this context, we need a method which, although idealized, can approximate costs of multiple projects over drainage areas much larger than a single site.

- What is the "multi-point" calibration method for BMPFIT model?

The method I'm calling BMPFIT extends the single point calibration described above to enable the costs of other BMP's applicable to each land use to be used in obtaining the nonlinear cost functions to be used in the screening optimization. The mathematical form I am using for the cost function is quite simple and well behaved for the purposes of nonlinear optimization. I call it a "saturation function" because it is used extensively to model chemical and biological processes that experience declining activity as the level of some resource approaches a saturation level. When we plot pollutant removal at the watershed level versus dollars invested in "treatment" we observe the same kind of phenomenon. The function is  $f = x/(h+x)$ , where  $f$  is the fraction of land treated (and approximately, the fraction of untreated pollutant's removed by all BMP's installed so far),  $x$  = the amount invested so far in \$ or \$K, and  $h$  = the half-saturation constant, which is the investment resulting in half of the land area (of each land use) being treated. I elaborate on the selection of this function in my "Phase 1 Report" for the Coastal Zone study of Springfield, PA which is available as a downloadable PDF file on my web site: <http://watershed.swarthmore.edu>. See pages 20-21 of the full report.

Since the mathematical form is so simple (a single parameter), it is possible (mathematically) to use just a single data point to fully specify the function. However, the specification of that point requires judgment regarding which BMP to use for the calibration and at what treatment fraction. For example, in the Coastal Zone studies, I calibrated using infiltrating bioretention at the 50% subwatershed treatment point for residential and commercial land uses and grass swales at the 50% subwatershed treatment point for recreational and barren land

uses. I made these decisions based on close consultation with Springfield Township's environmental advisory committee and stormwater management staff.

Now, in BMPFIT, I am allowing several BMP's to be specified as well as the subwatershed treatment percentage at which they would likely be deployed, based on the judgment of the watershed manager, who I assume has some knowledge of such things. The order of BMP deployment is determined by the marginal costs, which can be calculated fairly easily from site specific data. The least expensive is deployed first, up to a certain land use treatment percentage, followed by the second least expensive up to its limit of applicability, and so forth. Since the order is based on data in the literature from previous projects, the "judgment" calls are limited to specifying the treatment percentages that will likely apply for each BMP deployed in each land use. I believe that there are potential users of StormWISE who will be able to do a reasonable job of specifying these levels, but I will greatly appreciate hearing what others think about this matter. Technically, the methodology used by BMPFIT is nonlinear curve fitting, minimizing the sum of the ABSOLUTE deviations (rather than least squares) so as to minimize the negative effects of any outliers.

The attached PDF file shows two examples of BMPFIT for commercial and residential land uses. NOTE: the graphs do not identify the BMP's used in the calibration. They are, in order of increasing marginal costs: (1) wet detention ponds, (2) constructed wetlands, (3) infiltration basins, (4) infiltration trenches, (5) grass swales, and (6) bioretention. The marginal costs are calculated from site specific data obtained from the Center for Watershed Protection's web site. Note: The \$/acre costs on the first two graphs are marginal costs: \$/treated acre whereas the \$/acre costs on the third graph are average costs over the entire land use area, some treated, some not treated. Multiply these numbers by the total land area in each land use to get total amounts invested in a specific drainage area.

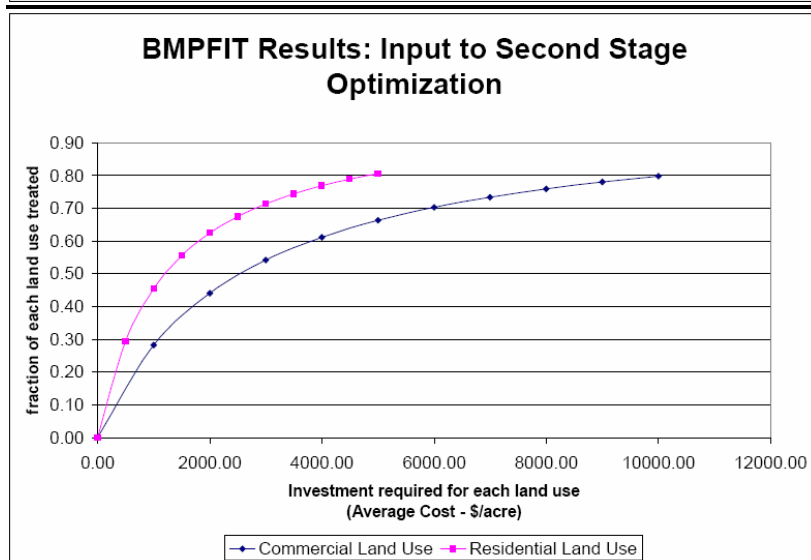
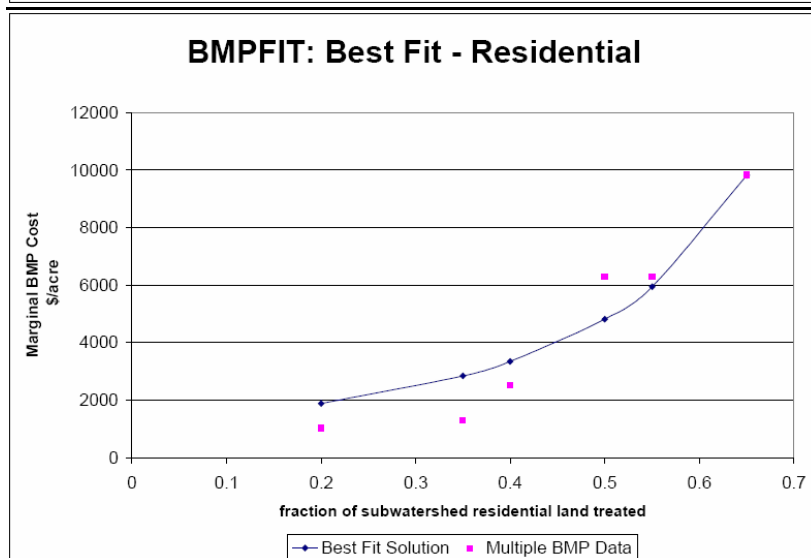
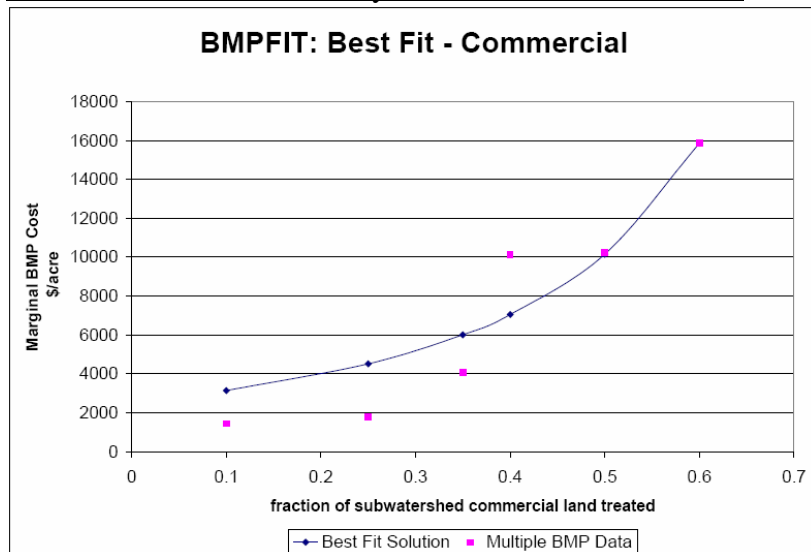
- It seems that the subwatershed-level pollutant-removal/cost functions is related only to land use. Would soil property be considered as a factor in the pollutant-removal/cost functions development?

Presently, soil properties are considered in determining costs through their effects on average BMP efficiency. In the Springfield, PA study, we had to deal with a high clay content soil over just about the entire area, with minimal soil variations. If the model is applied to an area with much soil variation (or to a much larger region, where such variations are likely to occur) then this could be a limitation of the present model formulation. However, it would be easy, conceptually, to add soil classification as another category in the analysis, and I will investigate extending the model in this way. The number of decision variables would increase causing the size limitations of low-cost or free optimization solvers to become relevant. So, expanding the model in this way could force the user to purchase solver software to handle the larger model. However, see my narrative under the heading TASK 4 in my recently completed third quarter progress report (attached) for some promising developments in the world of public domain nonlinear solvers.

- What's the optimization problem formulation for the NPSOPT model?

The second stage optimization formulation has not changed significantly since I wrote the Coastal Zone Phase I report which is on my web site: <http://watershed.swarthmore.edu>. See Section 3 of the full report, which begins on page 27.





## II. Abstract of paper presentation:

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AWRA 2006 ANNUAL WATER RESOURCES CONFERENCE

Baltimore, MD  
November 6-9, 2006

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### **A COST MINIMIZATION MODEL TO PRIORITIZE URBAN CATCHMENTS FOR STORMWATER BMP IMPLEMENTATION PROJECTS**

Arthur E. McGarity \*

**ABSTRACT:** Watershed managers, stewardship organizations, and government funding and regulatory agencies have the problem of selecting sites for projects that implement stormwater best management practices (BMP's) for reducing nonpoint source (NPS) loadings. This problem is particularly difficult to solve in heavily developed areas where NPS loading reductions must be achieved through a combination of nonstructural management and educational programs and retrofit structural BMP's. This paper presents a mathematical optimization model that can be used to help decision makers identify high priority BMP implementation projects in urban areas. Prioritization is accomplished by specifying desired NPS pollutant load reductions in the watershed and then solving the model to find solutions that minimize the total BMP cost over the area. This model works in concert with a user-selected nonpoint pollutant loading model and a nonlinear solver to generate its results. The model, named StormWISE (Storm Water Investment Strategy Evaluator), is implemented in two stages. The first stage, BMPFIT, generates nonlinear cost functions for delineated catchments within the study area using a multipoint calibration incorporating cost data from the literature for the various BMP options that are suited for the catchment. BMP options include bioretention, infiltration filters, green roofs, street sweeping, constructed wetlands, permeable pavement, community education programs, etc. The second stage, NPSOPT, generates optimal levels of investment in BMP projects for each catchment and landuse category, which can be used to develop rankings. An example of the model's application in the Philadelphia metropolitan region is included. The model's results provide a scientifically and economically sound basis for setting priorities in BMP implementation programs. This model does not attempt to assign projects to specific land parcels, since many other factors besides cost and pollutant loadings must be considered at the site level, and because watershed pollutant loading models do not usually have sufficient resolution. However, the model does provide valuable guidance to decision makers that can help them narrow the search for specific BMP sites and to rank competing proposals for site-specific BMP projects. The model also has potential applications in total maximum daily load (TMDL) implementations where it is important to minimize the regional costs of satisfying regulatory requirements.

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### **III. Abstract of Invited Lecture**

From: AWRA-Philadelphia  
Sent: Friday, November 03, 2006 2:56 PM  
Subject: AWRA-PMAS November 16th Meeting - "New Cost-Benefit Model for Storm Water Management Facilities"

American Water Resources Association - Philadelphia Metropolitan Area  
Section

We hope you'll join us for our November meeting! Register to attend by reply to this e-mail and completion of form below.

When: Thursday, November 16, 2006, 11:30 - 1:30

Where: 1515 Arch Street, 18th Floor (Photo ID required to enter building) Philadelphia, PA

Featured Speaker:  
Arthur McGarity, Professor of Engineering and Coordinator of the  
Environmental Studies Concentration, Swarthmore College

Topic:  
" New Cost- Benefit Model for Storm Water Management Facilities"  
Regulatory controls for storm water management are becoming more stringent, while the cost of compliance is also increasing. There are many new methods (Best Management Practices and Low Impact Development) available to control the quantity and quality of storm water runoff.

A new stormwater management model, named stormWISE, has been developed at Swarthmore College that combines economic considerations with nonpoint pollutant loading. This "optimization screening model" can be used to determine which subwatersheds and land-use categories within a watershed should receive priority for installation of storm water management facilities.

Become a member of the AWRA-PMAS at any of our meetings.  
Visit our website: <http://www.awra.org/state/philadelphia>