The StormWISE Model: Prioritizing Subwatersheds and Land-Uses for Stormwater BMP Implementation.

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Abstract

StormWISE (**Storm W**ater **I**nvestment **S**trategy **E**valuator) is a new model for prioritizing stormwater BMP implementation projects on the basis of their costs and pollutant load reduction benefits. It is the result of more than a decade of water quality monitoring and computer-based modeling at Swarthmore College on nonpoint pollution from stormwater runoff in urban watersheds. StormWISE is designed for modeling at a high level of aggregation, and, as a result, the data input requirements can be kept fairly reasonable. Pollutant load estimates, aggregated by subwatershed, are obtained from a loading model such as AVGWLF or SWMM, or, if available, from monitoring data. Site specific BMP cost data are used to calibrate watershed-level cost-performance functions by equating marginal costs at multiple points on the BMP implementation saturation curve for each landuse category. An entire watershed is modeled, and the output displays those subwatersheds and landuse categories where the greatest effort should be applied to locate specific sites for BMP implementation projects that will obtain, at minimum cost, the required pollutant reductions. StormWISE is free and open source, and it includes, built in, the free MapWindow GIS display interface. StormWISE can be downloaded from http://watershed.swarthmore.edu.

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Introduction

This paper provides guidance on the application of the StormWISE model for the benefit of potential users. StormWISE is designed to assist watershed managers in their search for BMP implementation sites. The model 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. The model, named StormWISE, for Storm Water Investment Strategy Evaluator, is designed to generate 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 variation 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.

Background

StormWISE was developed as part of a research program 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, 2004), two research projects funded by the federal Coastal Zone Nonpoint Pollution program (McGarity and Horna, 2005a, 2005b and 2005c), and a cooperative agreement with the U.S. Environmental Protection Agency (McGarity, 2006a). These reports are available for download from http://watershed.swarthmore.edu. The theory underlying the model is described in the Coastal Zone and EPA reports, and in recent conference proceedings (McGarity, 2006b and 2006c).

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. Presently, we are building upon experience gained from applying StormWISE in suburban Philadelphia by extending the model for use by urban watershed managers in other areas of the country.

Recent development activities on StormWISE have addressed the following goals: (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) examination of 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. Significant progress has been made in each of these areas during the previous two years. Version 1.0 of the software is now available for free download, with source code. Also, the model's GIS capabilities are activated using the royalty-free MapWindow system developed at the University of Idaho.

BMP Cost 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 stormwater runoff. 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].

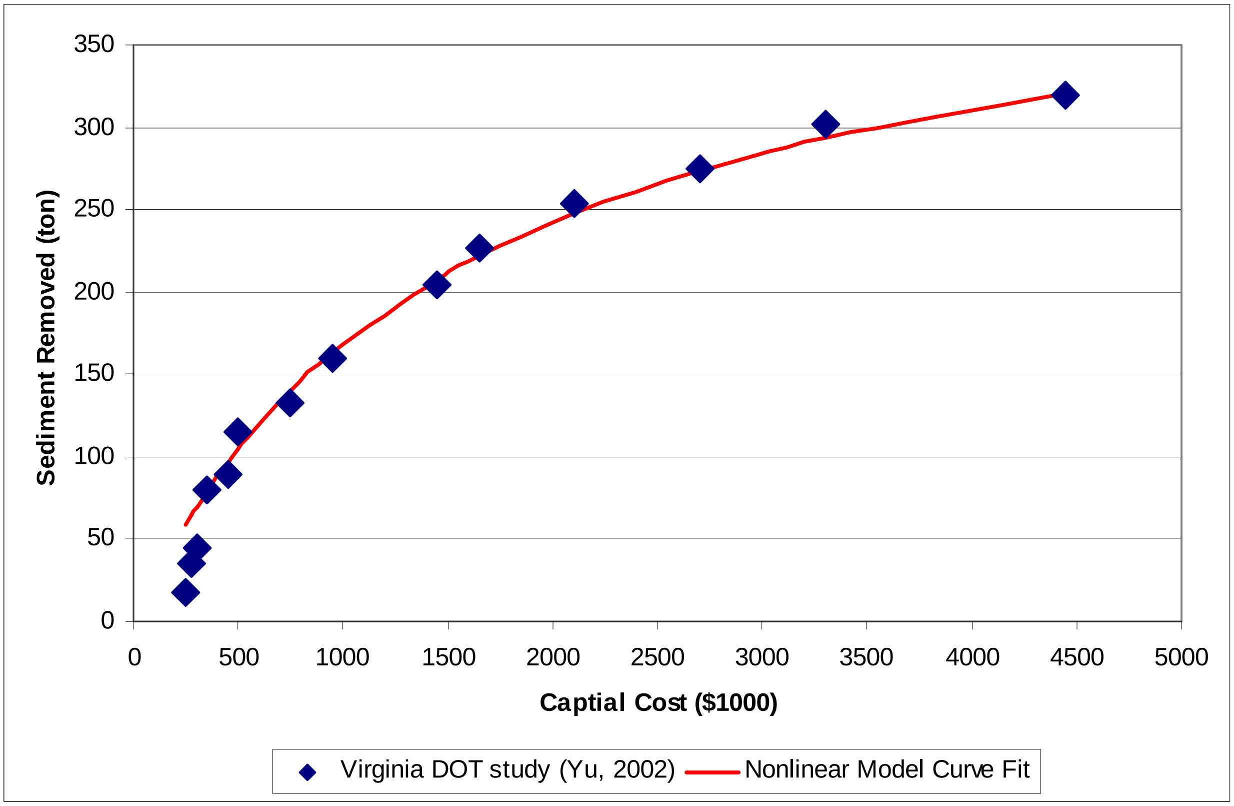


Figure 1. Langmuir surface saturation equation fit to data from results of an optimal BMP placement model developed by Yu, Zhen, and Zhai (2002) in a watershed-based study of BMP placement for minimization of cost. (Figure taken from McGarity and Horna, 2005, with permission)

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:

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

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.

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

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 (eg. 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)

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).

Calibration of Watershed BMP Cost Functions

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).

The methodology for constructing watershed-based cost functions has been 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:

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

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:

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

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 $i = 1,2,\ldots,m$ 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:

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

Subject to:

$$y_i^{'} = \frac{h}{(1 - f_i)^2} \qquad i = 1,2,\ldots,m$$

$$-e_i^- \le y_i^{'} - y_i \le e_i^+ \qquad i = 1,2,\ldots,m$$

$$0 \le f_i - f_{i-1} \le u_i \qquad i = 1,2,\ldots,m$$
$$e_i^+, e_i^-, f_i \ge 0 \qquad i = 1,2,\ldots m$$

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. An example of the application of BMPFIT to commercial and residential land uses is shown in Figure 2.

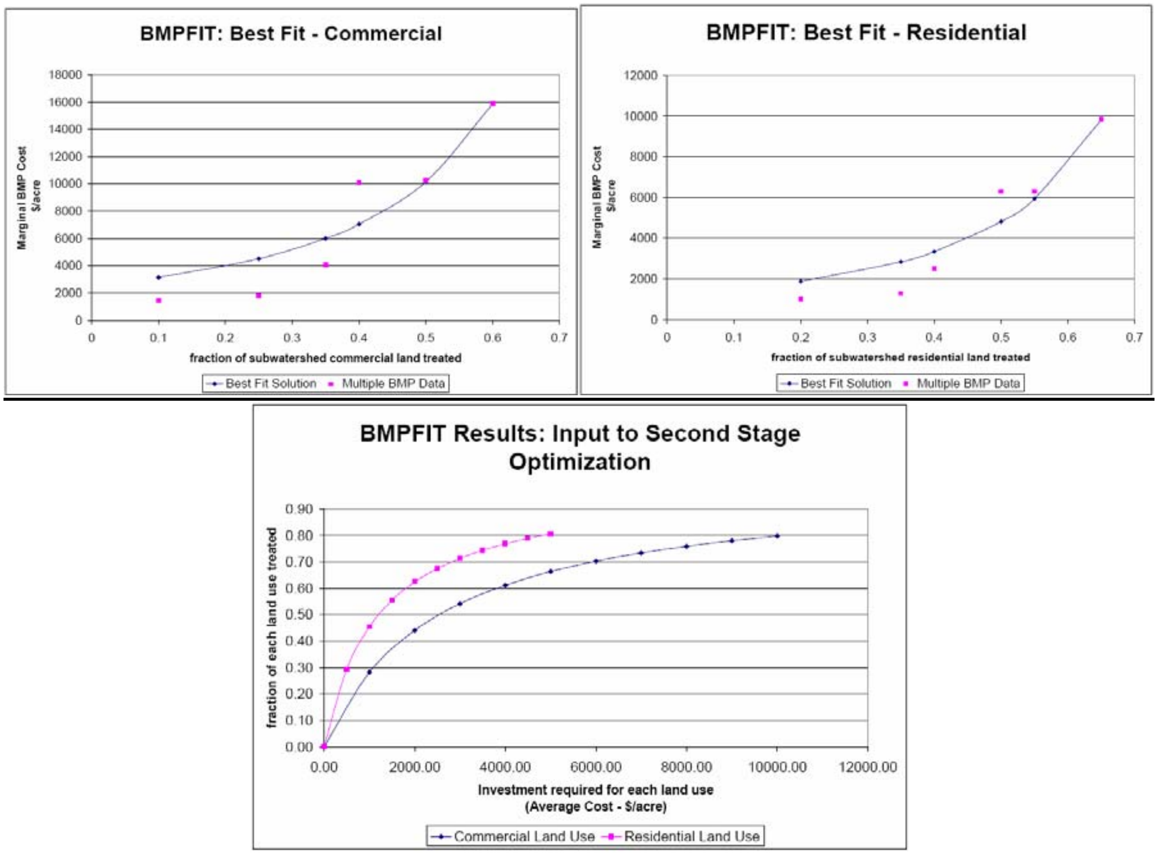


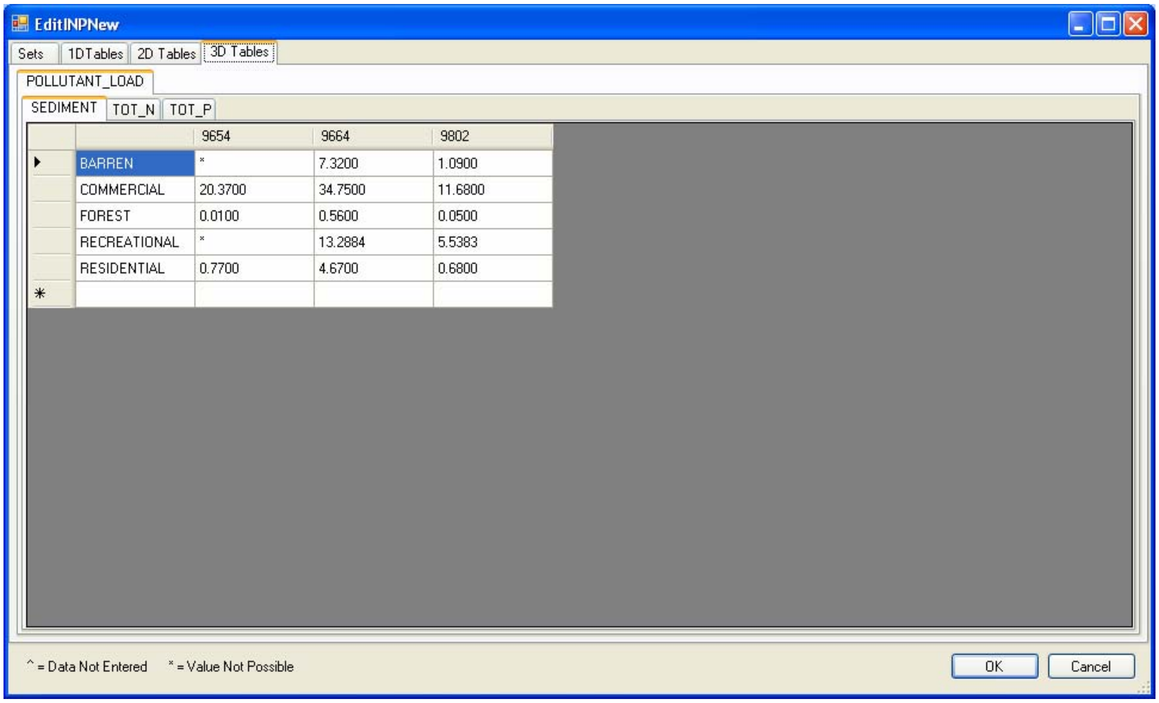
Figure 2. Marginal costs ($/acre) from several different BMP technologies are used to determine the best fit values for the half-cost "h" for both commercial and residential land-use categories (upper plots) and these half-costs are used to generate saturation curves that demonstrate how StormWISE models BMP costs.

StormWISE Model Example and Screenshots

Sample applications of StormWISE are provided with the download package. Excerpts from the Tacony example are shown here. Runoff and nonpoint pollutant loadings from Tacony Creek in Northeast Philadelphia were modeled using the AVGWLF model (Evans, et al., 2004), which is a GIS-based implementation of the GWLF model (Haith, 1987).

Only three subwatersheds were delineated for this example to keep the level of detail manageable for a tutorial. However, applications of StormWISE will typically involve many more subwatersheds. The only limitation on the number of drainage areas that can be modeled is the capability of the optimization solver that is used. StormWISE is distributed with the free version of the AMPL optimizer (Fourer, et al., 2003) which can handle up to 300 variables and constraints. Users have the option to purchase the commercial version of AMPL which can handle a virtually unlimited number of variables. The number of variables required depends on the number of pollutants, land-uses, and subwatersheds. For example, with the free version of AMPL, with three pollutants and five land-uses, a total of 15 subwatersheds can be handled. Decreasing the number of pollutants increases the potential numbers of land-use categories and subwatersheds.

Data Input and Editing. A utility program called GWLF_postprocessor, distributed with StormWISE, is used to automatically generate the StormWISE input file. The screenshot in Figure 3 shows one layer of a three-dimensional table used to display and edit pollutant loadings for each land-use category in each of the three numbered subwatersheds that were delineated for this example. The loadings, in Tons, for Sediment in the Tacony example are shown. 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. The user can manually edit these and all other input data to the model using such tables.



	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

^ = Data Not Entered * = Value Not Possible

Figure 3. StormWISE Pollutant Load Data Input and Editing Screen

Display of Model Output With or Without GIS. Figure 4 shows the output screen 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.

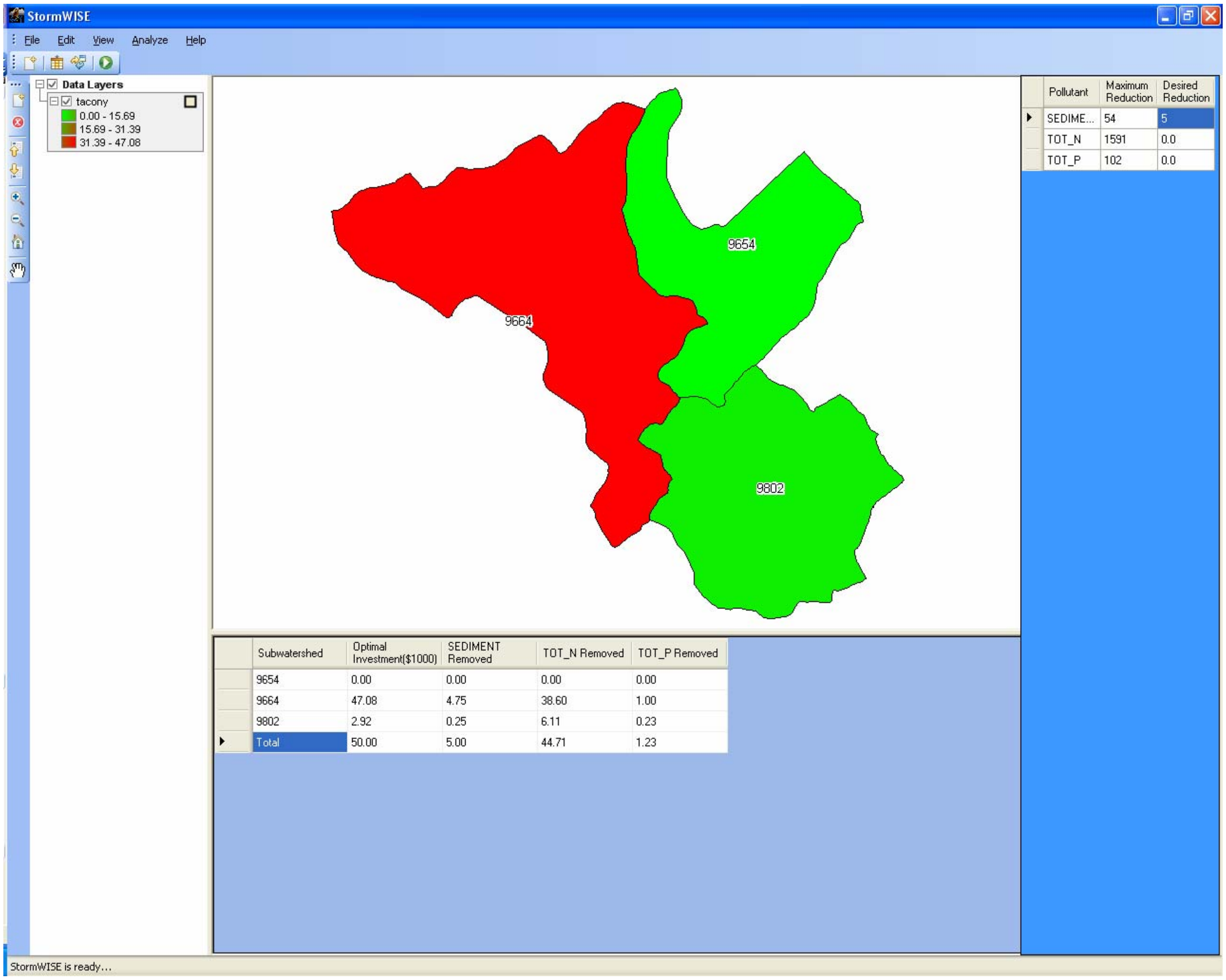
The display can be modified to show results for each specific land-use category and for any combination of land-uses. Also, if GIS "shapefiles" are not available for the study area, StormWISE will display the results as a simple "pie" diagram.

Summary and Conclusions

The StormWISE model, which has been under development for the past four years, is now available as in a software package for the Windows operating system which can be downloaded for free. It is distributed under the Mozilla Public Software agreement, which allows royalty-free use of the software, as well as access to the source code. The software provides a graphical user interface and includes GIS display of model output.

StormWISE is useful to watershed managers who want to approach BMP site selection problems strategically from a watershed perspective. It provides guidance on which drainage areas (subwatersheds) and land-use categories should be given priority for locating BMP implementation projects that control stormwater quantity and quality based on desired watershed-wide sediment and nutrient loading reductions and minimization of BMP costs.

A community of StormWISE users is beginning to emerge in the field of watershed management. This paper provides guidance to potential users who want to understand more about how the model works and about the range of problems to which it can be applied.



Pollutant	Maximum Reduction	Desired Reduction
SEDIME...	54	5
TOT_N	1591	0.0
TOT_P	102	0.0

Subwatershed	Optimal Investment($1000)	SEDIMENT Removed	TOT_N Removed	TOT_P Removed
9654	0.00	0.00	0.00	0.00
9664	47.08	4.75	38.60	1.00
9802	2.92	0.25	6.11	0.23
Total	50.00	5.00	44.71	1.23

Figure 4. StormWISE Prioritization Output Screen with GIS display

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