

ABSTRACT

Title of Document: Optimization of Best Management Practices for Watershed Planning in the State of Maryland

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Increases in nutrient loading are an on-going problem in many watersheds including the Chesapeake Bay watershed. Best management practices (BMPs) are used to reduce loadings to watershed tributaries. However, budget constraints often make determining the most effective nutrient load reducing BMP set a complex task. This study demonstrates a systematic approach to the BMP planning process by using deterministic optimization methods to find optimal BMP plans given a set of pre-existing loading and budget constraints. A geographic information system is used as a spatial computation and user interface tool to help perform these optimizations. The model that is developed and presented is used in a series of simple experiments to determine characteristics of optimal BMP plans. These experiments showed that optimal BMP plans can be more effectively developed by relying on numerical optimization methods than by using decisions made intuitively by experts.

OPTIMIZATION OF BEST MANAGEMENT PRACTICES FOR WATERSHED
PLANNING IN THE STATE OF MARYLAND

By

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Thesis submitted to the Faculty of the Graduate School of the
University of Maryland, College Park, in partial fulfillment
of the requirements for the degree of
Master of Science
2007

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Acknowledgements

I would like to acknowledge the Chesapeake Bay Program for providing both data and insight into the role BMPs play in water quality management in the Chesapeake Bay watershed. I would also like to thank the thesis committee, Dr. Kaye Brubaker, Dr. Richard McCuen, and Dr. Glenn Moglen for providing their time and advice. Most importantly, I would like to express my gratitude to my advisor, Dr. Glenn Moglen, for the time and effort he spent guiding me through my thesis research.

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Chapter 1: Scope and Background

1.1 Introduction

The state of Maryland is primarily located within the Chesapeake Bay watershed on the eastern seaboard of the United States. The Bay provides the economic, environmental, social lifeblood for the state. More than ninety percent of the state lies within the Chesapeake Bay's 64,000 square mile watershed.

Because of the significance of the Bay in the everyday life of the state of Maryland, its health is essential to the health of the state and is, therefore, a primary concern for state and federal agencies. The Maryland Department of the Environment (MDE), the Maryland Department of Natural Resources (DNR) and the United States Environmental Protection Agency (USEPA) through the Chesapeake Bay Program currently facilitate Bay-related programs and studies throughout the Chesapeake Bay watershed.

1.2 Value of the Research

The health of the Bay is dependent on what happens upstream in its tributaries. A number of Chesapeake Bay-related projects focus on these tributaries for pollutant reduction projects through the use of best management practices (BMPs). While emphasis on a healthy Chesapeake Bay watershed is paramount for many Marylanders, the budgets for state agencies working to keep the Bay and its watershed healthy are limited. Therefore, it is necessary that each Bay-related project be cost-efficient. Creating a BMP

optimization tool for planning the implementation of BMPs will help environmental planners create cost-efficient BMP strategies to control pollutant loadings in Chesapeake Bay tributaries. The automation built into the tool will allow environmental planners to create these plans more systematically, accurately, and efficiently than before.

1.3 Scope of the Research

The goal of this thesis is to develop and produce a tool to create optimal best management practice plans for watersheds and other study areas in the state of Maryland. The tool will assume a set of loading conditions and a set of BMPs (although these sets can vary depending on user input). As an extension of the tool development, certain measures of performance of the BMP Optimization Tool including the cost versus overall pollutant reduction relationship will be examined under different conditions including different physiographic regions, different land use distributions, and different sets of BMPs. Furthermore, the frequency with which certain BMPs are chosen as part of the optimal set will be examined for the purpose of establishing a system of ranking BMP types.

1.4 Use of the Research

Using funds in the most efficient manner possible is important. By developing a computational tool that finds the best plan from a quantitative perspective, BMP planners can identify plans that can achieve pollution reduction and satisfy budgetary limits. The notion of the optimal BMP plan is from a planning level perspective only. This is the

level at which the tool is designed to be used. The optimal plan delivered by the BMP Optimization Tool to be developed in this study would most likely not be implemented verbatim. Rather, it serves as a guide to developing a comprehensive BMP plan that satisfies the real-world constraints of limited budgets and regulatory needs

1.5 Background

Given an area of land or a watershed divided into parcels of land, each with a certain land use, an approximation of each parcel's pollutant load contribution can be determined via multiplication by established land use-specific loading rate coefficients. When summed across all land uses in the given area, the total pollutant loadings for the study area can be determined.

One of the primary goals of water quality agencies is pollutant load reduction from pollutants on the land, specifically through the use of BMPs. These BMPs vary in reduction performance and come in a variety of types. The goal of many water quality and environmental groups is to deploy these BMPs in a cost-efficient manner. In some cases, the goal takes the form of the question, "how can we meet predetermined water quality goals for a minimum cost?" In other cases, the question is the complement: "how can we allocate our given budget to reduce pollutant loadings as much as possible?"

For either question, the answer focuses on three key components:

- 1) What types of BMPs should be used?
- 2) How many acres should each type of BMP treat?
- 3) Where should these BMPs be deployed around the study area in question?

For most agencies, the sheer volume of choices quickly makes the problem quite complicated. Environmental agencies may have 50-100 approved BMPs that can be used in their jurisdiction. Each BMP has a specific set of rules on how and where it can be applied as well as a different efficiency for each type of pollutant it is designed to remove. Furthermore, study areas can be as small as a single acre or as large as several thousand square miles, thus limiting the detail with which the problem can be examined by hand.

1.6 Problem Definition (Objectives and Boundaries)

The thesis will develop a way to manage BMP performance information and to generate a solution method that will create optimal BMP plans for study areas of all sizes and any set of BMPs. Specifically, the objectives are:

- 1) To formulate best management practice planning as an optimization problem
- 2) To incorporate facets of best management practice planning and evaluation native to the state of Maryland into the problem

- 3) To identify mathematical and logical strategies to solve the optimization problem
- 4) To solve problems of four different types
 - a. Minimize cost subject to loading constraint(s) given a discrete set of possible BMPs
 - b. Minimize loading(s) subject to a budget given a discrete set of possible BMPs
 - c. Minimize cost subject to loading constraint(s) in a generalized approach to BMP implementation
 - d. Minimize loading(s) subject to a budget given in a generalized approach to BMP implementation
- 5) To perform a series of simple experiments using the optimization tool to look for trends of optimal best management practice plans in the state of Maryland.

The BMP Optimization Tool will employ existing land conditions, use those conditions with a set of loading coefficients to simulate existing pollutant loads and then output the optimal BMP plan with the type, size and location of each BMP used. The specifications of the optimal plan are that it meets the predetermined set of water quality standards for minimum cost or meets a predetermined budget and produces minimum loadings, depending on the situation.

The BMP Optimization Tool should be able to find the global optimal BMP plan as long as deterministic methods (such as linear or non-linear programming) are used.

Furthermore, the tool should be robust enough to handle different sets of BMPs, study areas, pollutants, and loading coefficients so as to allow it to be used in different jurisdictions within the state of Maryland and possibly other geographic locations.

Chapter 2: Previous and Current Research

2.1 Introduction

This chapter provides the background for the research documented in this paper. The following sections will describe what water quality is, define Best Management Practices (BMPs) citing some of the more important papers on the topic as well as document efforts made by federal agencies as well as state and local agencies in Maryland to improve water quality via BMPs. Finally, a brief summary of previous research seeking to integrate BMP planning with mathematical optimization will be given.

2.2 BMPs and Water Quality

2.2.1 Water Quality

The health of any watershed can be tied to measurements of its water quality. Water quality metrics seek to quantitatively describe the health of the water via levels of materials in the water, both good and bad. Examples of these materials are biota such as algae, plankton and fish, inorganic chemicals such as zinc, lead and iron, and some of the most common indicators, such as nitrogen and phosphorus. An additional important indicator is the level of sediments suspended in the water. Sediment levels affect other indicators and are therefore, very important to measuring the health of a waterway.

Indicators are often measured in two ways: on a micro level as a concentration (grams/milliliter) and on a macro level as a load (pounds/acre/year). Effects of land use are most easily applied to water quality on the macro level because of the sheer size of the watershed that contributes to most streams (often measured in acres or square miles).

2.2.2 BMPs

Best management practices can be identified as facilities or methods which seek to reduce the levels of pollutants in natural waters. Examples of BMP facilities include storm water detention ponds, infiltration trenches and sediment control fences. BMP methods include ideas such as cover cropping, rotational grazing of livestock and nutrient management plans. Each of these BMPs removes pollutants in a different way and at a different rate for each pollutant. Most BMPs are designed to primarily remove three pollutants: nitrogen, phosphorus, and sediments. The idea of the BMP was introduced in the 1972 Federal Water Pollution Control Act Amendments which also separated point source pollution from non-point source pollution (Ice, 2004).

Most of the work on BMPs has been regulatory in nature although a significant amount of academic work exists on the subject of individual BMP effectiveness. Studies have been conducted seeking to quantify the benefits of BMPs. Newton and Norgren (1977) performed a study measuring concentrations of herbicides in forest streams. Later studies after the implementation of forest buffers showed dramatic drops in the levels of herbicides (Rashin and Graber, 1993). Williams, et al. (2000) performed a similar study

of timber harvesting before and after the use of timber harvesting BMPs. The study showed significant reductions in sediment discharge levels after the application of BMPs.

2.2.3 Efforts in Maryland

Because of the importance of the Chesapeake Bay watershed to Maryland, the state has been a leader in modeling the Bay's water quality, focusing efforts on reducing pollution in the Bay's watershed via BMPs. State agencies such as the Maryland Department of Natural Resources and the Maryland Department of the Environment have teamed up with regional and federal agencies such as the Chesapeake Bay Program and the United States Environmental Protection Agency as well as with local agencies such as the county level environmental and planning agencies to reduce levels of the pollutants in the Bay and its tributaries.

The Chesapeake Bay Program, under the jurisdiction of the U.S. E.P.A. has spent years producing and updating the "Chesapeake Bay Watershed Model", a mathematical and geographic information system (GIS)-based model that quantifies and predicts pollutant loadings based on land use and BMPs in the Bay and its sub-watersheds (Chesapeake Bay Program, 2006). The Bay Program has also worked to create and continue running the Chesapeake Bay Monitoring Program to take physical measurements of the Bay's watershed and its tributary waters and to measure levels of various pollutants.

The Maryland Department of the Environment (MDE) has worked since the inception of the Clean Water Act of 1972 to administer a total maximum daily loads (TMDL) program across the state in an effort to keep waters clean. The TMDL program establishes guidelines and plans for meeting water quality standards for all waters in the state that exceed maximum levels of pollution. Other programs such as the Stormwater Pollution Control Program (Maryland Department of the Environment, 2007) and the Maryland Linked Deposit Program (Maryland Department of the Environment, 2007) distribute funds from MDE towards the implementation of BMPs.

The Maryland Department of Natural Resources (DNR) also participates in the preservation of Maryland's waters. DNR focuses efforts on studying various watersheds around the state to assess water quality and the effectiveness of BMPs. Examples of these studies include a study of the Upper Pocomoke watershed in Wicomico County, Maryland with a focus on agricultural BMPs (Maryland Department of Natural Resources, 2007), a restoration of approximately half a mile of Little Pipe Creek in Carroll County, Maryland (Maryland Department of Natural Resources, 2007) and studies of timber harvesting BMPs in the Sugarloaf Mountain region of Montgomery County, Maryland (Maryland Department of Natural Resources, 2007). Each of these efforts relies on knowledge of the land use in the area as well as effectively choosing and implementing BMPs to keep project costs down and improve water quality.

A key program under DNR is the Chesapeake Bay Tributary Strategy Program. This program provides an environmental and ecological assessment of the Bay's Maryland

tributaries and lays out plans for restoring those tributaries. Each tributary strategy is a plan that focuses on reducing pollutant loadings from all sources (urban, suburban, agricultural, etc.) in a tributary's watershed via BMPs and other nutrient and sediment control actions (Maryland Department of Natural Resources, 2006).

2.3 BMPs and Optimization

The idea of using mathematical optimization techniques to facilitate best management practice planning is not new. There are several existing examples of BMP optimization in the literature. These works can be categorized by the different factors they account for:

1. Development type
2. Objective function
3. Optimization technique
4. BMP characteristic being optimized (e.g. by type, by size, by location)
5. Scale of optimization problem

While not all research addresses all possibilities in these categories, each work addresses at least one of the categories in some way. More recent work incorporates geographic information systems into the optimization program, usually in order to perform spatially-

oriented computations as well as to provide a visual input and output interface with the user.

Some of the earliest work linking optimization and hydrology did not involve water quality but water quantity. Mays and Bedient (1982) sought to optimize the size and location of stormwater detention ponds in a watershed. Their methodology involved integrating dynamic programming algorithms with traditional hydrologic and flood routing procedures in order to simulate a system of detention ponds in a given watershed. Subsequent work includes additional investigations into optimization of flood routing procedures (Behera, et al., 1999) and new examinations of optimizations developed to control pollutant runoff and deposition via the use of BMPs. Kao (1997) used multi-objective linear programming in order to optimize the amounts of certain crops grown with the intent of maximizing reduction of total phosphorus (TP) outputs while minimizing cost and equity.

Recent work into optimizing BMPs has used newer techniques such as genetic algorithms (GAs) in order to stochastically determine an optimum solution to different BMP problems, specifically, agriculturally based BMPs. Srivastava et al. (2002) showed that a genetic algorithm could be used in conjunction with a non-point source pollution model (AnnAGNPS – Srivastava et al., 2002) to identify BMPs that maximized net annual farm return and minimized water quality degradation over time. Their work was echoed by Veith et al. (2003) who also incorporated GIS to maximize soil loss reductions while minimizing cost using a GA.

In addition to optimizing for best BMP types and sizes, finding the optimal locations for BMPs, also known as spatial optimization or spatial allocation has been investigated. Veith et al. (2004) showed that spatial optimization is more cost effective than location targeting, a process where possible BMP locations are determined based on how they meet a predetermined set of requirements. Similar work included a methodology building on the work of Srivastava et al.(2002) with AnnAGNPS and using a GA-like method called “scatter-search” to develop optimal solutions in order to maximize reduction in sediment transports and minimize cost of stormwater pond construction. Work centered on more urban environments includes Perez-Pedini et al. (2005). They sought to optimize the location of infiltration BMPs in a suburban watershed. This work, like Mays and Bedient (1982), combined hydrologic methodologies with an optimization procedure, a GA in this case, to develop optimal solutions. Cerucci and Conrad (2003) used binary optimization to make ‘yes-no’ decisions on riparian buffer BMP locations with the interest of minimizing pollutant loadings while adhering to a budget. This work showed that there can be a deterministic solution to problems of this type.

The research documented in this paper provides a more holistic approach to BMP optimization. While the basic tenets remain the same, the range of BMPs used by Veith, et al. and Srivastava is expanded to include all types of urban, suburban and agricultural BMPs, both practices and facilities that could be applied in a given watershed as well as accounting for more than one pollutant in the optimization. Furthermore, the optimization types are expanded to include both ‘continuous’ optimization where a simple target area size is given for each BMP type and ‘discrete’ optimization where an optimal set of previously determined BMPs in a watershed is chosen from a larger pool.

Finally, two options for objectives are provided: minimize cost and minimize loadings.

By using a more holistic approach to BMP optimization a more dynamic and robust tool can be designed to be used in BMP planning.

Chapter 3: Problem Definition and Data Gathering

3.1 Problem Definition Overview

This chapter defines the BMP optimization problem in the framework of deterministic optimization, specifically linear and non-linear programming. Concepts of optimization and the problem are defined in general terms and then more specifically as the problem of BMP optimization is presented. This chapter also presents the GIS-based framework to perform BMP optimizations.

3.2 Optimization Mechanics

Most optimization problems feature three parts: the objective function(s), the constraints, and the variable boundaries. The goal of optimization is to find the variable values that yield the best objective function value while satisfying both the linear constraints of the problem and the variable boundary constraints. This chapter describes several methods with which these solutions can be obtained.

3.3 Types of Optimization

There are generally two approaches to optimization: stochastic optimization and deterministic optimization.

Stochastic optimization is based on random number generation and involves initializing a group of solution sets and choosing the best solution set of the entire group. Because the solutions of stochastic optimization algorithms are based on random numbers, they may not be truly optimal and are usually referred to as “best” or “quasi-optimal” solutions.

While choosing from a larger set of solutions to find the best solution from usually yields a better estimate of the true optimal solution, the true optimal solution cannot be determined with complete confidence unless all possible solutions are found and compared. Monte Carlo simulation and, in part, genetic algorithms are based on stochastic optimization concepts.

Assuming the problem cannot be solved analytically, deterministic optimization provides a method to find the true optimal solution to the problem. Deterministic optimization differs from stochastic because it does not rely on random number generation to create solution sets. Deterministic optimization starts with an initial solution and moves in the direction of ‘steepest descent’ towards the best value of the objective function. The optimization continues in this manner until the most extreme value of the objective function is reached while still satisfying each of the constraints and variable boundaries of the problem. Because the value of the objective function is the most extreme value possible given the constraints, the solution set obtained is called the “optimal” solution. Deterministic optimization types include linear and non-linear programming, integer programming, and binary programming.

Linear programming is a simple deterministic approach to solving linearly constrained optimization problems. This type of optimization method assumes the problem form:

$$MIN / MAX (Z) = \sum_{i=1}^I C_i X_i \quad (3.1)$$

subject _ to :

$$A_{11}X_1 + A_{12}X_2 + \dots + A_{1i}X_i + \dots + A_{1I}X_I \leq B_1 \quad (3.2)$$

\vdots

$$A_{J1}X_1 + A_{J2}X_2 + \dots + A_{Ji}X_i + \dots + A_{JI}X_I \leq B_J \quad (3.3)$$

$$L \leq X \leq U \quad (3.4)$$

In any linear or non-linear program, equation 3.1 is referred to as the objective function.

The equation seeks to minimize or maximize a sum of I parts where each part consists of the variable X_i multiplied by a constant C_i . Equations 3.2 through 3.3 are a set of J linear constraints stating that the sum of I parts where each part consists of the variable X_i multiplied by a constant A_i must be less than a constant value B_j . Equation 3.4 is a variable boundary constraint on X_i where L_i is the lower bound and U_i is the upper bound.

3.4 Defining the General Problem

BMP optimization is a balancing act. Land use change may cause increases in the loadings of various deleterious pollutants and BMPs may be used to mitigate these loading increases. Figure 1 describes the BMP optimization scenarios. Scenario one addresses the question, how can an assumed limited budget for allotting these BMPs be administered to most effectively mitigate pollutant loading increases? In scenario two the question is, how can these BMPs be administered to meet pollutant reduction goals for a minimum cost? In either of these cases, the balancing act exists between money (a budget) and pollutant reduction. For each of these scenarios, shown in Figure 3.1, a

subset of scenarios must be considered. Scenario 1-A or 2-A is that the optimizer finds the optimum land areas to use for each type of BMP. Scenario 1-B or 2-B is that the optimizer is choosing the optimum set of predetermined BMPs (type and land area defined) from a larger pool of predetermined BMPs.

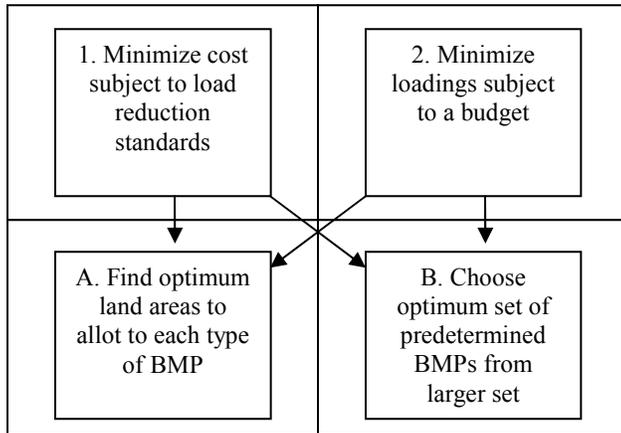


Figure 3.1 Matrix of BMP optimization problem types.

In general, the mathematical way to achieve a ‘best balance’ where cost is minimized and simultaneously, pollutant reduction is maximized is through mathematical optimization. However, the specific tools used to perform this optimization depend on the properties of the specific problem.

3.5 Properties of the BMP Optimization Problem

Once this problem is converted from general terms to a specific environment with specific loading, BMP and cost parameters, it takes on several properties which are critical to determining the method with which to solve the problem. In this case, the

specific environment is the state of Maryland within the Chesapeake Bay watershed. Therefore, the problem will reflect the rules regarding pollutant loading in this environment as well as rules for how BMPs reduce pollutant loading from a quantitative perspective.

3.6 Determining Pollutant Loadings

In order to remain consistent with efforts in Maryland to quantify nutrient pollution problems, the existing loadings for the three typical pollutants in question (nitrogen, phosphorus, sediments) are quantified based on loadings determined for larger areas by the Chesapeake Bay Program's Bay Model (Chesapeake Bay Program, 2006). Phase V of the Bay Model determines unique loads for each of the pollutants in each 'land-river segment' which is an area of land whose boundaries are determined by both watershed and county boundaries.

Within each land river segment, the loading is broken down into contributing loadings from each of the 26 land uses modeled in the Bay Model. The loading for the study area of each pollutant is determined by taking the land use area in the study area for a particular land river segment, and multiplying it by a loading coefficient for that pollutant in that land river segment. For example, if the study area has 100 acres of forest land use in land river segment 1 and the loading coefficient for nitrogen is 0.10 lbs/ac-year, then the contributing nitrogen loading from forest land use in land river segment 1 to the total nitrogen loading in the study area is 100 multiplied by 0.10 or 10 lbs/year. This is

repeated for all land river segments, all land uses and all pollutants. The total loading for each pollutant is determined by summing the contributing loadings from each land use in each land river segment.

Table 3.1 Nitrogen Loading Development Example

Land Use (acres)	Segment 1	Segment 2	Segment 3	Segment 4	
Forest	5	23	15	19	
Hi Till	22	98	15	43	
Low Till	19	31	88	82	
High Intensity Developed	69	19	88	77	
Low Intensity Developed	78	30	60	30	
Hay with Nutrients	28	63	81	38	
Loading Rates (lbs/ac-year)					
Land Use	Segment 1	Segment 2	Segment 3	Segment 4	
Forest	0.68	1.73	0.05	0.08	
Hi Till	0.73	0.34	2.97	2.41	
Low Till	1.29	2.77	1.65	1.31	
High Intensity Developed	0.73	2.09	2.92	2.9	
Low Intensity Developed	1.85	0.83	0.34	2.39	
Hay with Nutrients	1.48	1.87	0.02	1.31	
Loadings (lbs/year)					
Land Use	Segment 1	Segment 2	Segment 3	Segment 4	Total Loading
Forest	3.4	39.79	0.75	1.52	45.46
Hi Till	16.06	33.32	44.55	103.63	197.56
Low Till	24.51	85.87	145.2	107.42	363
High Intensity Developed	50.37	39.71	256.96	223.3	570.34
Low Intensity Developed	144.3	24.9	20.4	71.7	261.3
Hay with Nutrients	41.44	117.81	1.62	49.78	210.65
				Total	1648.31

3.7 BMP Rules

Maryland has two general types of BMPs in terms of how they are mathematically applied to loading reduction formulas: additive and multiplicative (Maryland Department of Natural Resources, 2006). Additive BMPs, when applied together, reduce loading

individually based on the area each BMP serves (X_i) and then individual reductions are added together to yield the total load of pollutant taken out by the combination of additive BMPs (Equation 3.5).

$$M = LU[ac] * LR[lb / ac] * \left[1 - \frac{\left[X_1[ac] * \left(\frac{R_{X_1} \%}{100} \right) \right] + \left[X_2[ac] * \left(\frac{R_{X_2} \%}{100} \right) \right]}{LU[ac]} \right] \quad (3.5)$$

In contrast, multiplicative BMPs, when applied together, reduce the total load of pollutant removed as a product of the removal rates of the individual multiplicative BMPs (Equation 3.6).

$$M = LU[ac] * LR[lb / ac] * \left[\left(1 - \left[\frac{X_1[ac]}{LU[ac]} \left(\frac{R_{X_1} \%}{100} \right) \right] \right) * \left(1 - \left[\frac{X_2[ac]}{LU[ac]} \left(\frac{R_{X_2} \%}{100} \right) \right] \right) \right] \quad (3.6)$$

Furthermore, when applied together, the additive BMPs are applied together to produce a removal rate α and the multiplicative BMPs are applied together to produce a removal rate β . These rates are then multiplied together to produce an overall removal rate which is multiplied by the existing pollutant loading to determine the overall load of pollutant removed (Equations 3.7, 3.7.1, 3.7.2).

$$M = LU[ac] * LR[lb / ac] * \alpha * \beta \quad (3.7)$$

where,

$$\alpha = 1 - \frac{\left[X_1[ac] * \left(\frac{R_{X_1} \%}{100} \right) \right] + \left[X_2[ac] * \left(\frac{R_{X_2} \%}{100} \right) \right]}{LU[ac]} \quad (3.7.1)$$

$$\beta = \left(1 - \left[\frac{X_1[ac]}{LU[ac]} \left(\frac{R_{X_1} \%}{100} \right) \right] \right) * \left(1 - \left[\frac{X_2[ac]}{LU[ac]} \left(\frac{R_{X_2} \%}{100} \right) \right] \right) \quad (3.7.2)$$

Appendix B provides a mathematical explanation of these rules. Because of the multiplication of the BMP land use variable X_i , the equations to determine overall pollutant reduction from a set of BMPs become nonlinear. Finally, multiplicative BMPs, because of their physical nature (usually a practice applied to the land) may be applied to the same land area. In contrast, additive BMPs are generally mutually exclusive with respect to the land area they cover.

3.8 Use of a Non-linear Programming Solver

Because of the non-linearity of some of BMP optimization problem parameters, non-linear programming was identified as a logical solution method for the BMP optimization problem. The optimization program used a steepest-descent method to obtain the optimal solution.

There are several computer-based solvers on the market to perform the computations necessary to arrive at a deterministic solution to this problem and to the discrete non-linear optimization problem. One such solver, *TOMLAB*, provided a straightforward way to input the problem parameters and was thought to be robust enough to solve large ordered optimization problems similar to the BMP optimization problems.

However, computation time became intractable as many problems given to the optimizer took nearly an hour or longer to produce suitable results. In addition, the results for one set of parameters were not always consistent, leading to questions about the reliability of the *TOMLAB* optimizer. For example, for a single set of inputs, variations were seen in the value of the objective function. These results of early test optimizations indicated that *TOMLAB* might be finding local optima rather than global optima which lead to incorrect solutions. Because this problem could not be overcome with current technology and because the goal of this optimizer is to be able to give quick, reliable, and optimal solutions, the problem definition was simplified to an exclusively linear form so the linear programming solvers could be used and all optima located would be global optima.

3.9 Developing a BMP Optimizer in a Linear Programming Framework

Prior to developing the linear program several simplifying assumptions were made.

These assumptions were:

- 1) All BMPs are assumed to be additive in nature
- 2) All BMP costs are assumed to be a rate in dollars per acre.
- 3) All BMPs are exclusive in terms of the area they cover meaning a given area of land may be covered by, at most, one BMP.

After the decision was made to simplify the BMP optimization to a linear program, the specific parameters of the problem were applied to each of the three components of the linear program: the objective function, the linear constraints, and the variable boundaries.

3.9.1 Objective Functions

There are two objective functions used in the BMP Optimization program and are specific to the scenario type the user intends to solve. During the user-input phase of the program, the user specifies whether the optimization program should pursue the least expensive BMP plan or the BMP plan that maximizes pollutant loading reductions.

Internally, these objective functions are programmed via the following mathematical functions. If minimizing cost, Z , while maintaining a certain standard in water quality is the goal, then the objective function equation is:

$$MIN(Z) = \sum_{i=1}^I C_i X_i \quad (3.8)$$

where C_i is the cost (\$/acre) of BMP i , I is the total number of BMPs, and X_i is the number of acres allotted to BMP i . If minimizing loads, Z , while maintaining a budget is the goal, the objective function is:

$$MIN(Z) = \sum_{n=1}^N Y_n \sum_{i=1}^I F_{ni} X_i \quad (3.9.1)$$

where F_{ni} is the linear loading constraint coefficient defined as:

$$F_{ni} = \frac{-R_{ni}}{LU_{(X_i)}} \quad (3.9.2)$$

and Y_n is the weighting of each pollutant n (from user input), N is the total number of pollutants, R_{ni} is the reduction efficiency for pollutant n of BMP i , X_i is the optimal land area allotted to BMP i , and $LU_{(X_i)}$ is the total area of the land use in the study area or watershed that BMP i is applied to. $LU_{(X_i)}$ represents the feasible upper bound of X_i .

3.9.2 Linear Constraints

The BMP optimization program constraints are derived from the physical system and from rules of BMP implementation as given by the Maryland Department of Natural Resources. The linear constraints are programmed using the functions *lincon1*, *lincon2*, *lucon*, *lucon2*, *buffcon*, and *buffcon2* (Appendix C) depending on the type of optimization (generalized or discrete) that the user selects. No matter what type of optimization is selected, the two basic linear constraints remain the same:

- 1) **Linear Constraint #1:** For each land use, the sum of all acres applied to all BMPs of that land use type must be less than or equal to the total acres of that land use type. This constraint uses the equation:

$$\sum_{i=1}^I A_{ji} X_i \leq B_j \quad (3.10)$$

where A_{ji} is one if BMP i is applied to land use j and is zero otherwise, X_i is the land area allotted to BMP i by the optimizer and B_j is the total area of land use j in the watershed.

2) **Linear Constraint #2:** For each land use, the sum of all acres applied to all buffer BMPs of that land use type must be less than or equal to the total acres of that land use type within the stream buffer area. This constraint uses the format of Equation 3.10. However, in this case D_{ki} is one if BMP i is a buffer BMP and is applied to land use k (with K being the total number of buffer land uses) and is zero otherwise, X_i is the land area allotted to BMP i by the optimizer and G_k is the total area of land use k in the in the stream buffer portion of the watershed.

3) **Linear Constraint #3:** There is an additional constraint dependent on the objective function selected by the user

- a. If the user selects minimize loadings as the objective function, then the additional constraint is that the sum of each BMP land area multiplied by its unit cost must be less than the budget specified by the user. This constraint is represented by a modified version of Equation 3.1:

$$\sum_{i=1}^I C_i X_i \leq T \quad (3.11)$$

where C_i is the unit cost of BMP i in dollars per acre, X_i is the land area allotted to BMP i , and T is the total budget.

- b. If the user selects “minimize cost” as the objective function, then the additional constraint is that for each pollutant specified by the user, the negative value of the load removed must be less than the minimum load removed specified by the user. Thus, if the user specifies three pollutants, then there will be three additional constraints. The equation for this constraint is:

$$\sum_{i=1}^I F_{ni} \leq -W_n \quad (3.12)$$

where F_{ni} is defined in Equation 3.9.2 and W_n is the desired fraction of load reduction for pollutant n .

When applied to the optimization program, the additive BMPs can be modeled with linear constraints. Therefore, by simplifying the problem to make all BMPs additive, the problem becomes linear in form and can be solved with a linear program as shown in Figures 3.2.1 and 3.2.2.

3.9.3 Variable Boundaries

The variable boundaries are derived from the physical system. The only limits placed on the variables are that the number of allotted acres must be greater than or equal to zero.

The upper limits placed on the variables (limiting how many acres can be allotted to each BMP type) are accounted for in the constraints of the optimization problem. Because of the way a linear program is solved, variables which are unbounded or bounded by constraints do not need additional bounds on the values they can take.

$$\begin{aligned}
 \text{MIN } (Z) &= \sum_{i=1}^I C_i X_i \\
 \text{subject } &\text{to} \\
 A_{11} X_1 + \dots + A_{1i} X_i + \dots + A_{1I} X_I &\leq B_1 \\
 \vdots & \\
 A_{j1} X_1 + \dots + A_{ji} X_i + \dots + A_{jI} X_I &\leq B_j \\
 \vdots & \\
 A_{J1} X_1 + \dots + A_{Ji} X_i + \dots + A_{JI} X_I &\leq B_J \\
 \\
 D_{11} X_1 + \dots + D_{1i} X_i + \dots + D_{1I} X_I &\leq G_1 \\
 \vdots & \\
 D_{k1} X_1 + \dots + D_{ki} X_i + \dots + D_{kI} X_I &\leq G_k \\
 \vdots & \\
 D_{K1} X_1 + \dots + D_{Ki} X_i + \dots + D_{KI} X_I &\leq G_K \\
 \\
 F_{11} X_1 + \dots + F_{1i} X_i + \dots + F_{1I} X_I &\leq -W_1 \\
 \vdots & \\
 F_{n1} X_1 + \dots + F_{ni} X_i + \dots + F_{nI} X_I &\leq -W_n \\
 \vdots & \\
 F_{N1} X_1 + \dots + F_{Ni} X_i + \dots + F_{NI} X_I &\leq -W_N \\
 \\
 L &\leq X_i \text{ for all } i
 \end{aligned}$$

Figure 3.2.1 Problem statement for “minimize cost” objective in the generalized environment.

$$\begin{aligned}
\text{MIN } (Z) &= \sum_{n=1}^N Y_n \sum_{i=1}^I F_{ni} X_i \\
\text{subject to} & \\
A_{11} X_1 + \dots + A_{1i} X_i + \dots + A_{1I} X_I &\leq B_1 \\
\vdots & \\
A_{j1} X_1 + \dots + A_{ji} X_i + \dots + A_{jI} X_I &\leq B_j \\
\vdots & \\
A_{J1} X_1 + \dots + A_{Ji} X_i + \dots + A_{JI} X_I &\leq B_J \\
\\
D_{11} X_1 + \dots + D_{1i} X_i + \dots + D_{1I} X_I &\leq G_1 \\
\vdots & \\
D_{k1} X_1 + \dots + D_{ki} X_i + \dots + D_{kI} X_I &\leq G_k \\
\vdots & \\
D_{K1} X_1 + \dots + D_{Ki} X_i + \dots + D_{KI} X_I &\leq G_K \\
\\
C_{11} X_1 + \dots + C_{1i} X_i + \dots + C_{1I} X_I &\leq T \\
\\
L &\leq X_i \text{ for all } i
\end{aligned}$$

Figure 3.2.2 Problem statement for “minimize loads” objective in the generalized environment.

3.9.4 Adjustments for Discrete Optimization

In order to perform discrete optimization, that is to optimize by choosing the best set of predetermined candidate BMPs from a pool of predetermined BMPs, there are several adjustments to the linear program that must be made. Unlike the general case where the variable to be optimized, X_i represented the optimal land area to be used for BMP i , the optimization framework must be adjusted to create a binary integer program where the variable to be optimized, x_i can take on either a “yes” value of 1 or a “no” value of 0 for each predetermined BMP i . Rather than representing all possible types of BMPs, the variable vector x represents the pool of predetermined BMPs with type and land area already specified.

The “minimize cost” objective function becomes:

$$MIN(Z) = \sum_{i=1}^I c_i x_i \quad (3.13.1)$$

where c_i is defined as:

$$c_i = C_{(x_i)} a_i \quad (3.13.2)$$

where $C_{(x_i)}$ is the unit cost of the BMP type of BMP i , a_i is the area of BMP i . The variable x_i is the decision variable for BMP i . Like wise, the “minimize loadings” objective function becomes:

$$MIN(Z) = \sum_{n=1}^N Y_n \sum_{i=1}^I f_{ni} x_i \quad (3.14.1)$$

where f_{ni} is defined as:

$$f_{ni} = -\frac{R_{ni} a_i}{LU_{(x_i)}} \quad (3.14.2)$$

where Y_n is the weighting of each pollutant n (from user input), R_{ni} is the reduction efficiency for pollutant n of the BMP type of BMP i , a_i is the land area allotted to BMP i , $LU_{(x_i)}$ is the total area of the land use to which BMP i is applied and x_i is the decision variable for BMP i .

Several of the linear constraints are posed in a slightly different manner in discrete optimization. Linear constraint #1 is adjusted such that the value of A_{ji} is now represented by a_{ji} which is now the land area allotted to BMP i if the land use that BMP i applies to is land use j . If BMP i does not apply to land use j , then a_{ji} is zero. Linear constraint #2 is adjusted in the same manner where D_{ki} becomes d_{ki} . If the objective function is to “minimize load” linear constraint #3 becomes:

$$\sum_{i=1}^I c_i x_i \leq T \quad (3.15)$$

where c_i is defined in equation 3.13.2, x_i is the decision variable for BMP i , and T is the budget. If the objective function is to minimize cost, then linear constraint #3 becomes:

$$\sum_{i=1}^I f_{ni} x_i \leq -W_n \quad (3.16)$$

where f_{ni} is defined in equation 3.14.2, x_i is the decision variable for BMP i , and W_n is the desired fraction of load reduction for pollutant n . These adjustments, when applied to the linear programs shown in Figures 3.3.1 and 3.3.2, form a binary integer program that can solve the discrete BMP optimization problem. When solved, the optimal solution is represented by the array x which is the array of decisions for using (represented by a “1”) or not using (represented by a “0”) the predetermined BMPs.

$$\begin{aligned}
\text{MIN } (Z) &= \sum_{i=1}^I c_i x_i \\
\text{subject } &\text{to} \\
a_{11} x_1 + \dots + a_{1i} x_i + \dots + a_{1I} x_I &\leq B_1 \\
\vdots & \\
a_{j1} x_1 + \dots + a_{ji} x_i + \dots + a_{jI} x_I &\leq B_j \\
\vdots & \\
a_{J1} x_1 + \dots + a_{Ji} x_i + \dots + a_{JI} x_I &\leq B_J \\
\\
d_{11} x_1 + \dots + d_{1i} x_i + \dots + d_{1I} x_I &\leq G_1 \\
\vdots & \\
d_{k1} x_1 + \dots + d_{ki} x_i + \dots + d_{kI} x_I &\leq G_k \\
\vdots & \\
d_{K1} x_1 + \dots + d_{Ki} x_i + \dots + d_{KI} x_I &\leq G_K \\
\\
f_{11} x_1 + \dots + f_{1i} x_i + \dots + f_{1I} x_I &\leq -W_1 \\
\vdots & \\
f_{n1} x_1 + \dots + f_{ni} x_i + \dots + f_{nI} x_I &\leq -W_n \\
\vdots & \\
f_{N1} x_1 + \dots + f_{Ni} x_i + \dots + f_{NI} x_I &\leq -W_N \\
\\
x_i &= \{0,1\} \text{ for all } i
\end{aligned}$$

Figure 3.3.1 Problem statement for “minimize cost” objective in the discrete environment.

$$\begin{aligned}
\text{MIN } (Z) &= \sum_{n=1}^N Y_n \sum_{i=1}^I f_{ni} x_i \\
\text{subject } &\text{to} \\
a_{11} x_1 + \dots + a_{1i} x_i + \dots + a_{1I} x_I &\leq B_1 \\
\vdots & \\
a_{j1} x_1 + \dots + a_{ji} x_i + \dots + a_{jI} x_I &\leq B_j \\
\vdots & \\
a_{J1} x_1 + \dots + a_{Ji} x_i + \dots + a_{JI} x_I &\leq B_J \\
\\
d_{11} x_1 + \dots + d_{1i} x_i + \dots + d_{1I} x_I &\leq G_1 \\
\vdots & \\
d_{k1} x_1 + \dots + d_{ki} x_i + \dots + d_{kI} x_I &\leq G_k \\
\vdots & \\
d_{K1} x_1 + \dots + d_{Ki} x_i + \dots + d_{KI} x_I &\leq G_K \\
\\
c_{11} x_1 + \dots + c_{1i} x_i + \dots + c_{1I} x_I &\leq T \\
\\
x_i &= \{0,1\} \text{ for all } i
\end{aligned}$$

Figure 3.3.2 Problem statement for “minimize loads” objective in the discrete environment.

The final optimization program gathers land use data from a user-specified study area, converts the land use data into loadings for pollutants specified by the user and, using BMP information for the state of Maryland and either a budget or a set of pollutant reduction goals, finds the optimal set of BMPs that provide either maximum pollutant reduction for the user-specified budget, or meet the set of user-specified pollutant reduction goals for the least cost. All BMPs are assumed to be additive and all types of land uses and BMPs are available to be used in the optimization. Furthermore, the optimizer has the ability to consider multiple pollutants in the problem. Once the linear simplification was complete, the results were consistent and timely for each problem sent to the optimizer.

3.10 Geographic Information System Interface

A geographic information system (GIS), Environmental Systems Research Institute (ESRI)'s Arcview 3.3 provided the optimization program with a user-friendly visual interface for input and output as well as to perform some spatially-oriented computations. Several of the inputs to the optimization problem, including land cover used to determine land use, physiographic region used to determine buffer BMP reduction efficiencies, and watershed boundaries which often define study areas, are more easily conveyed in a spatial context than in a verbal or numerical one. Mathematical computations involving these attributes can be easily performed by the GIS.

3.10.1 Optimization Program Initiation

In the context of the overall optimization program, the GIS provides an interface to the program that the engineer sees and manipulates. The engineer uses the optimization program in the GIS environment and is immediately shown a map of Maryland with several layers of information:

1. County boundaries
2. Stream locations
3. Land Cover
4. Physiographic Region boundaries
5. Land and River segmentation

Once the engineer adds a GIS layer showing the limits of the study area, typically a delineated watershed boundary, the optimization program can be activated. After executing, the optimization writes and displays a text file showing the optimal BMP set as well as cost and loading results. In the case that a candidate BMP set is provided, the GIS map is updated with a new layer showing the chosen BMP locations.

3.10.2 Optimization Program Dialog

Once the optimization program is activated, a dialog box requests optimization information from the engineer. The information requested includes the objective function choice (minimize cost or minimize load), the value(s) of the loading reduction standards for the cost minimization problem or a budget for loading minimization problem, the pollutants to consider in optimization (total nitrogen, total phosphorus, and total sediments), the maximum available width of stream buffers and whether there exists in the GIS a layer showing specific BMPs to choose from during the optimization as shown in Figure 3.4.

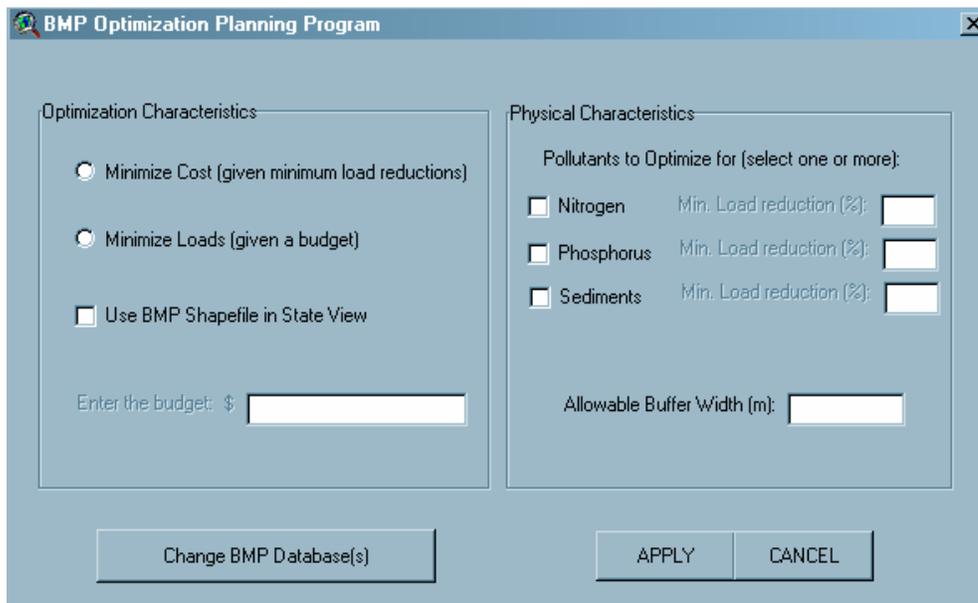


Figure 3.4 User dialog box to set BMP Optimization program parameters.

3.10.3 Study Area Land Cover Tabulation

Once the GIS passes the problem formulation from the dialog to the optimizer, the preprocessing begins by totaling the area of each land cover type inside the study area.

The GIS passes the cross tabulated totals as shown in the example given in Table 3.2 to the optimizer.

Table 3.2 Cross-tabulation of Land Cover Area by Land-River Segment (“*Fipscatwat*”) and Land Cover Type (land cover categories are truncated, area in square meters)

<i>Fipscatwat</i>	<i>Value-1</i>	<i>Value-2</i>	<i>Value-3</i>	<i>Value-4</i>
A24003wM3_4060_0001N	0.000	128700.000	0.000	1800.000
A24003wM0_3961_0000N	0.000	286200.000	0.000	2700.000
A24003wL2_4270_4650N	0.000	166500.000	0.000	900.000
A24003wL0_4420_0000N	13500.000	22372200.000	81000.000	383400.000
A24003wL0_4390_0000N	0.000	453600.000	0.000	1800.000
A24003wL0_4421_0000N	87300.000	14620500.000	3600.000	96300.000
A24003wL0_4421_0000Y	2462400.000	121500.000	0.000	5400.000
A24003wL0_4392_0000N	0.000	453600.000	0.000	0.000
A24003wL0_4422_0000N	135900.000	5848200.000	0.000	29700.000
A24003wL0_4422_0000Y	9840600.000	142200.000	0.000	10800.000
A24003wL0_4600_0000N	0.000	150300.000	900.000	0.000
A24003wL0_4423_0000N	209700.000	16691400.000	52200.000	56700.000
A24003wL0_4423_0000Y	9717300.000	352800.000	900.000	31500.000
A24003wL0_4603_0000N	0.000	138600.000	0.000	0.000
A24003wL0_4601_0000N	0.000	5400.000	0.000	0.000

3.10.4 Buffer Creation and Buffer Land Cover Tabulation

The GIS then creates a buffer around all streams in the study area and the land cover inside the buffer is totaled by land cover type and land river segment area. The buffer width is specified by the engineer in the dialog shown in Figure 3.2. This buffer defines land where buffer BMPs can be applied. The GIS also passes these totals to the optimizer. After each land cover extraction and computation, the GIS creates a new map

showing first the study area-only view and then the stream buffer-only view along with the appropriate land cover cells and the study area boundary. An example is shown in Table 3.3.

Table 3.3 Cross-tabulation of Buffer Land Cover Area by Land-River Segment (“Fipscatwat”) and Land Cover Type (land cover categories are truncated, area in square meters)

<i>Fipscatwat</i>	<i>Value-1</i>	<i>Value-2</i>	<i>Value-3</i>	<i>Value-4</i>
A24003wLO_4420_0000N	3600.000	3351600.000	7200.000	58500.000
A24003wLO_4421_0000N	25200.000	1623600.000	0.000	11700.000
A24003wLO_4421_0000Y	1406700.000	47700.000	0.000	2700.000
A24003wLO_4422_0000N	9000.000	124200.000	0.000	1800.000
A24003wLO_4422_0000Y	1869300.000	10800.000	0.000	0.000
A24003wLO_4600_0000N	0.000	0.000	0.000	0.000
A24003wLO_4423_0000N	81900.000	736200.000	0.000	3600.000
A24003wLO_4423_0000Y	4635900.000	145800.000	0.000	19800.000

3.10.5 Optimization

Following the preprocessing computations described in the previous sections, the GIS unites all of the information about the study area into three data files which are then passed to the optimization program. The parameters specified by the user in the dialog shown in Figure 3.4, are passed via a text file. A table containing land cover for the study area broken down by land river segment and by land cover type as shown in Table 3.2 is passed via a text file and a similar table showing the land cover breakdown for the study area within the stream buffer as shown in Table 3.3 is passed via a text file. In the case that a file containing predetermined BMPs is to be used in optimization, that is also passed via a text file. Once this information is passed to the optimizer, the GIS sends a message to the optimizer to execute given the information that has been passed to it.

3.10.6 Post-optimization

Upon termination of the optimization sub-routine, the optimizer passes the results back to the GIS. The GIS then formats these results into a user-friendly output file shown in Figure 3.5, which is saved on the user's machine as well as output to the screen. If a map showing candidate BMP locations was used in the optimization, the GIS also creates a new theme showing the selected optimal set of BMPs.

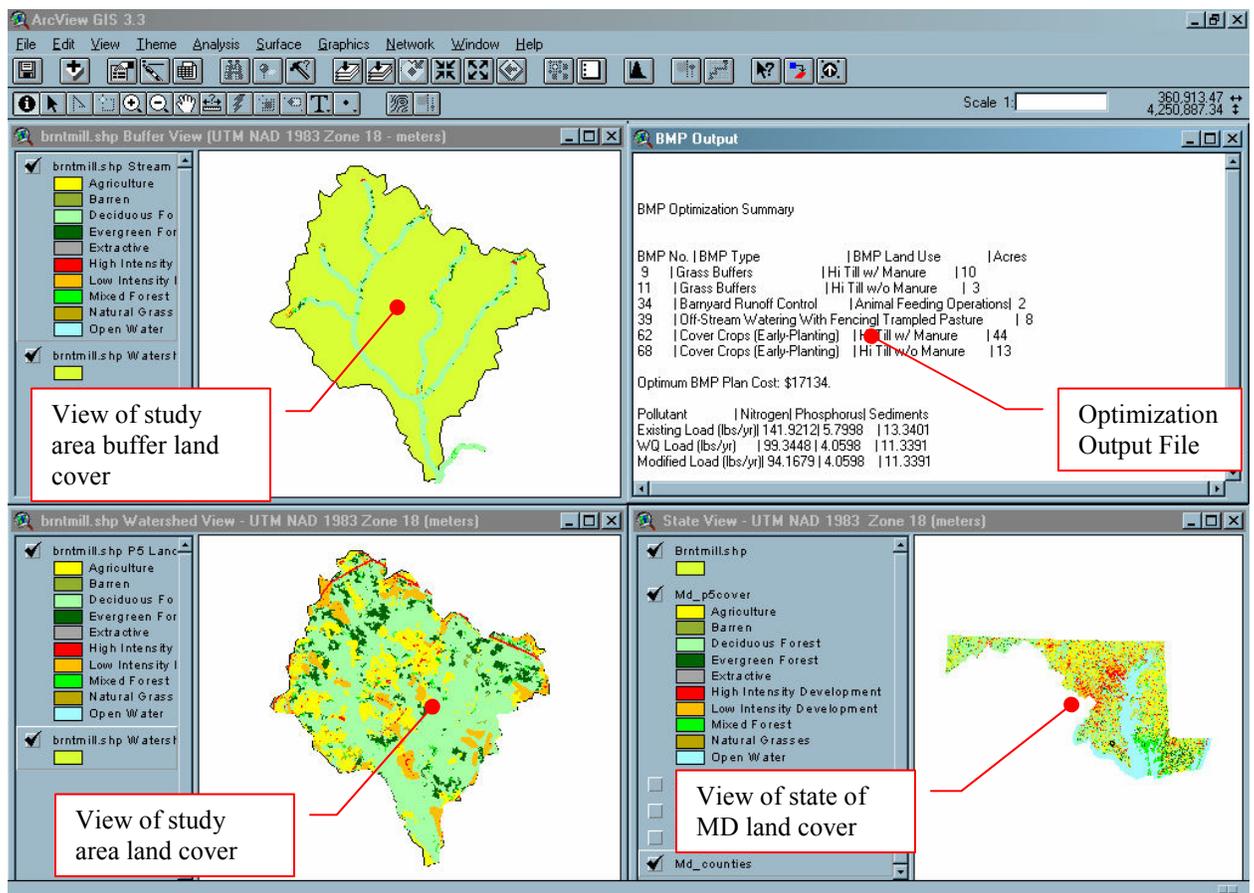


Figure 3.5 Illustration of the BMP optimization summary in GIS user interface after optimization program has run.

3.11 Experiment Data

In order to test the optimizer as well as perform the series of experiments presented in the following chapter, data were gathered to be used in each component of the optimization.

The data required included the following:

- 1) Loading rates for each land river segment in Maryland for nitrogen, phosphorus, sediments
- 2) Land use totals for each land river segment in Maryland so land cover could be converted to land use.
- 3) GIS data layers for Maryland
 - a. Land cover distribution dataset
 - b. Physiographic regions
 - c. Land River segments
 - d. Waterways
- 4) BMPs used in Maryland
 - a. BMP Removal Efficiencies for nitrogen, phosphorus, and sediments (%)
 - b. BMP Unit Cost – the cost per unit area treated (\$/acre)

- c. Other BMP properties included land use applicability and BMP application method (i.e. additive or multiplicative – this study is imposing additive properties on all BMPs)

5) Sample study areas in Maryland

3.11.1 Loading Rates and Land Use Totals

The loading rates for each land river segment in Maryland were derived from the load targets determined in the Phase 5 Bay Model from the Chesapeake Bay Program (Chesapeake Bay Program, 2006). A land river segment is a segment of land whose boundaries are defined by watershed and county boundaries. For each segment and land use, the Bay Model sets out a load calibration target based on known loadings from the land and concentrations in waterways in pounds of pollutant per year. In the case of sediments, this target is in tons of sediment per year. The land use totals are also derived in the Bay Model. Therefore, the loading rate is assumed to be constant across any land use in any land river segment and is obtained by dividing the load target for each pollutant and each land use in the segment by the land use area in the segment. The resulting loading rate for each land use in each land river segment is in pounds (or tons) per acre per year.

3.11.2 GIS Data Layers

GIS data were obtained from two sources. The land cover data set, the physiographic region data set and the land river segment data set were obtained from the Chesapeake Bay Program. The background information for Maryland, including the waterways data set and the counties data set were obtained from GISHydro (<http://www.gishydro.umd.edu>).

3.11.3 BMPs Used in Maryland

The list of BMPs used in the optimizations present was gleaned from documents obtained from the Maryland Department of Natural Resources. In some cases, costs or pollutant removal efficiencies were not available for a particular BMP and that BMP was removed from the list of BMPs. After paring the list down to only BMPs used in Maryland that had all the required data, the total number of available BMPs for the optimizer was 78 (Appendix E). These BMPs include both facility BMPs and practice BMPs and predominately address agricultural and urban/developed land uses.

3.11.4 Sample Study Areas in Maryland

A data set of 53 watersheds across Maryland was selected for use in several experiments presented in the next chapter. For ease of data gathering, watersheds around Maryland were selected as opposed to non-watershed based study areas such as counties or cities. Each watershed was obtained from data and GIS-routines in the GISHydro (Moglen,

2000) program. For each, watershed land cover distributions and the dominant physiographic region were recorded to be used in optimization (Appendix F).

3.12 Chapter Summary

This chapter presented a summary of the development of the optimization program as well as some of the logic behind the linear program used to find optimal BMP plans for continuous and discrete BMP optimizations for the “minimize cost” and “minimize loads” objective functions. Furthermore, GIS was presented as the framework for the optimization including user input and output. The GIS allows for graphical interface between the user and the optimizer and performs the necessary spatial computations more efficiently than other means. Finally, a brief summary of the data input into the optimization program was presented as well as the 53 study watersheds to be used in the experiments described in Chapter 4.

Chapter 4: BMP Optimization Experiments

4.1 Experiments Overview

While the BMP Optimizer is designed to automatically create optimal BMP solutions for water quality management problems, it is important to understand some of the general trends surrounding optimal BMP solutions for various environmental factors. The following experiments document some of the trends and allow for additional work into exploring BMP optimization trends in much greater detail.

4.2 Preface: The Simple Case

Before conducting and analyzing any experiments or simulations made with the BMP optimizer, it is useful to focus on the mechanics of a simple BMP optimization. These mechanics show that the optimizer does not always pick the most cost effective BMPs first nor does it always pick them in the largest quantity (consuming the most acres). In fact, in many cases, the BMP optimizer may sacrifice pure cost effectiveness in favor of maximum pollutant removal. Put more simply, the BMP optimizer will sometimes choose BMPs that remove a higher percentage of pollutant over BMPs that remove a lesser percentage of pollutant but do so for a smaller unit cost. This occurs more often as the optimizer is given more money to spend, or the water quality restrictions are made to be more stringent.

In order to illustrate these mechanics, a simple test case is presented here. Tables 4.1 and 4.2 present the parameters of this test case.

Table 4.1 Land Use Data for Simple Case Experiment

Land Use	A	B	Units
Area	30	70	Ac.
Load Rate (TN)	0.5	0.3	lbs/ac.
Loading (TN)	15	21	lbs.
Load Rate (TP)	0.05	0.03	lbs/ac.
Loading (TP)	1.5	2.1	lbs.
Load Rate (TS)	10	7	lbs/ac.
Loading (TS)	300	490	lbs.

Table 4.2 BMP data for Simple Case Experiment

BMP	1	2	3	Units
Cost	\$2.50	\$100.00	\$70.00	\$/acre
Reduction (TN)	0.02	0.35	0.25	
Cost Efficiency (TN)	1.25	2.86	2.80	\$/% removed
Reduction (TP)	0.02	0.25	0.50	
Cost Efficiency (TP)	1.67	4.00	1.40	\$/% removed
Reduction (TS)	0.01	0.30	0.10	
Cost Efficiency (TS)	3.33	3.33	7.00	\$/% removed
Applies to Land Use:	A	A	B	

Formulated into a linear program by applying the data in Tables 4.1 and 4.2 to the equations presented in Chapter 3, the problem reads:

$$\begin{aligned}
 & \text{MIN } -0.01x_1 - 0.175x_2 - 0.075x_3 - 0.00075x_1 - 0.0125x_2 - 0.015x_3 - \\
 & \quad 0.075x_1 - 3x_2 - 0.7x_3 \\
 & \text{S. T.} \\
 & \quad x_1 + \quad x_2 \quad \leq 30 \\
 & \quad \quad \quad x_3 \leq 70 \\
 & \quad 2.5x_1 + 100x_2 + 70x_3 \leq \text{<BUDGET>} \\
 & \quad x_1 \quad \geq 0 \\
 & \quad \quad x_2 \quad \geq 0 \\
 & \quad \quad \quad x_3 \geq 0 \\
 & \text{END}
 \end{aligned}$$

Figure 4.1 Linear Program formulation of simple case experiment optimization.

In Figure 4.1, x_1 , x_2 , and x_3 represent the number of acres used for each BMP 1, 2 and 3, respectively. The coefficients in the objective function are derived from the removal rates for each BMP 1, 2, and 3 in such a way that when they are multiplied by the area

used for each BMP x1, x2, and x3, the negative of the load removed can be quantified. Thus when summed, the value is equal to the negative of the total load removed with that specific BMP plan. By minimizing the negative of the load, the optimization program is actually maximizing the amount of pollutant removed, which is the goal of BMPs. Finally, the coefficients in the last constraint are the unit costs for each BMP 1, 2, and 3. Thus when summed, the total dollars spent on BMPs must be less than the budget specified by the user.

As the budget increases from a low of 50 dollars to a high of 8000 dollars, the optimal solution shifts from choosing BMP 1 for 100% of area of Land Use A, to choosing BMP 2 for 100% of the area of Land Use A, to choosing BMP 2 for 100% of the area of Land Use A, and finally to BMP 3 for 100% of the area of Land Use B.

Table 4.3 Results of Simple Case Optimization over Array of Budgets

Budget	BMP 1 (%LU A)	BMP 2 (%LU A)	BMP 3 (%LU B)	Nitrogen Load (lbs)	Phosphorus Load (lbs)	Sediment Load (lbs)	Budget Spent
\$50.00	66.67%	0.00%	0.00%	35.80	3.58	788.00	\$50.00
\$75.00	100.00%	0.00%	0.00%	35.70	3.57	787.00	\$75.00
\$100.00	99.13%	0.87%	0.00%	35.66	3.57	786.24	\$100.45
\$500.00	85.47%	14.53%	0.00%	34.98	3.52	774.36	\$500.00
\$1,000.00	68.37%	31.63%	0.00%	34.13	3.46	759.48	\$1,000.18
\$2,000.00	34.20%	65.80%	0.00%	32.44	3.34	729.75	\$1,999.65
\$3,000.00	0.00%	100.00%	0.00%	30.75	3.23	700.00	\$3,000.00
\$4,000.00	0.00%	100.00%	20.41%	29.68	3.01	690.00	\$4,000.09
\$5,000.00	0.00%	100.00%	40.81%	28.61	2.80	680.00	\$4,999.69
\$6,000.00	0.00%	100.00%	61.23%	27.54	2.58	670.00	\$6,000.27
\$7,000.00	0.00%	100.00%	81.63%	26.46	2.37	660.00	\$6,999.87
\$7,900.00	0.00%	100.00%	100.00%	25.50	2.18	651.00	\$7,900.00
\$8,000.00	0.00%	100.00%	100.00%	25.50	2.18	651.00	\$7,900.00

As seen in Figure 4.2, as the budget increases, the optimizer is no longer held to using the more cost efficient BMP and can sacrifice cost in order to remove more pollutant load.

In addition, once the best possible load reduction scenario is found (in this case BMP 2 = 30 acres, BMP 3 = 70 acres), the cost at that point (\$7,900.00) can be referred to as the *maximum actual BMP cost*. This is the highlighted line in Table 4.3. Beyond a budget of \$7900.00, all of the area is being treated with the best and most effective and expensive BMP. Therefore, after this point there will always be budgeted funds which are not spent.

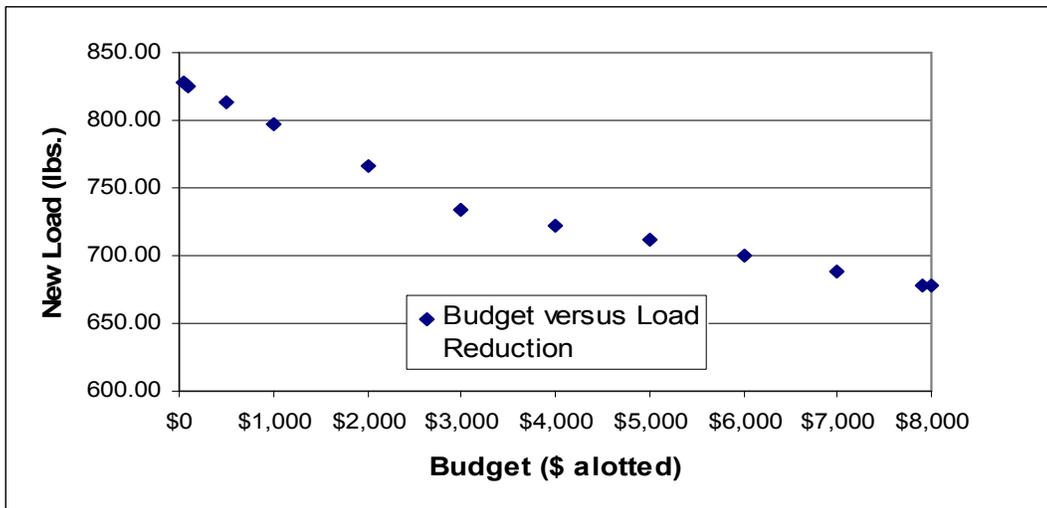


Figure 4.2 Budget versus actual loading after BMP application for simple case experiment

4.2 Experiment 1

4.2.1 Overview

The goal of this experiment was to examine the load reducing capacities as a function of unit budget (dollars spent per acre of watershed) of a watershed with a dominant land use

type. Prior to the experiment, each of the study watersheds was partitioned based on its land use into three land use categories: Agriculture, Urban and Natural. For Experiment 1, four watersheds were selected: one with a dominant agricultural land use (#9 – Morgan Creek), one with a dominant urban land use (#42 – Jones Falls), one with a dominant natural land use (#19 – Deep Run), and one with an even distribution of the three land uses (#33 – North Branch of the Patapsco River).

Table 4.4 Summary of Land Use Distribution for Watersheds Used in Experiment 1

Watershed		Area (ac.)	% Land Use		
No.	Name		Agriculture	Urban	Natural
9	Morgan Creek	2206	69%	8%	23%
19	Deep Run	27788	0%	1%	99%
33	North Br. Patapsco	41981	33%	27%	40%
42	Jones Falls	26394	6%	81%	13%

The independent variable for this experiment is the unit budget and varies between \$1/acre and \$85,000/acre. The dependent variable is the reduction in pollutant loadings relative to the existing loadings for each of three pollutants: nitrogen, phosphorus and sediment. The reductions in pollutant loadings were obtained by running the BMP optimizer for the case where the objective function seeks to minimize total pollutant loadings (an evenly weighted sum of all three pollutants) subject to a budget which is determined on a watershed-by-watershed basis by multiplying the unit budget by the total watershed area.

After running the optimizer for each of the unit budgets, the reductions for each pollutant were plotted against the unit budgets and examined to address four questions:

1. Which of the three land use types yield the greatest reductions in a given pollutant?
2. At what point does the optimal solution cost become less than the budgeted amount?
3. What is the maximum load reduction at this point?
4. What do the load reduction trends and the cost trends look like?

4.2.2 Results and Discussion of Experiment 1

As shown in Figure 4.3, the cost of the optimal solution at each unit budget level ranged from being 100% of the budget to being a small fraction of the budget. In general, as the unit budget increased, the actual cost equaled the budget until the *maximum actual cost* was reached. At this point, the actual cost remained at the same level no matter how high the budget went.

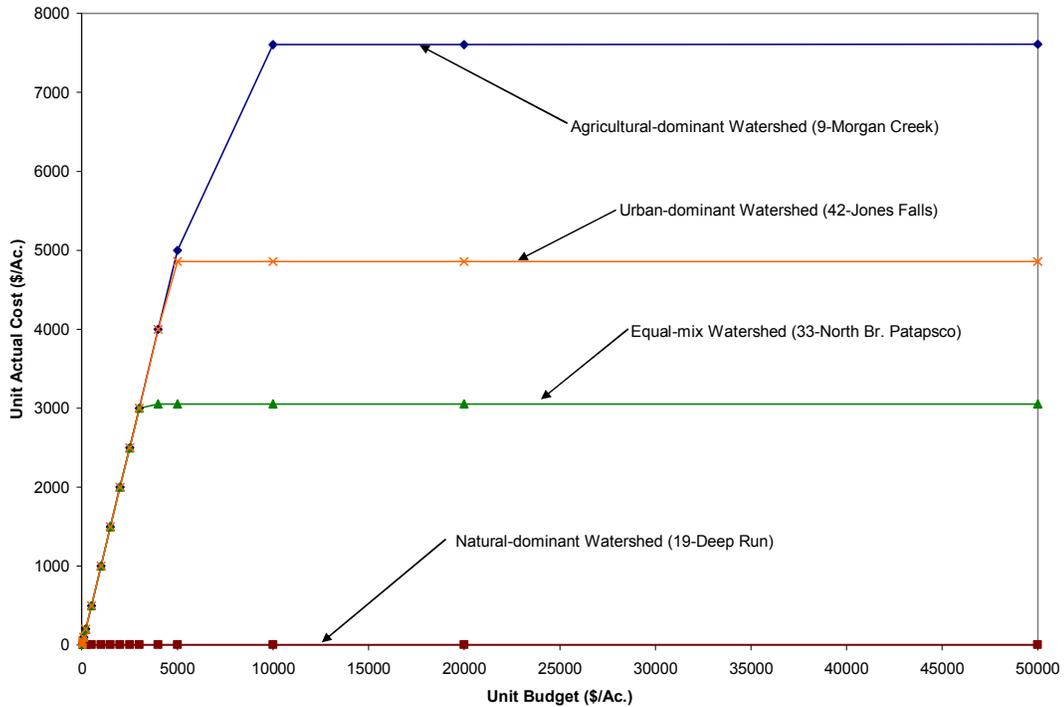


Figure 4.3 Unit actual cost versus unit budget for Experiment 1.

Relative to each other, the trends indicate that watersheds with higher portions of natural land use, and therefore less area to implement BMPs have the lowest maximum actual costs. Agriculture land use-dominant watersheds tend to have higher maximum actual costs than watersheds dominated by other land uses. Urban-dominant watersheds tend to have lower maximum actual costs than their agriculturally-dominant counterparts but higher than well-mixed watersheds or natural-dominant watersheds.

An important point to note is the relative costs of applying agricultural BMPs versus applying urban BMPs. Urban BMPs are generally more expensive than agricultural BMPs and often achieve less load reduction per dollar spent. Therefore, it is more likely

to use leftover dollars on additional BMPs in an agricultural land use-dominated watershed than in an urban land use-dominated one. Therefore, agricultural land use-dominant watersheds generally have a higher maximum actual cost than urban land use-dominant watersheds. Furthermore, agricultural land use-dominant watersheds also generally have a higher maximum load reduction than their urban counterparts because of this trend.

As shown in Figures 4.4-4.6, pollutant reduction trends show diminishing returns as the budget increases. As the unit budget increases, the rate of increase in pollutant reduction becomes progressively smaller. At the point of the maximum actual cost, this rate of increase is zero and the reduction in pollutant load, the *maximum reduction* is reached. Each of the pollutants approaches its maximum reduction levels at a different unit budget. Total nitrogen reaches its maximum reduction around approximately the \$500/acre level while total phosphorus and total sediments reach their maximum reduction around the \$5000/acre level.

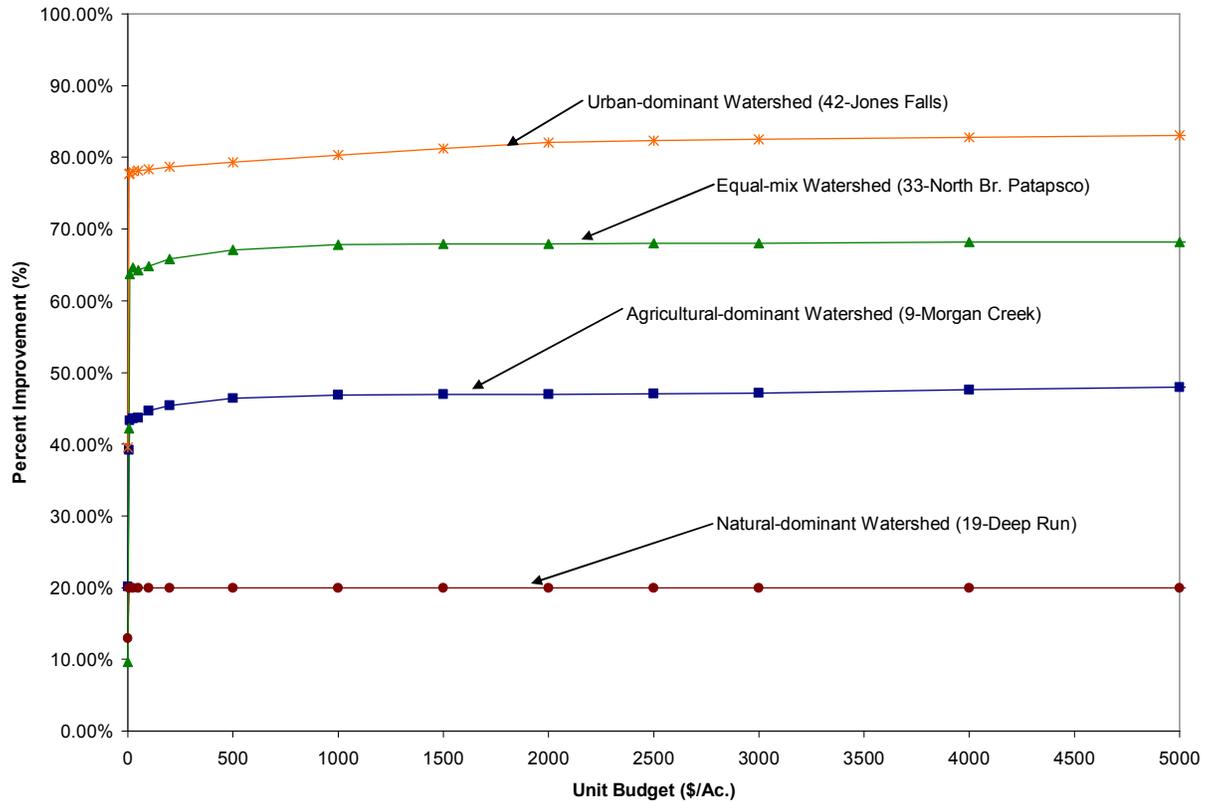


Figure 4.4 Percent improvement in total nitrogen versus unit budget for Experiment 1.

Like the pollutants, each of the four study watersheds approaches its maximum reduction for each pollutant at a different unit budget. The agricultural land use-dominant Morgan Creek (#9) reaches its maximum reduction for total nitrogen at approximately the \$3000/acre level while the natural land use-dominant Deep Run (#19) reaches its maximum reduction for total nitrogen at the \$5/acre level (Figure 4.4). For phosphorus, Deep Run hits its maximum reduction level around the \$5/acre level, followed by the well-mixed land use North Branch of the Patapsco River (#33) at approximately \$3000/acre, the urban land use-dominant Jones Falls at \$5000/acre and then the agricultural land use-dominant Morgan Creek around \$10,000/acre (Figure 4.5). For sediment, the amount of reduction is much lower compared to nitrogen or phosphorus as

the maximum reduction level occurs for the mixed North Branch of the Patapsco River at less than 40% (Figure 4.6).

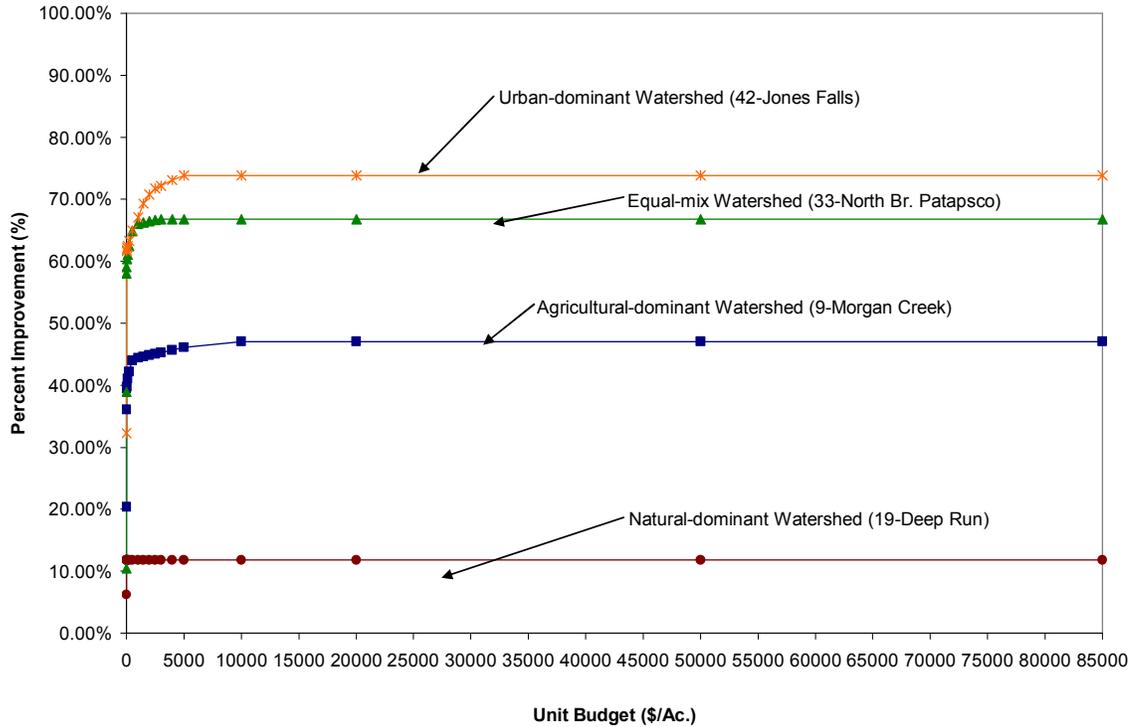


Figure 4.5 Percent improvement in total phosphorus versus unit budget for Experiment 1.

At the maximum actual cost budget level, the optimal plan produces the best reduction for a given unit budget. In Experiment 1, the urban-dominant Jones Falls produces the best reduction for total nitrogen and total phosphorus followed by the North Branch of the Patapsco River, Morgan Creek and then Deep Run. It should be reiterated here that although Deep Run has the lowest reduction rates, that is not necessarily indicative of poor watershed conditions as its natural land use produces, on average, the smallest loadings of any of the watersheds. For total sediment, the mixed North Branch of the Patapsco River and Morgan Creek are first and second, respectively, in terms of total

sediment reduction, followed by Jones Falls and finally Deep Run. This indicates that more agricultural land use allows for BMPs with better sediment load-reducing properties.

Table 4.5 Maximum Load Reduction Percentages for Each Watershed and Pollutant in Experiment 1

Watershed		% Reductions		
No.	Name	Total Nitrogen	Total Phosphorus	Total Sediments
9	Morgan Creek	49%	47%	30%
19	Deep Run	20%	12%	8%
33	North Br. Patapsco	68%	67%	37%
42	Jones Falls	83%	74%	21%

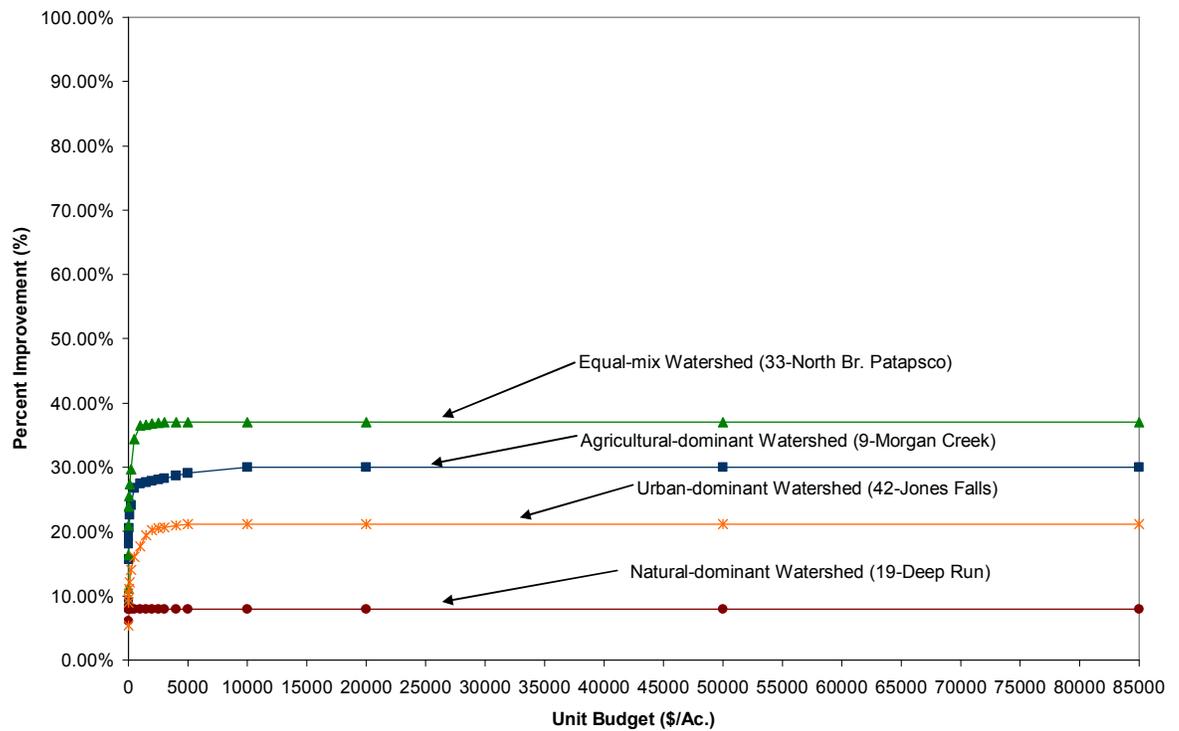


Figure 4.6 Percent improvement in total sediments versus unit budget for Experiment 1.

4.3 Experiment 2

4.3.1 Overview

The goal of this experiment was to examine if a relationship exists between the land use makeup of a watershed and the load reducing potential of the watershed with respect to the BMPs that can be applied to it. Based on its land use, each of the 53 study watersheds described in Chapter 3 and in Appendix F was partitioned into three land use categories: agriculture, urban and natural. For the purposes of visualizing the distribution of land use across the study watersheds, each watershed was plotted on a ternary diagram shown in Figure 4.7 based on the proportion of each of the three land use classes in it.

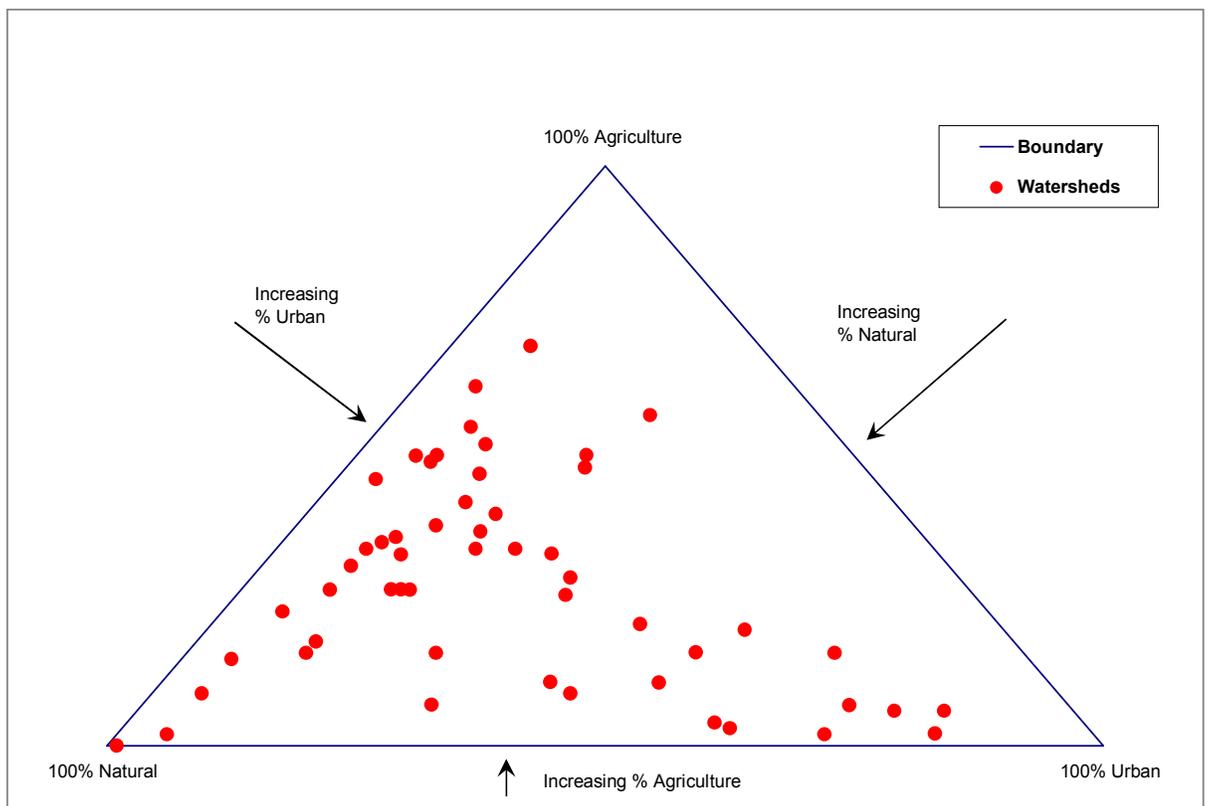


Figure 4.7 Ternary diagram plot of each of the 53 watersheds based on their land use distribution.

The independent variable for this experiment is the fraction of land use category 'x' (where 'x'= agricultural, urban, or natural) and varies between 0 and 1. The dependent variable is the reduction in pollutant loadings relative to the existing loadings for each of three pollutants: nitrogen, phosphorus, and sediments. The reductions in pollutant loadings were obtained by running the BMP optimizer for the case where the objective function is to minimize total pollutant loadings (an evenly weighted sum of all three pollutants) subject to a budget which is determined on a watershed-by-watershed basis by multiplying the unit budget by the total watershed area.

After running the optimizer for each of the unit budgets (\$10/Ac., \$100/Ac., \$200/Ac., \$500/Ac., \$1000/Ac., and \$5000/Ac.), the reductions for each pollutant were graphed against the fraction of land use for each of the three land uses: agricultural, urban and natural, and for each of the three pollutants: nitrogen, phosphorus, and sediment. Several questions were specifically addressed:

1. Is there a relationship between land use fraction and pollutant load reduction?
2. What dominant land use type is associated with the greatest (and smallest) reduction in each pollutant?
3. What role does land use mixing play in this phenomenon?
4. Are there any other trends that can be identified?

4.3.2 Results and Discussion of Experiment 2

Experiment 2 was carried out in two parts. The first part was a simple two land use case where a fictitious watershed contained only “High Till with Manure” and “High Intensity Developed – Impervious” land uses (and therefore only their respective BMPs were applicable). The results, shown in Figure 4.8 demonstrated very smooth trends as the percentages of each land use varied from 0% to 100% in 10% increments.

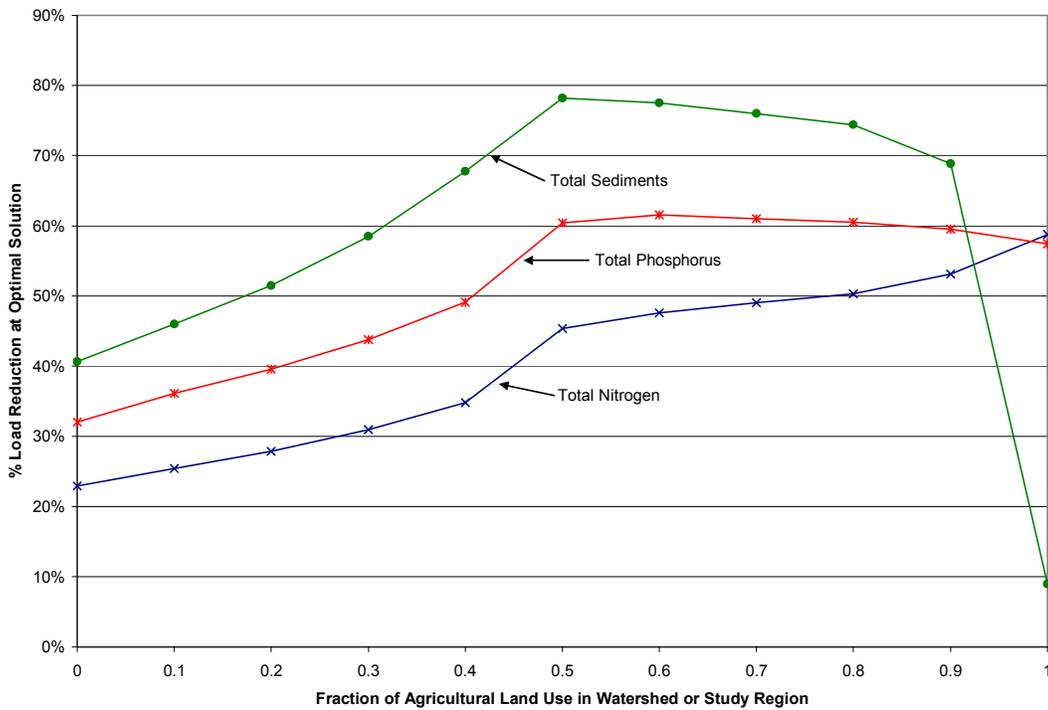


Figure 4.8 Results of two land use experiment for urban and agricultural land uses and a unit budget of \$1872.23/ac.

Figure 4.8 indicates that certain nutrients are treated better by agricultural BMPs than urban BMPs and vice versa. For example, when the fraction of urban land use is low, the load reduction for total nitrogen is high and decreases as urban land use increases (and agricultural land use decreases). However, for total sediment, the highest load reduction

occurs when the ratio of urban land use to agricultural land use is approximately one to one and is lowest when the fraction of agricultural land use dominates.

The results from a three land use experiment also produced smooth trends when the pollutant reduction versus the fraction of each land use type was plotted on a three-dimensional ternary diagram. As each of the three diagrams indicates, load reduction for each pollutant trends towards a specific land use. For example, Figure 4.9 indicates that higher nitrogen reduction can be achieved in areas where pasture is the dominant land use (as shown by the darker shading). Figure 4.10 shows that somewhat higher phosphorus reduction (approximately 15%) can be achieved in areas dominated by the high till with manure land use. Finally, Figure 4.11 shows that load reductions in sediments are slightly higher (approximately 3-5%) in areas dominated by the high intensity developed – impervious land use.

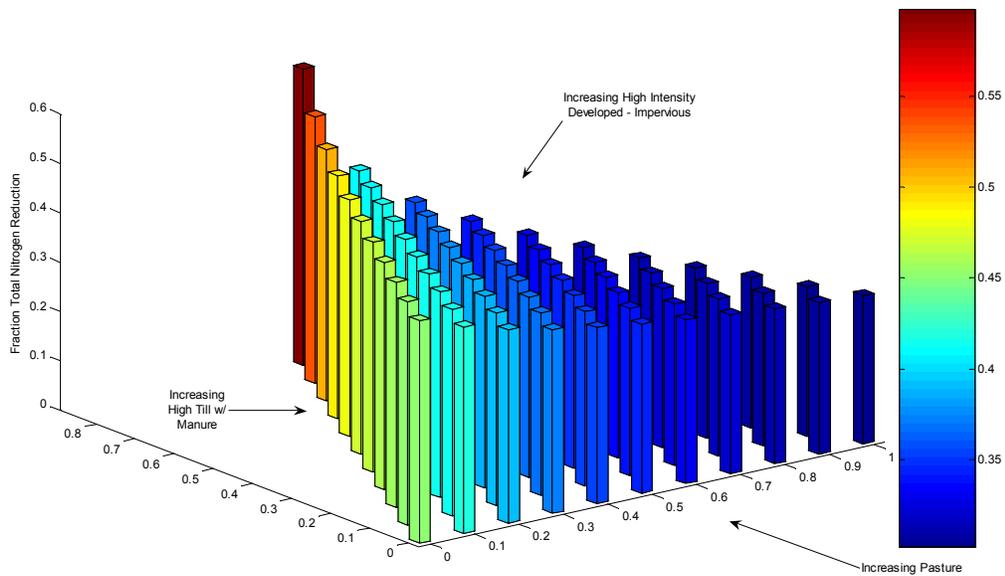


Figure 4.9 Three-dimensional ternary plot of nitrogen reduction versus watershed makeup (three land uses and a unit budget of \$1872.23/ac.).

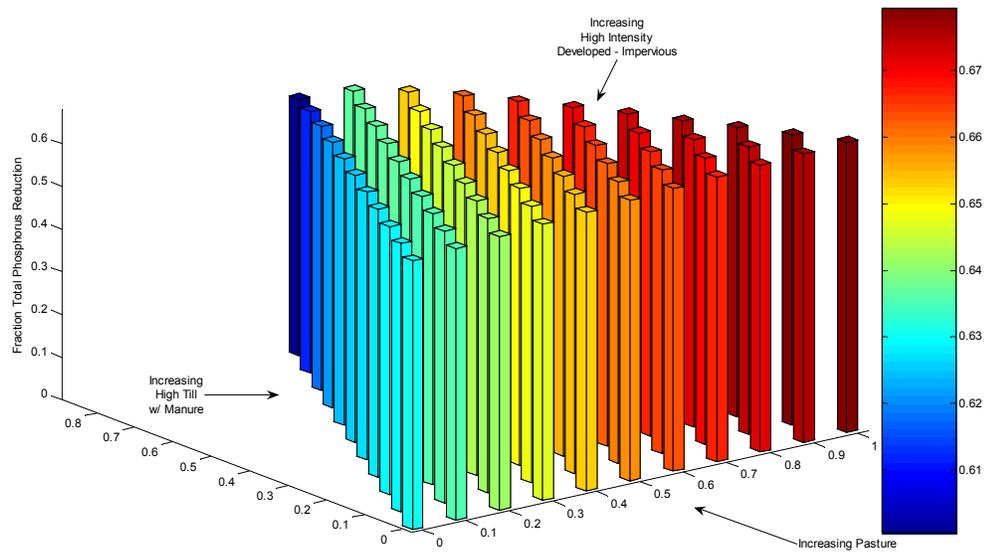


Figure 4.10 Three-dimensional ternary plot of phosphorus reduction versus watershed makeup (3 land uses and a unit budget of \$1872.23/ac.).

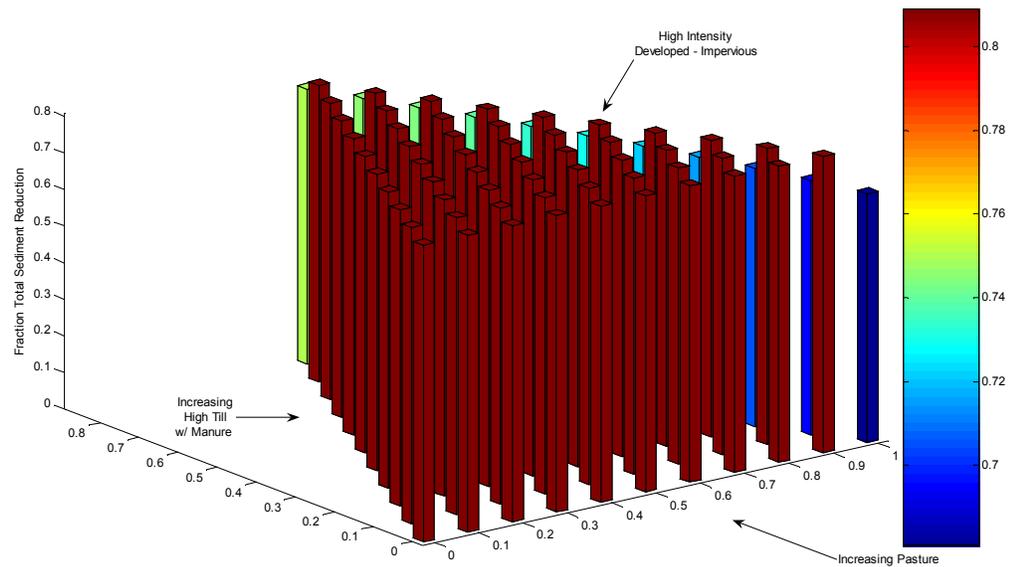


Figure 4.11 Three-dimensional ternary plot of sediment reduction versus watershed makeup (three land uses and a unit budget of \$1872.23/ac.).

The second major part of the experiment was to repeat the experiment for the sample 53 watersheds which have a more complex array of land uses than the ones used in the first part of the experiment. Results from this experiment were much more varied; no trends

between fraction of land use and fraction of pollutant removed for total nitrogen, total phosphorus, or total sediments could be identified in the plots. Although the results varied, there were a several observations that could be made from the plots.

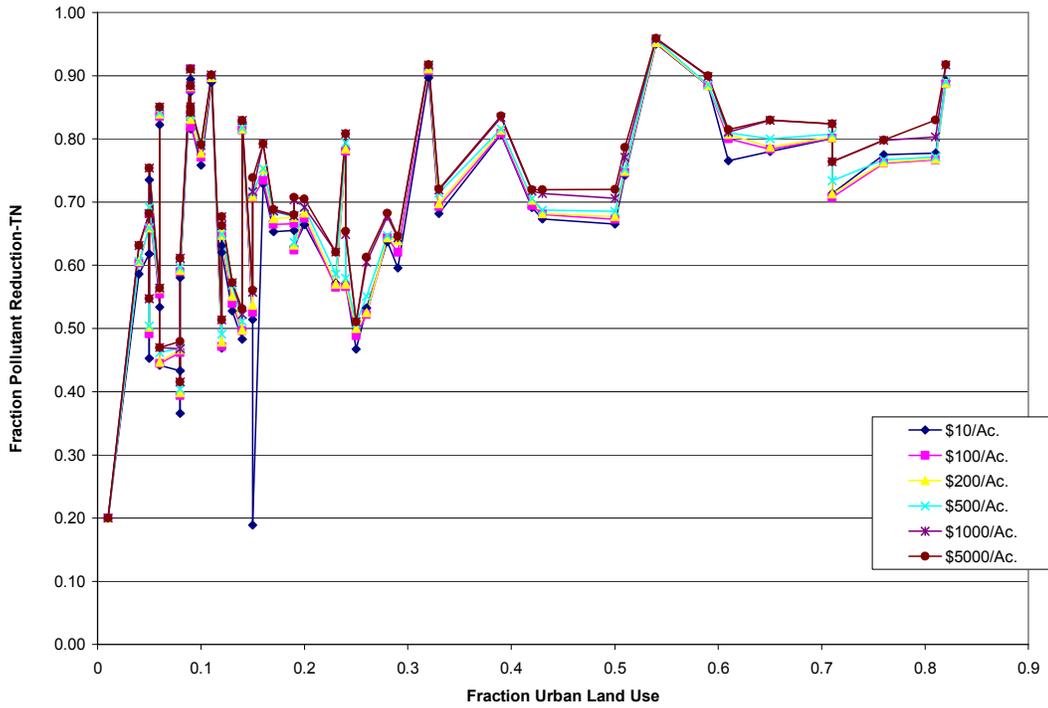


Figure 4.12.1 Fraction of total nitrogen reduction versus fraction of urban land use for several unit budgets. Each point represents the results of a watershed BMP optimization given the unit budget defined in the legend.

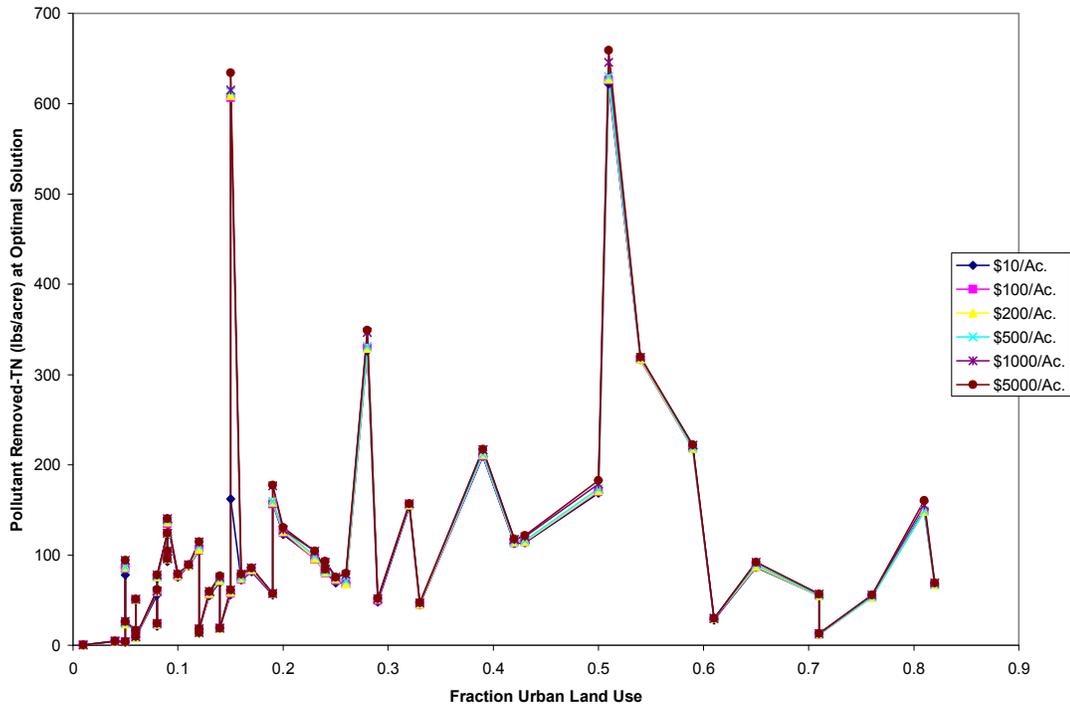


Figure 4.12.2 Total nitrogen (lbs./ac.) reduction versus fraction of urban land use for several unit budgets. Each point represents the results of a watershed BMP optimization given the unit budget defined in the legend.

The first observation is the concept of maximum actual BMP cost. As mentioned in the previous two sections, the maximum actual cost is the highest cost BMP plan that would occur in a ‘limitless’ budget scenario. In Figures 4.12 through 4.14, it can be seen that for some of the points, the plots for different budgets coincide, thus indicating that for either of the highest two budgets and fraction of land use, the load reduction achieved will be the same. This means that the lowest budget plot containing (or including) that point is at or near the maximum actual cost level and any additional budget will not improve the load reduction.

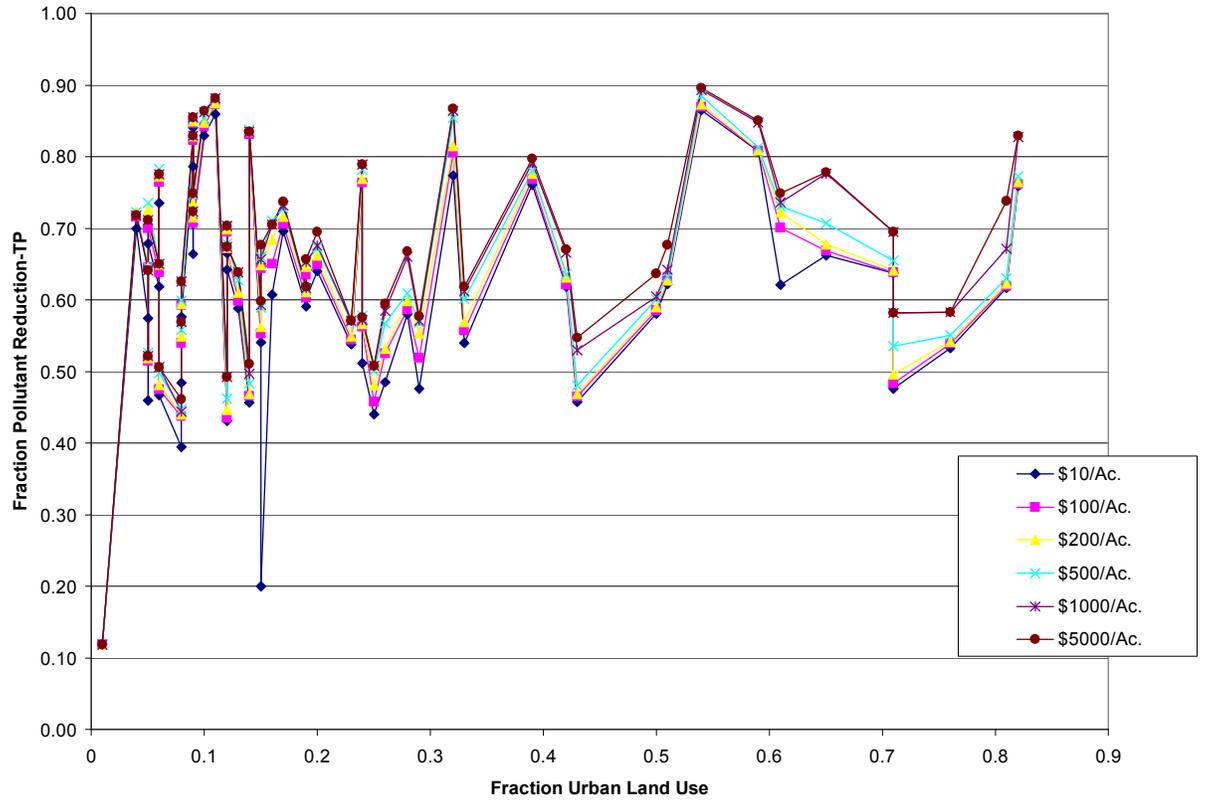


Figure 4.13.1 Fraction of total phosphorus reduction versus fraction of urban land use for several unit budgets. Each point represents the results of a watershed BMP optimization given the unit budget defined in the legend.

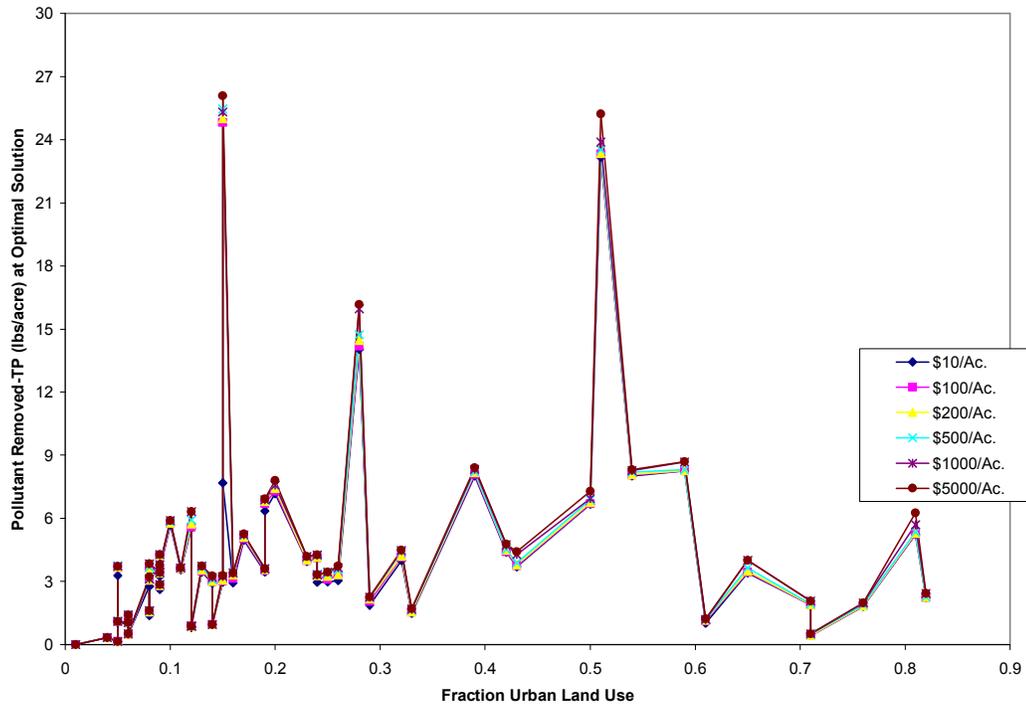


Figure 4.13.2 Total phosphorus reduction (lbs./ac.) versus fraction of urban land use for several unit budgets. Each point represents the results of a watershed BMP optimization given the unit budget defined in the legend.

The second observation from Experiment 2 is the relationship between individual load reduction points for each budget. As the budget increases, the realized load reductions for a given watershed grow closer together. This is especially true and easiest to see in the points for total sediments. Each point for the \$10/acre budget is much further below the corresponding \$100/acre budget point as that point is to the \$200/acre budget and so on. This continues along the range of budgets up to \$5000/acre, the highest budget used in this particular experiment.

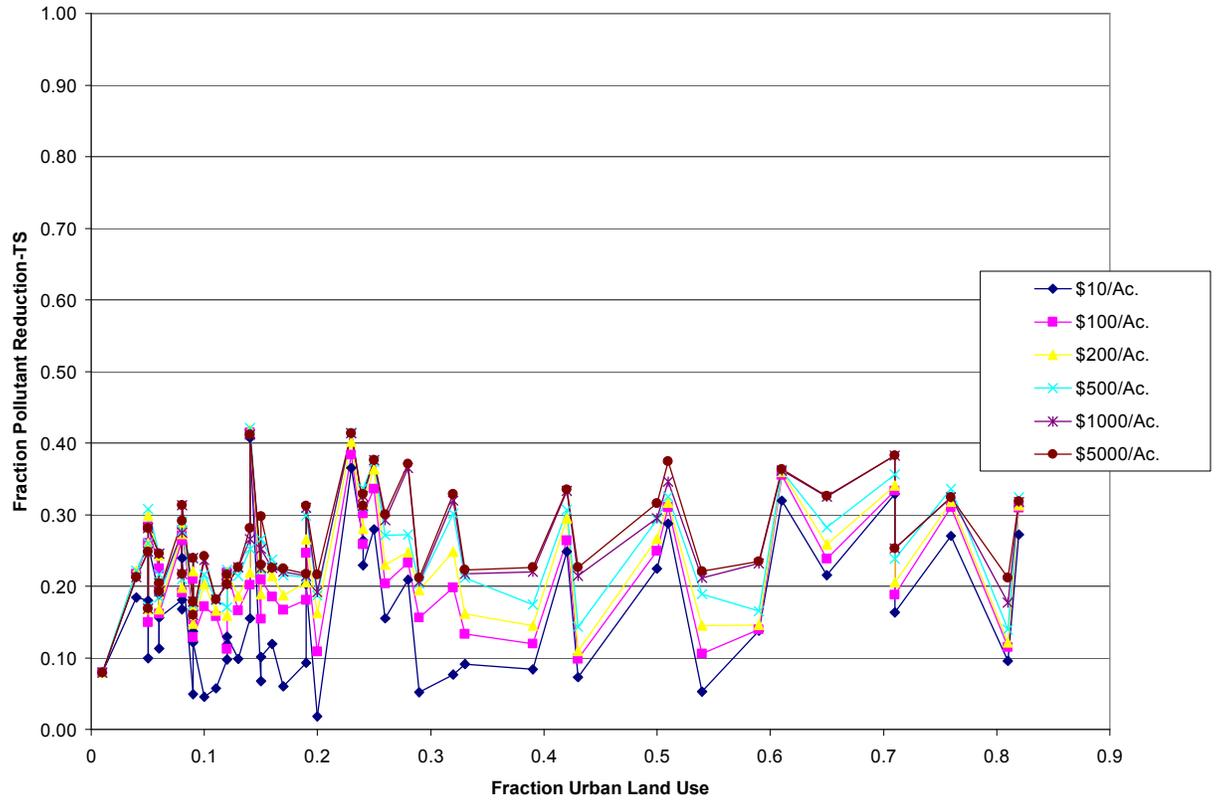


Figure 4.14.1 Fraction of total sediment reduction versus fraction of urban land use for a range of unit budgets. Each point represents the results of a watershed BMP optimization given the unit budget defined in the legend.

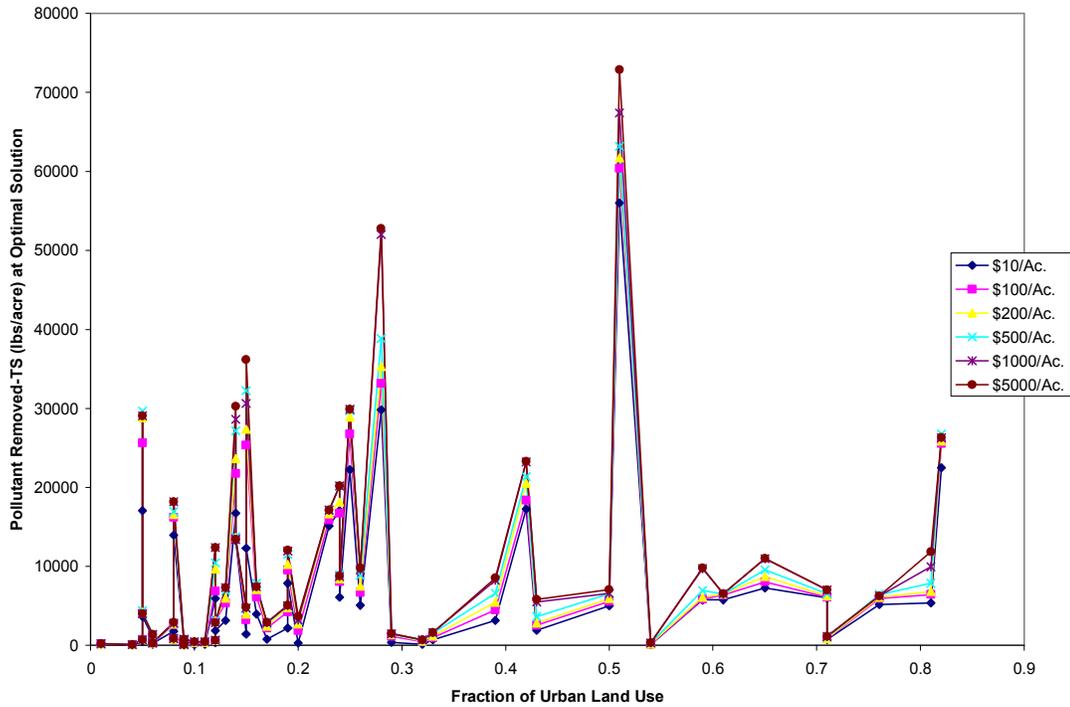


Figure 4.14.2 Total sediment reduction (lbs./ac.) versus fraction of urban land use for a range of unit budgets. Each point represents the results of a watershed BMP optimization given the unit budget defined in the legend.

This phenomenon is consistent with the results of Experiment 1, which show diminishing increases in pollutant reduction as the budget increases.

4.4 Experiment 3

4.4.1 Overview

Experiment three sought to find a correlation between the attractiveness of a BMP prior to use in an optimal BMP plan and the actual use of that BMP in the plan. Attractiveness is defined as dollars spent per fraction of pollutant removed. This experiment addresses two questions:

- 1) Is a highly attractive BMP (indicated by a low “dollars per fraction removed” value) necessarily the best BMP to use to reduce pollutant loading?
- 2) Should this BMP be used as much as it possibly can because of its highly attractive (cost efficient) nature?

A simple experiment, formulated in Figure 4.15, demonstrates the central focus of Experiment 3. Consider a 100 acre one-land use situation with two possible BMPs. BMP 1 costs \$100/acre and has a reduction efficiency of 5% for pollutant x . BMP 2 costs \$1800/acre and has a reduction efficiency of 60%. For an existing load of 1000 lbs. and a water quality reduction goal of 50% for pollutant x , the linear program is written as follows:

```

MIN 100x1 + 1800x2
ST
      x1 +      x2 <= 100
    0.5x1 +    6x2 >= 500
      x1          >= 0
              x2 >= 0
END

```

Figure 4.15 Linear program formulation of simple optimization for Experiment 3.

Based on the cost and reduction efficiencies for each of the BMPs, BMP 1 would rank higher because its perceived attractiveness is \$100/5% or twenty dollars per 1% pollutant reduction as opposed to BMP 2 whose perceived attractiveness is \$1800/60% or thirty dollars per 1% reduction. However, after performing the linear optimization, the optimal solution is 81.81 acres of BMP 2 and 18.18 acres of BMP 1 for total minimum cost of \$149,090.90. Thus, BMP 2 is actually more effective than BMP 1 even though the

opposite scenario was perceived to be the case based on cost per reduction rate. The key to this shift is the difference in the rate at which pollutant is removed. BMP 1, while more cost efficient, has a reduction rate lower than the desired water quality reduction. BMP 2 has a reduction rate that is greater than the desired water quality rate. Because using BMP 2 meets the water quality goal while using BMP 1 cannot do so, BMP 2 is preferred. This shows the advantage of using optimization methods such as linear programming to develop cost efficient BMP plans in order to achieve a high level of pollutant removal for a minimal cost.

Experiment 3 involved ranking each BMP by its perceived attractiveness as well as by its actual performance in several optimizations (53 watersheds for meeting low, medium and high water quality standards). Figures 4.16.1- 4.16.4 show the BMP performance for each pollutant, total nitrogen, total phosphorus, and total sediments and an average of all three, versus the performance for each water quality level, low, medium, and high as well as an average of all three. Table 4.6 summarizes the specific water quality reduction goals used in this experiment.

Table 4.6 Water Quality Reduction Goals

Water Quality Level	Nitrogen Reduction	Phosphorus Reduction	Sediment Reduction
Low	25%	25%	5%
Medium	30%	30%	15%
High	40%	40%	20%

The actual performance ranking was based on the fraction of the amount of land used for a BMP versus the amount of potential land that the BMP could occupy. Specifically, the

actual performance is the land area occupied by a BMP divided by the total possible land area that BMP could occupy which is also the land use that the BMP is applied to. The rankings were graphed with the perceived BMP attractiveness ranking as the independent variable and the ranking of actual BMP use as the dependent variable. A perfect relationship between perceived and actual attractiveness would be indicated by a straight line at a 45 degree angle.

4.4.2 Results and Discussion

The initial results, shown in Figures 4.16.1-4.16.3 of the experiment showed moderate correlation between perceived attractiveness and actual use. For all plots, there seemed to be some visual correlation between a BMP's perceived attractiveness and its actual use in the optimal BMP plan. In addition, the computed Spearman correlation coefficients agreed that some correlation exists between perceived attractiveness and actual use.

Table 4.7 Spearman Correlation Coefficients for BMP Attractiveness versus Actual Use

ρ	Low WQ	Medium WQ	High WQ
TN	0.487	0.496	-0.284
TP	0.494	0.449	0.301
TS	0.495	0.370	0.215

However, upon closer investigation, several of the more attractive BMPs were not being used as much because they didn't address land uses whose pollutant loadings were high contributors to the overall pollutant load for the watershed. In other words, the applicability of a BMP to a given land use has a strong influence on the level of use of that particular BMP.

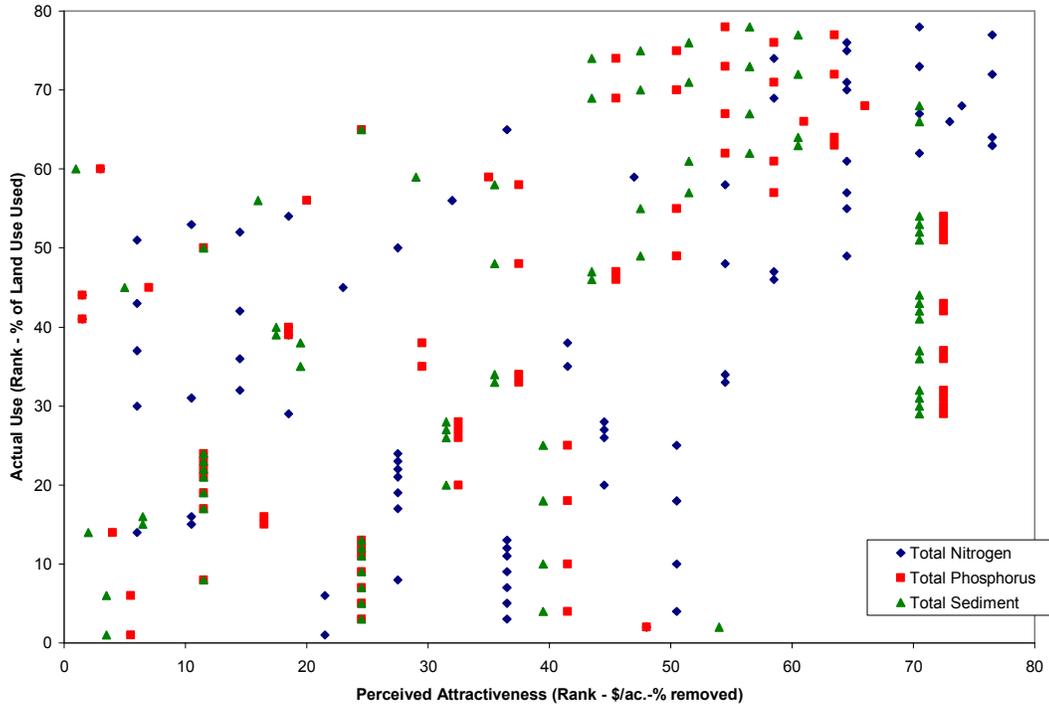


Figure 4.16.1 Actual performance rank versus perceived BMP attractiveness rank for low water quality levels.

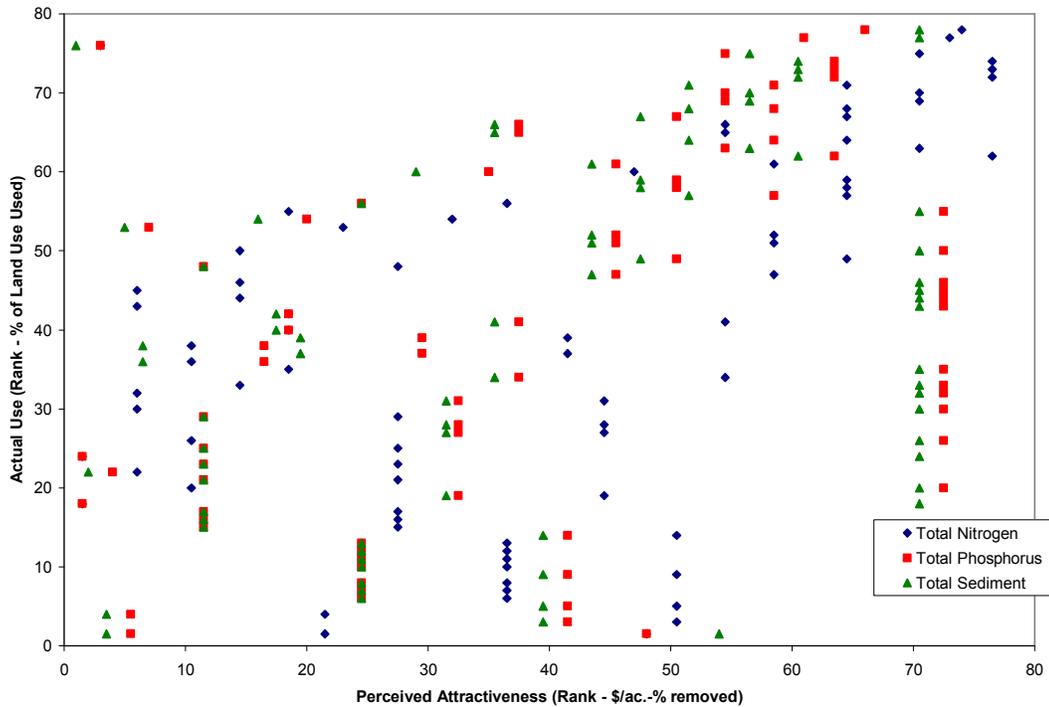


Figure 4.16.2 Actual performance rank versus perceived BMP attractiveness rank for medium water quality levels.

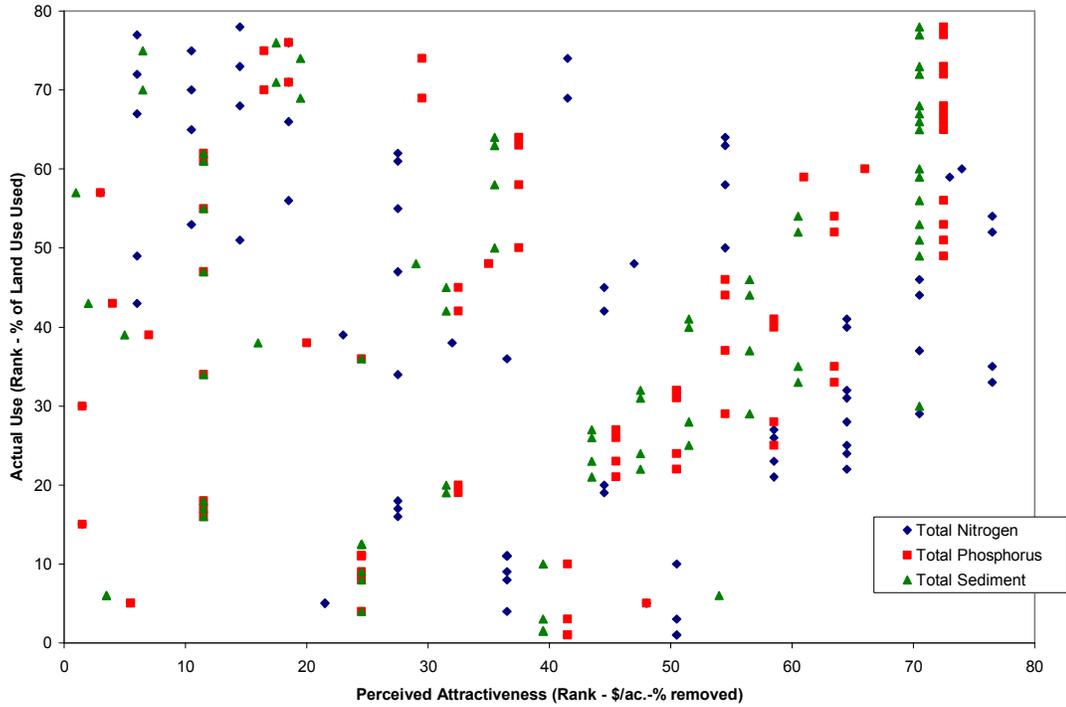


Figure 4.16.3 Actual performance rank versus perceived BMP attractiveness rank for high water quality levels.

To account for this influence, a coefficient is defined based on that fraction of total loading contributed by a given land use that can be mitigated by the BMP in question.

The coefficient is computed as:

For BMP i , applying to land use j and pollutant k :

$$C_i = 1 - \frac{\text{Existing_Load}(j,k)}{\sum_j \text{Existing_Load}(k)} \quad (4.1)$$

For example, a BMP whose land use contributed to 75% of a watershed's total nitrogen loading would be perceived as more attractive even if it had a high cost per fraction of

pollutant removed. When ranked against all other BMPs, the BMP in question would be given a higher ranking which would correlate better to its actual performance ranking.

Results of the modified attractiveness rankings were slightly better than those of the original attractiveness rankings. While Figure 4.17 shows there is still considerable scatter in the relationship between a BMP’s attractiveness and its actual performance in a BMP optimization, the improved Spearman correlation coefficients indicate that there is a significant relationship between a BMP’s perceived attractiveness and its actual use in the optimal plan. Correlation between perceived and actual BMP attractiveness was similar for low and medium water quality levels but less for high water quality.

Table 4.8 Spearman Correlation Coefficients of Modified BMP Attractiveness versus Actual Use

ρ	Low WQ	Medium WQ	High WQ
TN	0.503	0.503	-0.278
TP	0.497	0.449	0.300
TS	0.505	0.374	0.218

At high water quality levels where the goal is to remove a lot of pollutant, more BMPs are used in different quantities and cost is sacrificed to obtain the desired water quality level. Because of this, the actual rankings may not correlate to the perceived rankings as well as they do at lower water quality levels. In addition, the lower correlations between perceived and actual attractiveness for the total sediment perspective can be attributed to a lack of data for total sediment removal for many BMPs.

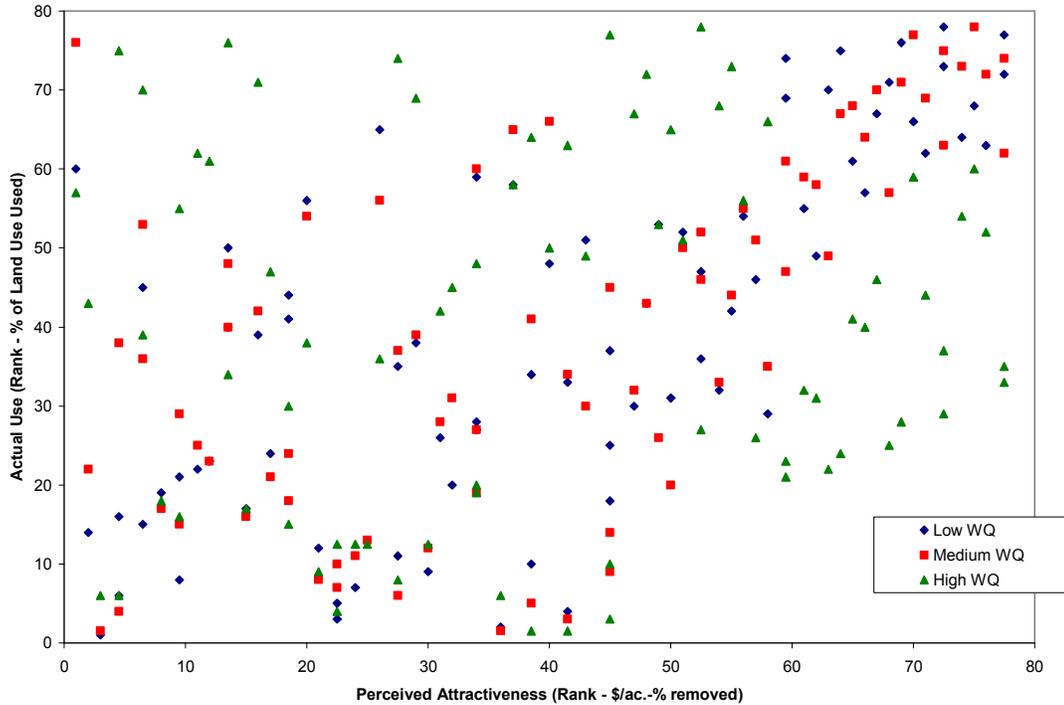


Figure 4.17 Rank of BMPs by their actual performance rank versus perceived attractiveness using a modified attractiveness value. Figure only shows average rankings over all pollutants.

While the results of the experiment were not conclusive, they did indicate a very important point: while certain BMPs may seem very attractive, they may not be the optimal BMPs to use.

Optimization methods may be able to pick up on certain nuances of problems with many dimensions such as an optimization of 78 BMPs over 26 land uses with a goal of reducing the loads of three different pollutants.

4.5 Experiments Summary

The results of each experiment provide some insight into phenomena surrounding BMP optimization. Experiment 1 shows how the law of diminishing returns applies to BMP

optimization and that progressively less pollutant load reduction is seen for progressively more money spent. Additionally, Experiment 1 identifies the concept of maximum actual cost which is the cost at which the best load reduction is achieved and for more money, no additional load reduction can be realized. Experiment 2 shows that for simple watersheds with only a few land uses, watersheds with a larger area of one type of land use realize greater load reductions than watersheds with a smaller area of that type of land use. However, Experiment 2 also showed that for more realistic watersheds where there are many types of land uses, the trend is weaker to see if existent at all. Finally, Experiment 3 shows that while there is a moderate connection between a BMP's perceived attractiveness and how much it is actually used in the optimum BMP plan, this relationship significant, it is not reliable for all BMPs all of the time. This observation indicates the importance of numerical BMP optimization to create optimal plans due to the nuances of a watershed unseen by the human eye.

The main observation to take from these experiments is that the BMP optimization problem as it is described in this work is far too complex to solve by hand or with intuition. Therefore, relying on numerical optimization methods to solve the problem is a more effective way to develop a BMP plan for a watershed or region.

Chapter 5: Summary and Conclusions

5.1 Summary of the Research

This thesis explores the notion of applying optimization techniques to Best Management Practices (BMP) planning using the Chesapeake Bay watershed and more specifically, the state of Maryland as the backdrop for the research. While there are several examples of previous efforts to link the two concepts into one practice, no single example has sought to create this link on the scale that this research has. Specifically, this work develops the capability to produce optimal BMP plans for multiple pollutants given study areas with varied land uses and loading coefficients, and an array of different BMPs, each with different reduction rates and unit costs.

A complicating factor to the linear programming approach used in this study is that BMP load reduction may be either additive or multiplicative in numerical structure. The additive structure of load reduction is consistent with a linear programming approach. However, applying multiplicative BMPs creates non-linear equations which require non-linear optimization to solve. While this approach was tried in the study, results proved too inconsistent to be used as optimal solutions.

After spending some time exploring non-linear solution methods, the difficulties of solving a non-linear optimization of many dimensions in an efficient manner became clear. The main difficulty was that the optima identified by the non-linear optimizer were local, rather than global, and were difficult to interpret. Simplifications to the problem formulation were made to obtain reliable global solutions. By treating all BMPs as additive, linear programming was re-introduced as the method with which to solve the BMP optimization problem.

In addition to the generic BMP optimization described above, a routine was developed to determine the optimal set of BMPs of specific size, location, and type as chosen from a larger set of candidate BMPs. These binary decisions (“build”/ “no build”) were made using binary programming, a relative of linear programming.

Several experiments were performed to explore different characteristics of optimized BMP plans. Experiment 1 showed that the law of diminishing returns applies to optimal BMP plans. As the available budget increases, progressively smaller improvements in load reduction were obtained. Experiment 2 showed that, for simple cases, trends exist between the fraction of a certain land uses and the load-reducing capabilities of the optimal BMP plan. However, for more complex and realistic cases, the trends are not as clear. In addition, Experiment 2 introduced the concept of “maximum actual cost” which is the highest dollar value of the optimal BMP plan. No improvement in load reduction can be realized beyond this cost. Experiment 3 showed that there is moderate correlation between ‘attractive’ BMPs (high reduction rates, low costs) and their prevalence in the

optimal BMP plan. While this observation indicates that there is some connection between a BMP's perceived attractiveness and its actual use, it is not high enough to always be reliable. This finding highlights the importance of BMP optimization: determining the optimal plan by inspection or intuition may not yield the optimal BMP plan. Optimization methods are, therefore, useful in generating cost efficient BMP plans.

5.2 Significance of the Research

This work is of greatest value to BMP implementation, most significantly at the planning stage. Because the optimizer gives the optimal area ratios for the available BMP types, it is a natural planning tool. For example, the research was performed in the Chesapeake Bay watershed. The Chesapeake Bay program, charged with monitoring and working with state and local agencies to keep the bay and its watershed healthy, develops 'tributary strategies' to reduce nutrient loading in the Bay's tributaries. With the BMP optimization program, the Bay program has the ability to quickly determine the loadings on each tributary's watershed based on its land use, and develop BMP implementation goals based on the output from the BMP optimizer.

The Bay program can then refine these BMP targets into specific BMP design and construction plans. While not all targets may be achieved according to the optimal plan, the costs will be near to the lowest possible or the load reductions will be close to the maximum reduction in loadings while still meeting the budget for that specific tributary.

The second class of optimizations considered in this work, choosing specific, predetermined BMPs from a larger set of candidate BMPs, may be used more frequently at a finer level of implementation. For a developer or land use planner seeking to plan for a specific parcel of land, laying out any number of BMPs and then optimizing to meet regulatory water quality standards for a minimal cost would bypass the tedious process of trial and error for designing a BMP plan and ultimately lead to cost savings by identifying the most cost or load reduction-efficient BMP plan.

The interface of the BMP optimizer, a geographic information system (GIS), provides a user-friendly method to input information to and receive output from the BMP optimizer. Because of the graphic nature of the GIS, the user can see the land use makeup and location of the study area on the screen. Furthermore, the spatial computations required to determine land use totals in the watershed are easily performed in the GIS.

5.3 Future Research

While this research continues the progress made by previous investigators into best management practice optimization, this study identified several pathways for future research. The most immediate avenue of study involves solving the non-linear version of this problem in an efficient manner where a global optimal solution is reliably obtained as opposed to confounding locally optimal solutions. While solving these non-linear problems is theoretically possible, current optimizers need to be improved to obtain these non-linear optima.

There are numerous ways to study trends associated with BMP optimization that have not yet been explored in this or other studies. Effects of non-linear cost functions, multiplicative BMPs, and variations in loadings and water quality standards are just a few possible areas that might be explored. Because the problem has so many dimensions and is sensitive to many of them, researching how the optimal solution changes with respect to changing any one or more of the parameters of the problem (e.g. nutrients considered, land use distributions, variation in loading rates with space) will lead to valuable insights into BMP optimization and possibly to finding better practical solutions more quickly.

Appendices

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Appendix A

Definition of Notation

A	\Rightarrow the matrix of linear land use constraint coefficients in the generalized case
a	\Rightarrow the matrix of linear land use constraint coefficients represented by the predetermined areas associated with BMPs in the discrete case (acres)
α	\Rightarrow additive load reduction multiplier in Maryland DNR load reduction equations
B	\Rightarrow the array of linear land use constraint upper bounds (acres)
β	\Rightarrow multiplicative load reduction multiplier in Maryland DNR load reduction equations
C	\Rightarrow the array of BMP unit costs (\$/acre)
c	\Rightarrow the array of predetermined BMP costs in the discrete case (\$)
D	\Rightarrow the matrix of linear buffer land use constraint coefficients in the generalized case
d	\Rightarrow the matrix of linear buffer land use constraint coefficients in the discrete case (acres)
F	\Rightarrow the matrix of linear loading constraint coefficients (1/acres) in the generalized case
f	\Rightarrow the matrix of linear loading constraint coefficients in the discrete case
G	\Rightarrow the array of linear buffer land use constraint upper bounds (acres)
I	\Rightarrow total number of eligible BMPs in the optimization
i	\Rightarrow incremental variable to define the BMP being referenced
J	\Rightarrow total number of linear land use constraints in the optimization
j	\Rightarrow incremental variable to define the linear land use constraint being referenced
K	\Rightarrow total number of buffer linear land use constraints in the optimization
k	\Rightarrow incremental variable to define the buffer linear land use constraint being referenced
L	\Rightarrow the lower bound placed on the variable X in the generalized case
LU	\Rightarrow land use area (acres)
$LU_{(X_i)}$	\Rightarrow total land use area in study area or watershed that BMP represented by X_i could possibly be applied to (acres)
$LU_{(x_i)}$	\Rightarrow total land use area in study area or watershed that BMP represented by x_i could possibly be applied to (acres)
LR	\Rightarrow loading rate (pounds/acre-year)
M	\Rightarrow modified load (pounds/year)
N	\Rightarrow the total number of linear loading constraints (equal to the total number of pollutants in the optimization)
n	\Rightarrow incremental variable to define the linear loading constraint being referenced
R	\Rightarrow BMP pollutant removal rate
T	\Rightarrow the value of the budget for the minimize loadings objective (\$)
U	\Rightarrow the upper bound placed on the variable X in the generalized case
W	\Rightarrow the array of linear loading constraint upper bounds for the minimize cost objective
X	\Rightarrow the array of BMP areas at any optimization iteration in the generalized case (acres)
x	\Rightarrow the array of BMP decisions at any optimization iteration in the discrete case
Y	\Rightarrow the weighting coefficient placed on each pollutant for the minimize loads objective
Z	\Rightarrow the value of the objective function at any iteration in the optimization

Appendix B

Maryland BMP Pollutant Reduction Computations

Method of Calculating Nutrient Loads from Landuses with Multiple Best Management Practices (BMPs)

LU = landuse

LR = landuse nutrient loading rate

BMP = BMP acres

E% = BMP nutrient reduction efficiency

Additive BMPs Nutrient Load

$$LU_{[ac]} * LR_{[lb/ac]} * \left[1 - \left(\frac{\left[BMP1_{[ac]} * \left(\frac{E_{BMP1} \%}{100} \right) \right] + \left[BMP2_{[ac]} * \left(\frac{E_{BMP2} \%}{100} \right) \right]}{LU_{[ac]}} \right) \right]$$

Multiplicative BMPs Nutrient Load

$$LU_{[ac]} * LR_{[lb/ac]} * \left[\left(1 - \left[\frac{BMP1_{[ac]} * \left(\frac{E_{BMP1} \%}{100} \right)}{LU_{[ac]}} \right] \right) * \left(1 - \left[\frac{BMP2_{[ac]} * \left(\frac{E_{BMP2} \%}{100} \right)}{LU_{[ac]}} \right] \right) \right]$$

Combination of Multiplicative and Additive BMPs Nutrient Load

$$LU_{[ac]} * LR_{[lb/ac]} * \alpha * \beta$$

where,

$$\alpha = \left[1 - \left(\frac{\left[BMP1_{[ac]} * \left(\frac{E_{BMP1} \%}{100} \right) \right] + \left[BMP2_{[ac]} * \left(\frac{E_{BMP2} \%}{100} \right) \right]}{LU_{[ac]}} \right) \right]$$

and

$$\beta = \left[\left(1 - \left[\frac{BMP3_{[ac]} * \left(\frac{E_{BMP3} \%}{100} \right)}{LU_{[ac]}} \right] \right) * \left(1 - \left[\frac{BMP4_{[ac]} * \left(\frac{E_{BMP4} \%}{100} \right)}{LU_{[ac]}} \right] \right) \right]$$

Sample Calculation for Nitrogen Load from Pasture Acres:

- Pasture Land = 1,000 acres
- BMP 1 Stream Protection with fencing (SPWF) = 100 acres (additive)
- BMP 2 Stream Protection without fencing (SPWOF) = 175 acres (additive)
- BMP 3 Soil Conservation & Water Quality Plan Implementation (SCWQPI) = 350 acres (multiplicative)

Using, *Combination of Multiplicative and Additive BMPs* equation:

$$\text{Nutrient Load} = (1,000 \text{ ac}) * (1.05 \text{ lbs/ac}) * \alpha * \beta$$

$$\alpha = \left[1 - \left(\frac{\left[100 \text{ ac} * \left(\frac{75\%}{100} \right) \right] + \left[175 \text{ ac} * \left(\frac{38\%}{100} \right) \right]}{1,000 \text{ ac}} \right) \right] = 0.859$$

$$\beta = \left[\left(1 - \left[\frac{350 \text{ ac} * \left(\frac{17\%}{100} \right) \right]}{1,000 \text{ ac}} \right) \right] = 0.941$$

$$\text{Nutrient Load} = (1,000 \text{ ac}) * (1.05 \text{ lbs/ac}) * 0.859 * 0.941$$

Nutrient Load = 848 pounds of nitrogen

Appendix C

MATLAB Computer Code

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C-1. MATLAB Code for *bmpmain.m*

```
%BMPOPTv2.2
%bmpmain.m
%Programmed by J. Blass
%2007
%Runs BMPOPT Program
clear all
%Initialize Test Variables to be used throughout test runs
bmptable=[];
costtable=[];
loadtable=[];
exloadtab=[];
filename1=strcat('fromgis/params0.txt');
filename2=strcat('fromgis/lcm0.txt');
filename3=strcat('fromgis/bufflcm0.txt');
%Loaddata - Loads all external data needed for optimization
[typeno, type1, am, typelu, bmppoll, remv, cost, lcm, segnames, bufflcm, shape, bmpid,
bmptype, bmparea, buffsegnames, lcsegareas, lcsegnames, lucat, lusegareas, lusegnames,
bw, npolls, polls, oc, oc2, oc3]=loaddata(filename1, filename2, filename3);

%Makeload - Computes Existing Loads, WQ Loads and the areas of each land
%use both for the entire watershed and just for the area in the stream
%buffer
[sumlum, sumbufflum, exload, wqload]=makeload(segnames, lcm, lcsegnames,
lusegnames, lcsegareas, lusegareas, buffsegnames, bufflcm, polls, npolls, oc, oc2);

%Lincon - Creates the linear constraints and establishes the bounds on the
%BMP areas to be optimized
if oc3==1
    [A, b, Aeq, beq, lb, ub, f, w] = lincon2(lucat, typelu, am, sumlum, type1, sumbufflum,
cost, oc, oc2, npolls, exload, remv, bmpid, bmptype, bmparea);
else
    [A, b, Aeq, beq, lb, ub, f, w] = lincon1(lucat, typelu, am, sumlum, type1, sumbufflum,
cost, oc, oc2, npolls, exload, remv);
end

if oc3==1
    %Bintprog - executes the binary interger program optimization based on
    %the user selected objective function and the set of linear constraints
    [x, fval, exitflag] = bintprog(f, A, b, Aeq, beq);
    exitflag
else
    %Linprog - executes the linear program optimization based on the user selected
    %objective function and the set of linear constraints
    options = optimset('LargeScale','off','Simplex','on');
    [x, fval, exitflag] = linprog(f, A, b, Aeq, beq, lb, ub);
    exitflag
end
```

```

%Compute Modified Loading
if oc3==1
    if oc==1
        sizeA = size(A);
        modload = sum(exload,1)+transpose((A([sizeA(1)-(npolls-
1):sizeA(1)],:).*0.0001*x));
        imp_pct = 1-(modload./sum(exload,1));
    else
        for j=1:npolls
            tmpload(j,[1:length(bmpid)])=f([1+(length(bmpid)*(j-
1)):length(bmpid)+(length(bmpid)*(j-1))]./(10000*w(j));
        end
        modload =
sum(exload,1)+transpose((tmpload([1:npolls(1)],:)*x([1:length(bmpid)])));
        imp_pct = 1-(modload./sum(exload,1));
    end
else
    if oc==1
        sizeA = size(A);
        modload = sum(exload,1)+transpose((A([sizeA(1)-(npolls-
1):sizeA(1)],:).*0.0001*x));
        imp_pct = 1-(modload./sum(exload,1));
    else
        for j=1:npolls
            tmpload(j,[1:length(type1)])=f([1+(length(type1)*(j-
1)):length(type1)+(length(type1)*(j-1))]./(10000*w(j));
        end
        modload =
sum(exload,1)+transpose((tmpload([1:npolls(1)],:)*x([1:length(type1)])));
        imp_pct = 1-(modload./sum(exload,1));
    end
end

%Store and Output Data
if oc3==1
    dataout2(cost, x, fval, polls, type1, typelu, typeno, exload, wqload, modload, oc,
bmptype, bmparea)
else
    dataout1(cost, x, fval, polls, type1, typelu, typeno, exload, wqload, modload, oc)
end

```

C-2. MATLAB Code for *loaddata.m*

```
%BMPOPTv2.2
%loaddata.m
%Programmed by J. Blass
%2007
%Loads data into program
function [typeno, type1, am, typelu, bmppoll, remv, cost, lcm, segnames, bufflcm, shape,
bmpid, bmptype, bmparea, buffsegnames, lcsegareas, lcsegnames, lucat, lusegareas,
lusegnames, bw, npolls, polls, oc, oc2, oc3]=loaddata(filename1, filename2, filename3)
%Load BMP Data File
%typeno = number assigned to each bmp type
%type = name of each bmp
%am = designation of A for additive or M for multiplicative for each bmp
%typelu = land use each bmp is applied to
%bmppoll = pollutants with available removal rates for each bmp
%remv = removal rates for each of the bmppoll for each bmp
%cost = cost of each bmp
%lcm = table of land cover areas in study area by land cover and land river
%segment
%segnames = list of segment names included in study area
%bufflcm = table of land cover areas in buffer by land cover and land river
%segment
%shape = list of shape types from proposed BMP list, [] if no list exists
%bmpid = list of BMP ID numbers from proposed BMP list, [] if no list
%exists
%bmptype = list of BMP type numbers from proposed BMP list, [] if no list
%exists
%bmparea = list of BMP areas from proposed BMP list, [] if no list exists
%buffsegnames = list of segment names included in buffer area
%lcsegareas = table of land cover areas for extent of the state of MD
%lcsegnames = list of all land river segments in MD (land cover)
%lucat = list of all land use categories in Phase 5
%lusegareas = table of land cover areas for extent of the state of MD
%lusegnames = list of all land river segments in MD (land use)
%bw = buffer width of study area
%npolls = number of pollutants requested by the user to be included in opt
%polls = names of pollutants requested by the user to be included in opt
%oc = optimization choice (1) for least cost, (2) for least load
%oc2 = opt. parameter WQ levels for least cost, budget for least load
%oc3 = opt. parameter indicating a continuous or discrete BMP optimization
%(does the optimizer have a proposed BMP list to choose from (1) or no (0)

%Load BMP Information
[typeno type1 am typelu bmppoll remv cost]=loadbmp();

%Load Optimization Parameters File
[pmr bw npolls polls oc oc2 oc3]=loadparams(filename1);
```

```

%Load BMP Shapefile if there is one specified
[shape bmpid bmptype bmparea]=loadbmpshape(oc3);

%Load Cross Tabulated Land Cover Areas from Study Area (output of GIS)
[lcm segnames]=loadlcm(filename2);

%Repeat for Stream/River Buffers
[bufflcm buffsegnames]=loadlcm(filename3);

%State-wide Phase 5 Land Cover & Land Use
%Read in land cover areas and land use areas for each segment and land
%cover type for the entire state
[lcsegareas lcsegnames lusegareas lusegnames lucat]=loadp5lulc();

%Add in Buffer Efficiencies to remv based on physiographic region (pmr)
[remv]=addbuffeff(pmr, remv, type1);

```

C-3. MATLAB Code for *loadbmp.m*

```

%BMPOPTv2.2
%loadbmp.m
%Programmed by J. Blass
%2007
%Loads BMP data into program
function [typeno type1 am typelu bmppoll remv cost]=loadbmp()
%Read in BMP Number, BMP type, whether its additive or multiplicative, BMP
%Land use
[typeno type1 am
typelu]=textread('optdata/bmp.txt','%f%s%s%s%*[\n]','delimiter',',','headerlines',1);
%Read in available BMP Pollutants to optimize for
bmp=textread('optdata/bmp.txt','%s','delimiter',',');
bmppoll=bmp(strmatch('BMP_Land_Use',bmp,'exact')+1:strmatch('BMP_Cost',bmp,'exact')-1);
%Read in BMP Removal Efficiency Rates
remv=dlmread('optdata/bmp.txt','', [1 strmatch('BMP_Land_Use',bmp,'exact')
length(typeno) strmatch('BMP_Cost',bmp,'exact')-2]);
%Read in BMP Costs
cost=dlmread('optdata/bmp.txt','', [1 strmatch('BMP_Cost',bmp,'exact')-1 length(typeno)
strmatch('BMP_Cost',bmp,'exact')-1]);

```

C-4. MATLAB Code for *loadparams.m*

```
%BMPOPTv2.2
%loadparams.m
%Programmed by J. Blass
%2007
%Loads user-defined optimization parameters into program
function [pmr bw npolls polls oc oc2 oc3]=loadparams(filename1)
%Load Optimization Parameter Line File
[optparams]=textread(filename1,'%s%*[\n]');
%Extract Physiographic Region to determine which Buffer Efficiencies to use
pmr=char(optparams(1));
%Extract Buffer Width to determine area of Stream Buffers
bw=str2num(char(optparams(2)));
%Extract the number of pollutants to read in those pollutant names
npolls=str2num(char(optparams(3)));
%Extract pollutants to be optimized
polls=optparams(4:4+npolls-1);
%Extract optimization choice
oc=str2num(char(optparams(4+npolls)));
%Extract third optimization parameter (oc3=1 - BMP Shapefile provided,
%oc3=0, no shapefile provided)
oc3=str2num(char(optparams(4+npolls+1)));
%Extract second optimization parameter (Reduction rates for oc=1, Budget
%for oc=2)
oc2=str2num(char(optparams(4+npolls+2:length(optparams))));
```

C-5. MATLAB Code for *loadbmpshape.m*

```
%BMPOPTv2.2
%loadbmpshape.m
%Programmed by J. Blass
%2007
%If provided, loads bmp shapefile data into program from GIS
function [shape bmpid bmptype bmparea]=loadbmpshape(oc3)
%Load BMP Shapefile Information if there is one specified
if oc3==1
    [bmpid bmptype
    bmparea]=textread('fromgis/bmpshape.txt','%f%f%f%*[\n]','delimiter',' ','headerlines',1);
    shape=[];
else
    shape=[];
    bmpid=[];
    bmptype=[];
    bmparea=[];
end
```

C-6. MATLAB Code for *loadlcm.m*

```
%BMPOPTv2.2
%loadlcm.m
%Programmed by J. Blass
%2007
%Loads land cover data matrix into program
function [lc segs]=loadlcm(filename)
%Load Cross Tabulated Land Cover Areas from Study Area (output of GIS)
lcmfile=importdata(filename);
%Sort LC values in order of increasing LC type value
for i=1:10
    name=strcat('Value-',num2str(i),'');
    lc(:,i)=lcmfile.data(:,strmatch(name,lcmfile.textdata(1,:),'exact')-1);
end
%Convert sq. meters to acres
lc=(10.763911/43560).*lc;
%Extract names of segments included in study area
[segs]=textread(filename,'%s%*[\n]','delimiter',' ');
segs=segs(2:length(segs),1);
```

C-7. MATLAB Code for *loadp5lulc.m*

```
%BMPOPTv2.2
%loadlcm.m
%Programmed by J. Blass
%2007
%Loads land use data matrix from Chesapeake Bay Model (Phase 5) into program
function [lcsegareas lcsegnames lusegareas lusegnames lucat]=loadp5lulc()
%State-wide Phase 5 Land Cover
%Read in land cover areas for each segment and land cover type for the
%entire state
lcsegareas=dlmread('optdata/lcsegareas.txt','t');
%Read in a list of all land cover segments in the state
[lcsegnames]=textread('optdata/lcsegnames.txt','%s%*[\n]');

%State-wide Phase 5 Land Use
%Read in land use areas for each segment and land use type for the entire
%state
lusegareas=dlmread('optdata/lusegareas.txt','t',1,0);
%Read in a list of all land use segments in the state
[lusegnames]=textread('optdata/lusegnames.txt','%s%*[\n]');
%Read in a list of all land use categories used in Phase 5
lucat=textread('optdata/lusegareas.txt','%s','delimiter','t');
lucat=lucat(1:length(lusegareas(1,:)));
```

C-8. MATLAB Code for *addbuffeff.m*

```
%BMPOPTv2.2
%addbuffeff.m
%Programmed by J. Blass
%2007
%Loads data for stream buffer efficiencies by physiomorphic region into program
function [remv]=addbuffeff(pmr, remv, type1)
%Add in Buffer Efficiencies to remv based on physiographic region (pmr)
%Load Buffer Land Uses
%Read in available Physiographic Regions
buff=textread('optdata/buff.txt','%s','delimiter','\t');
%Read in buffer efficiencies by physiographic region and buffer type
buff=dlmread('optdata/buff.txt','t',1,1);
%Read in pollutants available to be treated by buffers
buffpoll=buff(strmatch('Region',buff,'exact')+1:strmatch('APL',buff,'exact')-1);
%Match physiographic Region of Study area to one of four physiographic
%regions and assign buffer removal efficiencies based on that
switch pmr
    %Appalachian Plateau
    case 'APL'
        r=strmatch('Forest Buffers & Wetland Restoration',type1);
        for i=1:length(r)
            remv(r(i,:))=buff(1,1:3);
        end
        r=strmatch('Grass Buffers',type1);
        for i=1:length(r)
            remv(r(i,:))=buff(1,4:6);
        end
    %Blue Ridge
    case 'BLR'
        r=strmatch('Forest Buffers & Wetland Restoration',type1);
        for i=1:length(r)
            remv(r(i,:))=buff(2,1:3);
        end
        r=strmatch('Grass Buffers',type1);
        for i=1:length(r)
            remv(r(i,:))=buff(2,4:6);
        end
    %Piedmont Plateau
    case 'PDM'
        r=strmatch('Forest Buffers & Wetland Restoration',type1);
        for i=1:length(r)
            remv(r(i,:))=buff(3,1:3);
        end
        r=strmatch('Grass Buffers',type1);
        for i=1:length(r)
            remv(r(i,:))=buff(3,4:6);
        end
end
```

```

%Coastal Plain
case 'CPL'
    r=strmatch('Forest Buffers & Wetland Restoration',type1);
    for i=1:length(r)
        remv(r(i,:))=buff(4,1:3);
    end
    r=strmatch('Grass Buffers',type1);
    for i=1:length(r)
        remv(r(i,:))=buff(4,4:6);
    end
end
end

```

C-9. MATLAB Code for *makeload.m*

```

%BMPOPTv2.2
%makeload.m
%Programmed by J. Blass
%2007
%Converts land cover to land use and computes pollutant loadings
function [sumlum, sumbufflum, exload, wqload]=makeload(segnames, lcm, lcsegnames,
lusegnames, lcsegareas, lusegareas, buffsegnames, bufflcm, polls, npolls, oc, oc2)
%Determine the number of segments in the study area
seglength=length(segnames);
%Populate Phase 5 Land Use Matrix for Study Area
[lum sumlum]=genlum(seglength, segnames, lcm, lcsegnames, lusegnames, lcsegareas,
lusegareas);

%Compute Buffer Land Use Matrix (same as for entire study area)
buffseglength=length(buffsegnames);
[bufflum sumbufflum]=genlum(buffseglength, buffsegnames, bufflcm, lcsegnames,
lusegnames, lcsegareas, lusegareas);

%Compute Loads
[exload wqload]=genloads(sumlum, npolls, polls, segnames, lusegnames, lum, oc, oc2);

```

C-10. MATLAB Code for *genlum.m*

```
%BMPOPTv2.2
%genlum.m
%Programmed by J. Blass
%2007
%Converts land cover to land use
function [lu, sumlu]=genlum(sglength, segs, lc, lcsegnames, lusegnames, lcseareas,
luseareas)
%Populate Phase 5 Land Use Matrix for Study Area
%Loop over number of segments in study area
for i=1:sglength
    %Land Use 1 - Open Water
    %Extract segment name i
    charname=char(segs(i));
    %If segment name i ends in a "Y", then it is a river segment and its
    %area is all open water
    if findstr('Y',charname)==length(charname)
        lu(i,1)=(lc(i,1));
        lu(i,2:26)=0;
        continue;
    %If segment name i does not end in a "Y", proceed
    else
        j=1;
        k=1;
        %One at a time, extract the land cover segment names
        tempname=char(lcsegnames(j));
        %Continue until the land cover segment name matches the ith study
        %area segment name (the goal is to identify the index of the
        %segment in the state land cover and state land use tables)
        while strcmp(tempname,charname)~=1
            j=j+1;
            tempname=char(lcsegnames(j));
        end
        %Repeat for land use segments
        tempname=char(lusegnames(k));
        while strcmp(tempname,charname)~=1
            k=k+1;
            tempname=char(lusegnames(k));
        end
        %The land use area in the portion of the segment in the study area
        %is equal to the area of the land cover type in the portion of the
        %segment in the study area multiplied by a ratio of the land use
        %for the entire segment to the land cover for the entire segment
        lum(i,1)=lcm(i,1)*luseareas(k,1)/lcseareas(j,1);
    end
    %Land Use 2 - Forest Cover
    lu(i,2)=sum(lc(i,5:7))*luseareas(k,2)/sum(lcseareas(j,5:7));
    %Land Use 3 - Harvested Forest Cover
```

```

lu(i,3)=sum(lc(i,5:7))*lusegareas(k,3)/sum(lcsegareas(j,5:7));
%Land Use 4 - Natural Grasses
lu(i,4)=lc(i,9)*lusegareas(k,4)/lcsegareas(j,9);
%Land Uses 5 through 20 - Agriculture
for m=1:16
    lu(i,4+m)=lc(i,8)*lusegareas(k,4+m)/lcsegareas(j,8);
end
%Land Use 21 - Low Intensity Developed - Pervious Area
lu(i,21)=lc(i,2)*lusegareas(k,21)/lcsegareas(j,2);
%Land Use 22 - High Intensity Developed - Pervious Area
lu(i,22)=lc(i,10)*lusegareas(k,22)/lcsegareas(j,10);
%Land Use 23 - Extractive
lu(i,23)=lc(i,4)*lusegareas(k,23)/lcsegareas(j,4);
%Land Use 24 - Bare Construction
lu(i,24)=lusegareas(k,24)*sum(lc(i,:))/sum(lusegareas(k,:));
%Land Use 25 - Low Intensity Developed - Impervious Area
lu(i,25)=lc(i,2)*lusegareas(k,25)/lcsegareas(j,2);
%Land Use 26 - High Intensity Developed - Impervious Area
lu(i,26)=lc(i,10)*lusegareas(k,26)/lcsegareas(j,10);
end
%Set all non-numbers to zero - this occurs when there is land use but no
%land cover in an area in question
n=size(lu);
for i=1:n(1)
    for j=1:n(2)
        if isnan(lu(i,j))==1
            lu(i,j)=0;
        end
    end
end
end
%Sum across all of the segments to get one land use area value for each
%land use
sumlu=transpose(sum(lu,1));

```

C-11. MATLAB Code for *genloads.m*

```
%BMPOPTv2.2
%genloads.m
%Programmed by J. Blass
%2007
%Computes pollutant loadings
function [exload wqload]=genloads(sumlum, npolls, polls, segnames, lusegnames, lum,
oc, oc2)
%Compute Loads
%Set existing load values to zero for each of the pollutants to be
%optimized
exload=zeros(length(sumlum),npolls);
n=size(lum);
%Each Pollutant
for i=1:npolls
    %Load pollutant loading coefficients
    pollname=lower(char(strcat('optdata/',polls(i),'.txt')));
    temppoll=load (pollname);
    %Each Land Use
    for j=1:n(2)
        %Each Segment
        for k=1:n(1)
            %Extract the kth segment name in the study area
            charname=char(segnames(k));
            %If the segment name is a river segment, there is no loading
            if findstr('Y',charname)==length(charname)
                continue;
            %If the segment name is not a river segment, proceed
            else
                m1=1;
                m2=1;
                %Extract each segment name in the state land use table
                tempname=char(lusegnames(m1));
                %If the pollutant in question is sediments, proceed
                if strcmpi(polls(i),'sediments')==1
                    %Continue extracting segment names from the state land
                    %use table until a match is found
                    while strcmp(tempname,charname)~=1
                        m1=m1+1;
                        tempname=char(lusegnames(m1));
                    end
                    %Store the index
                    m=m1;
                %For all other pollutants (nitrogen and phosphorus)
                else
                    %Do the same action as for sediments but only for the
                    %land segment portion of the landriver segment name
                    while strcmp(tempname(1:6),charname(1:6))~=1
```

```

        oldtempname=tempname(1:6);
        m1=m1+1;
        tempname=char(lusegnames(m1));
        if strcmp(oldtempname,tempname(1:6))~=1
            m2=m2+1;
        end
    end
    end
    %Store the index
    m=m2;
end
%Compute the existing load for the segment(k) and land use(j)
%from pollutant(i) by multiplying the land use in the segment
%by the loading coefficient
if strcmpi(polls(i),'sediments')==1
    exload(j,i)=exload(j,i)+(2000*lum(k,j)*temppoll(m,j));
else
    exload(j,i)=exload(j,i)+(lum(k,j)*temppoll(m,j));
end
%If the Minimize Cost objective function is chosen, also
%compute the WQ load by multiplying the existing load by
%the reduction rate chosen by the user
if oc==1
    wqload(j,i)=exload(j,i)*(1-(oc2(i)/100));
else
    wqload(j,i)=0;
end
end
end
end
end
end

```

C-12. MATLAB Code for *lincon1.m*

```
%BMPOPTv2.2
%lincon1.m
%Programmed by J. Blass
%2007
%Creates Linear Constraints for Optimization w/o BMP Shapefile
function [A, b, Aeq, beq, lb, ub, f, w] = lincon1(lucacat, typelu, am, sumlum, type1,
sumbufflum, cost, oc, oc2, npolls, exload, remv)
%Define Objective Function based on oc value (oc=1 - cost, oc=2 - load)
if oc==1
    f=transpose(cost);
    Aeq=[];
    beq=[];
    w=[];
else
    %w=[1 1 1];
    w=ones(1,npolls);
    for i = 1:npolls
        for j = 1:length(typelu)
            e = exload(strmatch(typelu(j),lucacat),i);
            r = remv(j,i);
            landuse= sumlum(strmatch(typelu(j),lucacat));
            if landuse<0.001
                f(j+((i-1)*length(typelu)))=0;
            else
                f(j+((i-1)*length(typelu)))=w(i)*10000*((-e*r)/landuse);
            end
        end
    end
    Aeq=[];
    beq=[];
end

%Define Land Use Constraints
[A b Aeq beq]=lucon(lucacat, typelu, am, sumlum, npolls, oc);

%Define Buffer Constraints
[A b]=buffcon(A, b, type1, lucacat, typelu, sumbufflum);
n=size(A);
%Add Loading or Cost Constraint Depending on Objective Function Choice
%(oc=1 - Loading, oc=2 - Cost)
if oc==1
    for i = 1:npolls
        for j = 1:length(typelu)
            e = exload(strmatch(typelu(j),lucacat),i);
            r = remv(j,i);
            landuse= sumlum(strmatch(typelu(j),lucacat));
            if landuse<0.001
```

```

        A(n(1)+i,j)=0;
    else
        A(n(1)+i,j)=(-e*10000*r)/landuse;
    end
end
b(n(1)+i)=-(oc2(i)/100)*10000*sum(exload(:,i));
end
else
    A=[A; transpose(cost)];
    oldA=size(A);
    for i=1:npolls-1
        A=[A zeros(oldA)];
    end
    b=[b oc2];
end
b=transpose(b);

%Establish Lower ("lb") and Upper ("ub") bounds on x values and initialize
%x
lb=zeros(1,length(typelu));
ub=[];

```

C-13. MATLAB Code for *lucon.m*

```

%BMPOPTv2.2
%lucon.m
%Programmed by J. Blass
%2007
%Creates Linear Constraints land use area and water quality/budget for Optimization
w/o BMP Shapefile
function [A b Aeq beq]=lucon(lucatu, typelu, am, sumlum, npolls, oc)
%Define Land Use Constraints
A=zeros(length(lucatu),length(typelu));
for i=1:length(lucatu)
    bmpind=strmatch(lucatu(i),typelu,'exact');
    for j=1:length(bmpind)
        A(i,bmpind(j))=1;
    end
    b(i)=sumlum(i);
end
%Define Mathematical Equalities to make sure dummy BMPs are equal to real
%BMPs
if oc==2
    for i=0:npolls-2
        for j=1:length(typelu)
            Aeq(j+i*length(typelu),j)=1;
            Aeq(j+i*length(typelu),(i+1)*length(typelu)+j)=-1;
            beq(j+i*length(typelu),1)=0;
        end
    end
end

```

```

        end
    end
else
    Aeq=[];
    beq=[];
end

```

C-14. MATLAB Code for *buffcon.m*

```

%BMPOPTv2.2
%buffcon.m
%Programmed by J. Blass
%2007
%Creates Linear Constraints for Buffers in Optimization w/o BMP Shapefile
function [A b]=buffcon(A, b, type1, lucat, typelu, sumbufflum)
%Define Buffer Constraints
buffind=strmatch('Forest Buffers + Wetland Restoration',type1);
buffind=[buffind; strmatch('Grass Buffers',type1)];
buffind=[buffind; strmatch('Urban Forest Buffers',type1)];
j=1;
for i=1:length(lucat)
    if strmatch(lucat(i),typelu(buffind))
        bind=strmatch(lucat(i),typelu(buffind));
        A(length(lucat)+j,:)=zeros(1,length(typelu));
        A(length(lucat)+j,buffind(bind))=1;
        b(length(lucat)+j)=sumbufflum(i);
        j=j+1;
    end
end
end

```

C-15. MATLAB Code for *lincon2.m*

```

%BMPOPTv2.2
%lincon2.m
%Programmed by J. Blass
%2007
%Creates Linear Constraints for Optimization w/ BMP Shapefile
function [A, b, Aeq, beq, lb, ub, f, w] = lincon2(lucat, typelu, am, sumlum, type1,
sumbufflum, cost, oc, oc2, npolls, exload, remv, bmpid, bmptype, bmparea)
%Define Objective Function based on oc value (oc=1 - cost, oc=2 - load)
if oc==1
    for i=1:length(bmpid)
        f(i)=cost(bmptype(i))*bmparea(i);
    end
    Aeq=[];
    beq=[];
    w=[];
end

```

```

else
    %w=[1 1 1];
    w=ones(1,npolls);
    for i = 1:npolls
        for j = 1:length(bmpid)
            e = exload(strmatch(typelu(bmpid(j)),lucacat),i);
            r = remv(bmpid(j),i);
            landuse= sumlum(strmatch(typelu(bmpid(j)),lucacat));
            if landuse<0.001
                f(j+((i-1)*length(bmpid)))=0;
            else
                f(j+((i-1)*length(bmpid)))=w(i)*10000*((-e*r)/landuse);
            end
        end
    end
    end
    Aeq=[];
    beq=[];
end

%Define Land Use Constraints
[A b Aeq beq]=lucon2(lucacat, typelu, am, sumlum, npolls, oc, bmpid, bmptype, bmparea);

%Define Buffer Constraints
[A b]=buffcon2(A, b, type1, lucacat, typelu, sumbufflum, bmpid, bmptype, bmparea);
n=size(A);
%Add Loading or Cost Constraint Depending on Objective Function Choice
%(oc=1 - Loading, oc=2 - Cost)
if oc==1
    for i = 1:npolls
        for j = 1:length(bmpid)
            e = exload(strmatch(typelu(bmpid(j)),lucacat),i);
            r = remv(bmpid(j),i);
            landuse= sumlum(strmatch(typelu(bmpid(j)),lucacat));
            if landuse<0.001
                A(n(1)+i,j)=0;
            else
                A(n(1)+i,j)=(-e*10000*r)/landuse;
            end
        end
    end
    b(n(1)+i)=-((oc2(i)/100)*10000*sum(exload(:,i)));
end
else
    for i=1:length(bmpid)
        costconst(i)=cost(bmptype(i))*bmparea(i);
    end
    A=[A; costconst];
    oldA=size(A);
    for i=1:npolls-1
        A=[A zeros(oldA)];
    end
end

```

```

    end
    b=[b oc2];
end
b=transpose(b);

%Establish Lower ("lb") and Upper ("ub") bounds on x values and initialize
%x
lb=zeros(1,length(bmpid));
ub=[];

```

C-16. MATLAB Code for *lucon2.m*

```

%BMPOPTv2.2
%lucon2.m
%Programmed by J. Blass
%2007
%Creates Linear Constraints landuse and water quality/budget for Optimization w/ BMP
Shapefile
function [A b Aeq beq]=lucon2(lucatu, typelu, am, sumlum, npolls, oc, bmpid, bmptype,
bmparea)
%Define Land Use Constraints
A=zeros(length(lucatu),length(bmpid));
for i=1:length(lucatu)
    A(i,bmpid(strmatch(typelu(bmptype),lucatu(i),'exact')))=bmparea(bmpid(strmatch(
typelu(bmptype),lucatu(i),'exact')));
    b(i)=sumlum(i);
end
%Define Mathematical Equalities to make sure dummy BMPs are equal to real
%BMPs
if oc==2
    for i=0:npolls-2
        for j=1:length(bmpid)
            Aeq(j+i*length(bmpid),j)=1;
            Aeq(j+i*length(bmpid),(i+1)*length(bmpid)+j)=-1;
            beq(j+i*length(bmpid),1)=0;
        end
    end
else
    Aeq=[];
    beq=[];
end
end

```

C-17. MATLAB Code for *buffcon2.m*

```
%BMPOPTv2.2
%buffcon2.m
%Programmed by J. Blass
%2007
%Creates Linear Constraints for buffers for Optimization w/ BMP Shapefile
function [A b]=buffcon2(A, b, type1, lucat, typelu, sumbufflum, bmpid, bmptype,
bmparea)
%Define Buffer Constraints
buffind=strmatch('Forest Buffers + Wetland Restoration',type1);
buffind=[buffind; strmatch('Grass Buffers',type1)];
buffind=[buffind; strmatch('Urban Forest Buffers',type1)];
j=1;
for i=1:length(lucat)
    if strmatch(lucat(i),typelu(buffind))
        %bind=strmatch(lucat(i),bmptype(typelu(buffind)));
        A(length(lucat)+j,:)=zeros(1,length(bmpid));
        for k=1:length(bmpid)
            if find(bmptype(k)==buffind)&strmatch(typelu(bmptype(k)),lucat(i),'exact')
                A(length(lucat)+j,k)=bmparea(k);
            end
        end
        b(length(lucat)+j)=sumbufflum(i);
        j=j+1;
    end
end
end
```

C-18. MATLAB Code for *dataout1.m*

```
%BMPOPTv2.2
%dataout1.m
%Programmed by J. Blass
%2007
%Outputs Results of Optimization w/o BMP Shapefile
function []=dataout1(cost, x, fval, polls, type1, typelu, typeno, exload, wqload, modload,
oc)
delete('togis/BMP_Output.txt');
diaryname='togis/BMP_Output.txt';
diary(diaryname)
%Output Optimization Inputs
fprintf('\n\n\nBMP Optimization Summary\n\n');
fprintf('\n');
%Output Optimum BMP Plan
j=1;
for i=1:length(x)/length(polls)
    if x(i)>1
        xdisp(j)=x(i);
    end
end
```

```

        typedisp(j)=type1(i);
        ludisp(j)=typelu(i);
        nodisp(j)=typeno(i);
        spacer(j)='|';
        j=j+1;
    end
end
bmpno = strvcat('BMP No. ', num2str(transpose(nodisp)));
bmptype = strvcat('BMP Type', char(transpose(typedisp)));
bmplu = strvcat('BMP Land Use', char(transpose(ludisp)));
acres = strvcat('Acres', num2str(transpose(round(xdisp))));
spacer = strvcat('| ',char(transpose(spacer)));
bmpout=[bmpno spacer bmptype spacer bmplu spacer acres];
disp(bmpout);
fprintf('\n');
if oc==1
    %Output Optimum Cost
    format bank
    coutput=[sprintf('Optimum BMP Plan Cost: $%0.0f, fval) ');
    disp(coutput);
    fprintf('\n');
    %Output Exload and WQload
    loadout=[strvcat('Pollutant', 'Existing Load (lbs/yr)', 'WQ Load (lbs/yr)', 'Modified
Load (lbs/yr)');
    for i=1:length(exload(1,:))
        clear spacer
        spacer=['| '; '| '; '| '; '| '];
        loadout=[loadout char(spacer) strvcat(char(polls(i)), num2str(sum(exload(:,i),1)),
num2str(sum(wqload(:,i),1)), num2str(modload(i)))];
    end
    disp(loadout);
else
    %Output Optimum Cost
    format bank
    tcost=transpose(cost)*x(1:(length(x)/length(polls)));
    coutput=[sprintf('Optimum BMP Plan Cost: $%0.0f, tcost), ');
    disp(coutput);
    fprintf('\n');
    %Output Exload and WQload
    loadout=[strvcat('Pollutant', 'Existing Load (lbs/yr)', 'Modified Load (lbs/yr)',
'Reduction %');
    for i=1:length(exload(1,:))
        clear spacer
        spacer=['| '; '| '; '| '; '| '];
        loadout=[loadout char(spacer) strvcat(char(polls(i)), num2str(sum(exload(:,i),1)),
num2str(modload(i)), num2str(100*(1-(modload(i)/sum(exload(:,i),1)))));
    end
    disp(loadout);
end
end

```

diary off

C-19. MATLAB Code for *dataout2.m*

```
%BMPOPTv2.2
%dataout2.m
%Programmed by J. Blass
%2007
%Outputs Results of Optimization w/ BMP Shapefile
function []=dataout2(cost, x, fval, polls, type1, typelu, typeno, exload, wqload, modload,
oc, bmptype, bmparea)
delete('togis/BMP_Output.txt');
diaryname='togis/BMP_Output.txt';
diary(diaryname)
%Output Optimization Inputs
fprintf('\n\nBMP Optimization Summary\n\n');
fprintf('\n');
%Output Optimum BMP Plan
j=1;
for i=1:length(x)/length(polls)
    if x(i)>0
        selectbmpid(j)=i;
        xdisp(j)=x(i);
        typedisp(j)=type1(i);
        ludisp(j)=typelu(i);
        nodisp(j)=typeno(bmptype(i));
        spacer(j)='|';
        j=j+1;
    end
end
id    = strvcat('BMP ID ', num2str(transpose(selectbmpid)));
bmpno = strvcat('BMP No. ', num2str(transpose(nodisp)));
bmpkind = strvcat('BMP Type', char(transpose(typedisp)));
bmpplu = strvcat('BMP Land Use', char(transpose(ludisp)));
acres  = strvcat('Acres', num2str(transpose(round(xdisp))));
spacer = strvcat('|',char(transpose(spacer)));
bmpout=[id spacer bmpno spacer bmpkind spacer bmpplu spacer acres];
disp(bmpout);
fprintf('\n');
if oc==1
    %Output Optimum Cost
    format bank
    coutput=[sprintf('Optimum BMP Plan Cost: $%0.0f', fval) '.'];
    disp(coutput);
    fprintf('\n');
    %Output Exload and WQload
    loadout=[strvcat('Pollutant', 'Existing Load (lbs/yr)', 'WQ Load (lbs/yr)', 'Modified
Load (lbs/yr)')];
```

```

    for i=1:length(exload(1,:))
        clear spacer
        spacer=['|';'|';'|';'|'];
        loadout=[loadout char(spacer) strvcat(char(polls(i)), num2str(sum(exload(:,i),1)),
num2str(sum(wqload(:,i),1)), num2str(modload(i)))]];
        end
        disp(loadout);
    else
        %Output Optimum Cost
        format bank
        tcost=transpose(cost(bmptype))*(bmparea.*(x(1:(length(x)/length(polls)))));
        coutput=[sprintf('Optimum BMP Plan Cost: $%0.0f', tcost), '.'];
        disp(coutput);
        fprintf('\n');
        %Output Exload and WQload
        loadout=[strvcat('Pollutant', 'Existing Load (lbs/yr)', 'Modified Load (lbs/yr)',
'Reduction %')];
        for i=1:length(exload(1,:))
            clear spacer
            spacer=['|';'|';'|';'|'];
            loadout=[loadout char(spacer) strvcat(char(polls(i)), num2str(sum(exload(:,i),1)),
num2str(modload(i)), num2str(100*(1-(modload(i)/sum(exload(:,i),1)))))]];
            end
            disp(loadout);
        end
    end
diary off

```

Appendix D

Avenue (GIS) Computer Code

Table of Contents

- D-1. Avenue (GIS) Code for *Lum.Make*
- D-2. Avenue (GIS) Code for *Buffer.Make*
- D-3. Avenue (GIS) Code for *BOPP.Apply*

D-1. Avenue (GIS) Code for *Lum.Make*

```
'BMPOPTv2.2
'Lum.Make'
'Programmed by J. Blass
'2007
'This script creates a land cover matrix (P5 Land Cover)
'masked over the watershed elected by the user, converts the land
'cover to land use and exports those matrix as a text file.

'Get the View
theView=av.FindDoc("State View - UTM NAD 1983 Zone 18 (meters)")

'Get the Grid Themes
theShed=theView.FindTheme(_shedName)
_theShed=theShed
theLC = theView.FindTheme("Md_p5cover").GetGrid

'Extract by Polygon
'Get the Polygon
shedPoly=theShed.GetFTab.ReturnValue(theShed.GetFTab.FindField("Shape"),0)

'Set the Analysis Environment by the Watershed Polygon
theextent = (shedpoly.returnextent).expandby(60)
ae = theView.GetExtension(AnalysisEnvironment)
ae.SetExtent(#ANALYSISENV_VALUE, theextent)
ae.SetCellSize(#ANALYSISENV_VALUE, theLC.getcellsize)
ae.Activate

'Extract Function
theLC=theLC.ExtractByPolygon(shedPoly,theView.GetProjection,False)

'Make LC GTheme
theLCtheme=GTheme.Make(theLC)

'Set new Themes' names
theShed2=theShed.Clone
theShed2.SetName(_shedName.AsString++"Watershed")
theLCtheme.SetName(_shedName.AsString++"P5 Land Cover")

'Set up Parameters for positioning and sizing of Shed View Window
shedView=View.Make
shedView.SetName(_shedName.AsString++"Watershed View - UTM NAD 1983 Zone
18 (meters)")
stateWin=theView.GetWin
stWinSize=stateWin.ReturnExtent
stWinPos=stateWin.ReturnOrigin
shedWin=shedView.GetWin
shedWin.Resize(stWinSize.GetX,stWinSize.GetY)
```

```
shedWin.MoveTo(stWinPos.GetX,stWinPos.GetY)
shedWin.Open
```

```
'Add new Themes to View
```

```
shedView.AddTheme(theShed2)
theShed2.SetVisible(True)
theShed2.SetActive(True)
shedView.AddTheme(theLCtheme)
theLCtheme.SetVisible(True)
LClegend=Legend.Make(#SYMBOL_FILL)
LClegend.Load("c:\BOPP\GIS\lclegend.avl".AsFileName,#LEGEND_LOADTYPE_AL
L)
theLCtheme.SetLegend(LClegend)
theLCtheme.UpdateLegend
```

```
'Produce Cross Tabulated Table showing Phase 5 Land Cover
```

```
'by Phase 5 Land-River Segment
```

```
segsTab=theView.FindTheme("P5lrsegs.shp").GetFTab
shedXTab=theLC.TabulateArea(theLC.GetVTab.FindField("Value"),segsTab,theView.G
etProjection,segsTab.FindField("Fipscatwat"),False)
shedXTable=Table.Make(shedXTab)
shedXTable.SetName(_shedName.AsString++"Watershed Land Cover by Segment")
shedXTab.Export("c:\bopp\optimizer\lcm".asFileName,Dtext,False)
```

D-2. Avenue (GIS) Code for *Buffer.Make*

```
'BMPOPTv2.2
'Buffer.Make'
'Programmed by J. Blass
'2007
'Creates buffer of user specified width
'around all streams in study area

'Overhead Operations
theView=av.FindDoc("State View - UTM NAD 1983 Zone 18 (meters)")
theShed=theView.FindTheme(_shedName)
theStreams=theView.FindTheme("Mdstreams.shp")
theLC=theView.FindTheme("Md_p5cover").GetGrid

'Get Watershed Polygon
shedTab=theShed.GetFTab
shedPoly=shedTab.ReturnValue(shedTab.FindField("Shape"),0)

'Set the Analysis Environment by the Watershed Polygon
theextent = (shedpoly.returnextent).expandby(60)
ae = theView.GetExtension(AnalysisEnvironment)
ae.SetExtent(#ANALYSENV_VALUE, theextent)
ae.SetCellSize(#ANALYSENV_VALUE, theLC.getcellsize)
ae.Activate

'Make Stream Theme
streamsTab=theStreams.GetFTab
recnum=streamsTab.GetNumRecords-1
shpFld=streamsTab.FindField("Shape")

'Buffer the appropriate streams
streamBuff=Polygon.MakeEmpty
for each i in 0..recnum
    if(streamsTab.ReturnValue(shpFld,i).Intersects(shedPoly))then
        tempStream=streamsTab.ReturnValue(shpFld,i)
        tempBuffer=tempStream.ReturnBuffered(_bw.AsNumber)
        streamBuff=streamBuff.ReturnUnion(tempBuffer)
    end
end
buffLCGrid=theLC.ExtractByPolygon(streamBuff,theView.GetProjection,False)

'Make new GThemes
buffLCTheme = GTheme.Make(buffLCGrid)

'Set up Parameters for positioning and sizing of Buff View Window
buffView=View.Make
buffView.SetName(_shedName.AsString++"Buffer View (UTM NAD 1983 Zone 18 -
meters)")
```

```
stateWin=theView.GetWin
stWinSize=stateWin.ReturnExtent
stWinPos=stateWin.ReturnOrigin
buffWin=buffView.GetWin
buffWin.Resize(stWinSize.GetX,stWinSize.GetY)
buffWin.MoveTo(stWinPos.GetX,stWinPos.GetY)
buffWin.Open
```

'Set new Themes' Names and Add to Buff View

```
theShed3=theShed.Clone
theShed3.SetName(_shedName.AsString++"Watershed")
buffView.AddTheme(theShed3)
theShed3.SetVisible(True)
buffLCTheme.SetName(_shedName.AsString++"Stream Buffer P5 Land Cover")
buffView.AddTheme(buffLCTheme)
LClegend=Legend.Make(#SYMBOL_FILL)
LClegend.Load("c:\BOPP\GIS\lcllegend.avl".AsFileName,#LEGEND_LOADTYPE_ALL)
buffLCtheme.SetLegend(LClegend)
buffLCtheme.UpdateLegend
buffLCTheme.SetVisible(True)
buffLCTheme.SetActive(True)
```

'Produce Cross Tabulated Table showing Phase 5 Buffer Land Cover

'by Phase 5 Land-River Segment

```
segsTab=theView.FindTheme("P5lrsegs.shp").GetFTab
buffShedXTab=buffLCGrid.TabulateArea(buffLCGrid.GetVTab.FindField("Value"),segsTab,theView.GetProjection,segsTab.FindField("Fipscatwat"),False)
buffShedXTable=Table.Make(buffShedXTab)
buffShedXTable.SetName(_shedName.AsString++"Buffer Land Cover by Segment")
buffShedXTab.Export("c:\bopp\optimizer\bufflcm".asFileName,Dtext,False)
```

D-3. Avenue (GIS) Code for *BOPP.Apply*

'BMPOPTv2.2

'BOPP.Apply'

'Programmed by J. Blass

'2007

'Set this script as the click property of the

'Apply button. Runs Optimization Program

'Get the Dialog

theDialog=av.FindDialog("bopp.initiate")

'Get Parameter Field Names

bwField=theDialog.FindByName("buff_textbox")

costField=theDialog.FindByName("mincost_radio")

loadField=theDialog.FindByName("minload_radio")

bmpshapeField=theDialog.FindByName("bmpshape_check")

NField=theDialog.FindByName("nitrogen_check")

PField=theDialog.FindByName("phosphorus_check")

SField=theDialog.FindByName("sediments_check")

lrNField=theDialog.FindByName("loadredN_textbox")

lrPField=theDialog.FindByName("loadredP_textbox")

lrSField=theDialog.FindByName("loadredS_textbox")

bField=theDialog.FindByName("budget_textbox")

'Store Values as Global Variables

'Determine the Predominant Physiomorphic Region of the Watershed

shedName=MsgBox.Input("Please enter the name of the watershed gridtheme: ",
"Watershed Name", "A Watershed")

_shedName=shedName

theView=av.FindDoc("State View - UTM NAD 1983 Zone 18 (meters)")

theShed=theView.FindTheme(_shedName)

shedTab=theShed.GetFTab

shedPoly=shedTab.ReturnValue(shedTab.FindField("Shape"),0)

'Set the Analysis Environment by the Watershed Polygon

theextent = (shedpoly.returnextent).expandby(60)

ae = theView.GetExtension(AnalysisEnvironment)

ae.SetExtent(#ANALYSISENV_VALUE, theextent)

ae.SetCellSize(#ANALYSISENV_VALUE,

theView.FindTheme("Md_p5cover").GetGrid.getcellsize)

ae.Activate

thePMR=theView.FindTheme("P5provs").GetGrid

thePMR=thePMR.ExtractByPolygon(shedPoly,theView.GetProjection,False)

PMRTab=thePMR.GetVTab

shedField=shedTab.FindField("Id")

PMRField=PMRTab.FindField("Value")

```
PMRxTab=thePMR.TabulateArea(PMRField,shedTab,theView.GetProjection,shedField,
False)
```

```
maxValue=0
fieldsList=PMRxTab.GetFields
fieldsCount=fieldsList.Count-1
for each i in 0..fieldsCount
  pmrValue=PMRxTab.ReturnValue(fieldsList.Get(i),0)
  if(pmrValue>maxValue)then
    maxValue=pmrValue
    maxField=fieldsList.Get(i).asString
  end
end
if ("Value_1"=maxField)then
  _pmr="APL"
elseif("Value_2"=maxField)then
  _pmr="CPL"
elseif("Value_3"=maxField)then
  _pmr="PDM"
elseif("Value_4"=maxField)then
  _pmr="BLR"
end
_bw=bwField.GetText
_npoll=0
_pollList=List.Make
_param2=List.Make
if(costField.IsSelected)then
  _of=1
  if (bmpshapeField.IsSelected)then
    _param3=1
  else
    _param3=0
  end
  if (NField.IsSelected) then
    _npoll=_npoll+1
    _pollList.Add("Nitrogen".asString)
    _param2.Add(lrNField.GetText.asString)
  end
  if (PField.IsSelected) then
    _npoll=_npoll+1
    _pollList.Add("Phosphorus".asString)
    _param2.Add(lrPField.GetText.asString)
  end
  if (SField.IsSelected) then
    _npoll=_npoll+1
    _pollList.Add("Sediments".asString)
    _param2.Add(lrSField.GetText.asString)
  end
elseif(loadField.IsSelected)then
```

```

_of=2
if (bmpshapeField.IsSelected)then
  _param3=1
else
  _param3=0
end
_param2.Add(bField.GetText.asString)
if (NField.IsSelected) then
  _npoll=_npoll+1
  _pollList.Add("Nitrogen".asString)
end
if (PField.IsSelected) then
  _npoll=_npoll+1
  _pollList.Add("Phosphorus".asString)
end
if (SField.IsSelected) then
  _npoll=_npoll+1
  _pollList.Add("Sediments".asString)
end
end

```

*'Assemble a parameter list of all values to be passed
to optimizer*

```
paramList={_pmr.asString, _bw.asString, _npoll.asString}
```

*'Create Line File "params.txt" and write parameter list
to it*

```

lf=LineFile.Make("c:\bopp\optimizer\params.txt".AsFileName,#FILE_PERM_WRITE)
lf.write(paramList,3)
lf.write(_pollList,_npoll)
lf.write({_of.asString},1)
lf.write({_param3.asString},1)
if (_of=1)then
  numWrite=_npoll
elseif (_of=2)then
  numWrite=1
end
lf.write(_param2,numWrite)
lf.goToBeg
lf.Close

```

'Reset Fields for next run

```

theCheckBox=theDialog.FindByName("nitrogen_check")
theCheckBox.SetSelected(False)
theCheckBox=theDialog.FindByName("phosphorus_check")
theCheckBox.SetSelected(False)
theCheckBox=theDialog.FindByName("sediments_check")
theCheckBox.SetSelected(False)
theTextBox=theDialog.FindByName("buff_textbox")

```

```

theTextBox.SetText("")
theTextBox=theDialog.FindByName("loadredN_textbox")
theTextBox.SetText("")
theTextBox.SetEnabled(False)
theTextBox=theDialog.FindByName("loadredP_textbox")
theTextBox.SetText("")
theTextBox.SetEnabled(False)
theTextBox=theDialog.FindByName("loadredS_textbox")
theTextBox.SetText("")
theTextBox.SetEnabled(False)
theTextBox=theDialog.FindByName("budget_textbox")
theTextBox.SetText("")
theTextBox.SetEnabled(False)

'Close Dialog
theDialog.Close

'Run Land Use Matrix Generation Script
av.Run("Lum.Make", "")
av.Run("Buffer.Make", "")
system.execute("c:\BOPP\optimizer\control2")
TextWin.Make("c:\bopp\optimizer\BMP_Output.txt".AsFileName, "BMP Output")
av.TileWindows

```

Appendix E

BMPs Used in Optimization

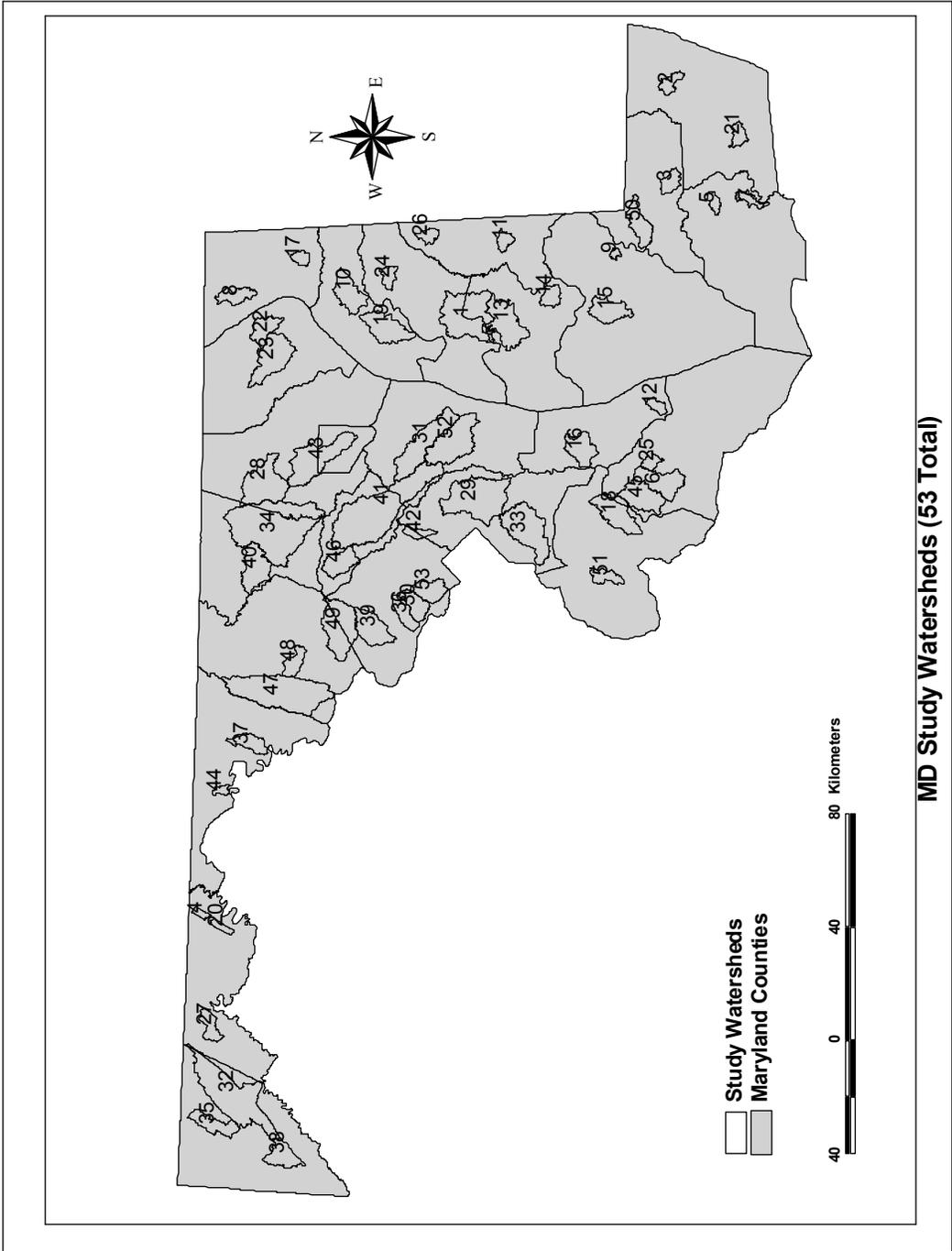
BMP No.	BMP Type	BMP Land Use	Reduction Efficiency			BMP Cost (\$/Acre)
			Nitrogen	Phosphorus	Sediment	
1	Animal Waste Management - Livestock	Animal Feeding Operations	1	1	0	66000
2	Animal Waste Management - Poultry	Animal Feeding Operations	1	1	0	27700
3	Barnyard Runoff Control	Animal Feeding Operations	1	1	1	7340
4	Conservation Plans	Hay w/ Nutrients	0.03	0.05	0.08	280
5	Forest Buffers & Wetland Restoration	Hay w/ Nutrients	-1	-1	-1	1040
6	Grass Buffers	Hay w/ Nutrients	-1	-1	-1	146
7	Conservation Plans	Hay w/o Nutrients	0.03	0.05	0.08	280
8	Forest Buffers & Wetland Restoration	Hay w/o Nutrients	-1	-1	-1	1040
9	Grass Buffers	Hay w/o Nutrients	-1	-1	-1	146
10	Conservation Plans	Hi Till w/ Manure	0.08	0.15	0.25	280
11	Cover Crops (Early)	Hi Till w/ Manure	0.45	0.15	0.2	40
12	Cover Crops (Late)	Hi Till w/ Manure	0.3	0.07	0.1	40
13	Forest Buffers & Wetland Restoration	Hi Till w/ Manure	-1	-1	-1	1040
14	Grass Buffers	Hi Till w/ Manure	-1	-1	-1	146
15	Small Grain Enhancement (Early)	Hi Till w/ Manure	0.25	0	0	20
16	Small Grain Enhancement (Late)	Hi Till w/ Manure	0.17	0	0	20
17	Conservation Plans	Hi Till w/o Manure	0.08	0.15	0.25	280
18	Cover Crops (Early)	Hi Till w/o Manure	0.45	0.15	0.2	40
19	Cover Crops (Late)	Hi Till w/o Manure	0.3	0.07	0.1	40
20	Forest Buffers & Wetland Restoration	Hi Till w/o Manure	-1	-1	-1	1040
21	Grass Buffers	Hi Till w/o Manure	-1	-1	-1	146
22	Small Grain Enhancement (Early)	Hi Till w/o Manure	0.25	0	0	20
23	Small Grain Enhancement (Late)	Hi Till w/o Manure	0.17	0	0	20
24	Conservation Plans	Low Till w/ Manure	0.03	0.05	0.08	280
25	Cover Crops (Early)	Low Till w/ Manure	0.45	0	0	40
26	Cover Crops (Late)	Low Till w/ Manure	0.3	0	0	40
27	Forest Buffers & Wetland Restoration	Low Till w/ Manure	-1	-1	-1	1040
28	Grass Buffers	Low Till w/ Manure	-1	-1	-1	146
29	Small Grain Enhancement (Early)	Low Till w/ Manure	0.25	0	0	20
30	Small Grain Enhancement (Late)	Low Till w/ Manure	0.17	0	0	20
31	Conservation Plans	Low Till w/o Manure	0.03	0.05	0.08	280
32	Cover Crops (Early)	Low Till w/o Manure	0.45	0	0	40
33	Cover Crops (Late)	Low Till w/o Manure	0.3	0	0	40
34	Forest Buffers & Wetland Restoration	Low Till w/o Manure	-1	-1	-1	1040
35	Grass Buffers	Low Till w/o Manure	-1	-1	-1	146
36	Small Grain Enhancement (Early)	Low Till w/o Manure	0.25	0	0	20
37	Small Grain Enhancement (Late)	Low Till w/o Manure	0.17	0	0	20
38	Conservation Plans	Pasture	0.05	0.1	0.14	280
39	Forest Buffers & Wetland Restoration	Pasture	-1	-1	-1	1040
40	Grass Buffers	Pasture	-1	-1	-1	146
41	Off Stream Watering w/ Fencing	Pasture	0.6	0.6	0.75	100
42	Off Stream Watering w/ Fencing & Rotational Grazing	Pasture	0.2	0.2	0.4	150
43	Off Stream Watering w/o Fencing	Pasture	0.3	0.3	0.38	60
44	Precision Rotational Grazing	Pasture	0.25	0.25	0.25	20
45	Off Stream Watering w/ Fencing	Trampled Pasture	0.6	0.6	0.75	100
46	Forest Buffers & Wetland Restoration	Harvested Forest	0.3	0.68	0.68	1040
47	Forest Harvesting Practices	Harvested Forest	-1	-1	-1	30
48	Grass Buffers	Harvested Forest	-1	-1	-1	146
49	Dry Detention Ponds w/ Hydrodynamics	Low Intensity Impervious	0.045	0.09	0.09	3675
50	Dry Extended Detention Ponds	Low Intensity Impervious	0.27	0.18	0.54	3675
51	Erosion & Sediment Control	Low Intensity Impervious	0.297	0.5	0.5	5800
52	Filtration	Low Intensity Impervious	0.36	0.54	0.765	3675
53	Infiltration	Low Intensity Impervious	0.45	0.63	0.81	3675
54	Urban Forest Buffers	Low Intensity Impervious	0.225	0.45	0.45	1200
55	Wet Ponds & Wetlands	Low Intensity Impervious	0.27	0.45	0.72	3675

56	Dry Detention Ponds w / Hydrodynamics	Low Intensity Pervious	0.045	0.09	0.09	3675
57	Dry Extended Detention Ponds	Low Intensity Pervious	0.27	0.18	0.54	3675
58	Erosion & Sediment Control	Low Intensity Pervious	0.297	0.5	0.5	5800
59	Filtration	Low Intensity Pervious	0.36	0.54	0.765	3675
60	Infiltration	Low Intensity Pervious	0.45	0.63	0.81	3675
61	Urban Forest Buffers	Low Intensity Pervious	0.225	0.45	0.45	1200
62	Urban Nutrient Management	Low Intensity Pervious	0.153	0.198	0	6
63	Wet Ponds & Wetlands	Low Intensity Pervious	0.27	0.45	0.72	3675
64	Dry Detention Ponds w / Hydrodynamics	High Intensity Impervious	0.045	0.09	0.09	3675
65	Dry Extended Detention Ponds	High Intensity Impervious	0.27	0.18	0.54	3675
66	Erosion & Sediment Control	High Intensity Impervious	0.297	0.5	0.5	5800
67	Filtration	High Intensity Impervious	0.36	0.54	0.765	3675
68	Infiltration	High Intensity Impervious	0.45	0.63	0.81	3675
69	Urban Forest Buffers	High Intensity Impervious	0.225	0.45	0.45	1200
70	Wet Ponds & Wetlands	High Intensity Impervious	0.27	0.45	0.72	3675
71	Dry Detention Ponds w / Hydrodynamics	High Intensity Pervious	0.045	0.09	0.09	3675
72	Dry Extended Detention Ponds	High Intensity Pervious	0.27	0.18	0.54	3675
73	Erosion & Sediment Control	High Intensity Pervious	0.297	0.5	0.5	5800
74	Filtration	High Intensity Pervious	0.36	0.54	0.765	3675
75	Infiltration	High Intensity Pervious	0.45	0.63	0.81	3675
76	Urban Forest Buffers	High Intensity Pervious	0.225	0.45	0.45	1200
77	Urban Nutrient Management	High Intensity Pervious	0.153	0.198	0	6
78	Wet Ponds & Wetlands	High Intensity Pervious	0.27	0.45	0.72	3675
<i>Note: An efficiency of "-1" denotes a buffer efficiency determined by physiographic region</i>						
<i>Source: Maryland Department of Natural Resources</i>						

Appendix F

Watersheds Used in Optimization Experiments

Watershed No.	Watershed Name	Area (Ac.)	Fraction Agricultural	Fraction Urban	Fraction Natural	PMR
1	Wye River	56891	0.52	0.12	0.36	Coastal Plain
2	Trappe Creek	7952	0.29	0.32	0.39	Coastal Plain
3	Tonytank Creek	9163	0.20	0.54	0.26	Coastal Plain
4	Terrapin Run	3050	0.02	0.05	0.93	Blue Ridge
5	Taylor Branch	5267	0.27	0.09	0.63	Coastal Plain
6	St. Clements Creek	25804	0.33	0.13	0.54	Coastal Plain
7	Rehobeth Branch	17972	0.34	0.09	0.57	Coastal Plain
8	Principle Creek	6165	0.37	0.19	0.44	Piedmont
9	Otter Pond Branch	11988	0.46	0.04	0.50	Coastal Plain
10	Morgan Creek	2206	0.69	0.08	0.23	Coastal Plain
11	Mill Creek - Caroline	22365	0.55	0.09	0.36	Coastal Plain
12	Mill Creek - Calvert	6457	0.03	0.61	0.36	Coastal Plain
13	Miles River	5598	0.34	0.20	0.46	Coastal Plain
14	Miles Creek	34015	0.49	0.08	0.43	Coastal Plain
15	Little Blackwater River	9172	0.35	0.10	0.56	Coastal Plain
16	Hunting Creek	20024	0.16	0.25	0.59	Coastal Plain
17	Hell Creek	19621	0.62	0.06	0.32	Coastal Plain
18	Gilbert Swamp Run	5658	0.27	0.15	0.58	Coastal Plain
19	Fore Creek	29078	0.50	0.08	0.43	Coastal Plain
20	Deep Run	27788	0.00	0.01	0.99	Blue Ridge
21	Corker's Creek	4055	0.23	0.06	0.72	Coastal Plain
22	Carsin Run	7618	0.26	0.33	0.41	Coastal Plain
23	Bynum Run	14902	0.21	0.43	0.36	Coastal Plain
24	Brown Branch	33930	0.50	0.06	0.44	Coastal Plain
25	Burnt Mill Creek	9584	0.18	0.12	0.70	Coastal Plain
26	Broadway Branch	7320	0.36	0.11	0.53	Coastal Plain
27	Braddock Run	6360	0.07	0.29	0.65	Appalachian
28	Western Run	6452	0.47	0.14	0.38	Piedmont
29	Western Br. Patuxant River	11312	0.11	0.50	0.38	Coastal Plain
30	Watts Branch	40689	0.06	0.76	0.18	Piedmont
31	Seyern River	59157	0.04	0.59	0.37	Coastal Plain
32	Savage River	14239	0.09	0.05	0.86	Appalachian
33	Piscataway Creek	42021	0.09	0.42	0.49	Coastal Plain
34	North Br. Patapsaco River	41981	0.33	0.28	0.40	Piedmont
35	North Br. Casselman River	74510	0.15	0.05	0.80	Appalachian
36	Muddy Branch	44026	0.07	0.71	0.22	Piedmont
37	Marsh Run	108723	0.48	0.24	0.28	Blue Ridge
38	Little Youghiogeny River	16842	0.27	0.16	0.57	Appalachian
39	Little Seneca Creek	12420	0.34	0.24	0.42	Piedmont
40	Little Pipe Creek	12530	0.57	0.26	0.17	Piedmont
41	Little Patuxant River	17536	0.16	0.51	0.34	Coastal Plain
42	Little Paint Branch	25244	0.02	0.71	0.27	Coastal Plain
43	Jones Falls	26394	0.06	0.81	0.13	Piedmont
44	Camp Spring Creek	100700	0.38	0.14	0.48	Blue Ridge
45	Chaptico River	6794	0.27	0.17	0.55	Coastal Plain
46	Cattail Creek	43033	0.50	0.23	0.28	Piedmont
47	Catoctin Creek	3370	0.42	0.15	0.43	Piedmont
48	Carroll Creek	25926	0.16	0.65	0.19	Piedmont
49	Bennett Creek	18232	0.40	0.19	0.41	Piedmont
50	Rewastico Creek	77588	0.31	0.09	0.60	Coastal Plain
51	Burgess Creek	11306	0.16	0.12	0.72	Coastal Plain
52	South River	16051	0.11	0.39	0.50	Coastal Plain
53	Cabin John Creek	42161	0.02	0.82	0.17	Piedmont



MD Study Watersheds (53 Total)

Bibliography

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