A WATERSHED-SCALE COST-EFFECTIVENESS MODEL OF AGRICULTURAL BEST MANAGEMENT PRACTICES FOR IMPROVING WATER QUALITY

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Anthony Charles Oliver

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Dedicated to my parents, Charles Oliver and Nadine Fillipucci-Oliver.

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ABSTRACT

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Poor water quality is an issue in the Eagle Creek watershed in Indiana. Best Management Practices (BMPs) are being considered to address the water pollutants of atrazine, sediment, nitrogen, phosphorus and E. coli in the watershed. When deciding on the types of BMPs to promote and which locations to promote them in the watershed, it is important to have an understanding of their cost and effectiveness at achieving the desired water quality outcome. In order to achieve this goal a general cost-effectiveness model is used. The cost-effectiveness model is specified as a mixed integer linear programming problem. The objective function of total cost is minimized subject to soft-constraints on the water quality of the receptor site. The water quality of the receptor site is determined by the pollutant output of a set of emission sites in the watershed, the transfer coefficient of the site, and the implemented BMPs chosen through the optimization process. The decision to implement a BMP at an emission site is determined by a binary choice variable, which contributes costs to the objective function. The generality of the model enables the possible applicability to other watersheds. The model is run using estimated pollutant emission data from the Eagle

Creek watershed, BMP effectiveness data from the literature, and cost data from multiple estimates. The model is run under six scenarios; five scenarios target each considered pollutant separately and one targets all pollutants simultaneously to attain results. The results show different costs, rates of pollutant abatement, and BMPs chosen for implementation under each different scenario.

CHAPTER I: INTRODUCTION

Overview

Food and water are essential to sustain human life. However, the processes by which food and other agricultural products are grown and produced in the United States cause considerable pollution of the fresh water supply. According to Cunningham (2005) three-fourths of the water pollution in the United States comes from soil erosion, fallout of air pollutants, and surface runoff from urban areas, farm fields, and feed lots. Water pollution can cause significant degradation of the natural environment and can raise health risks to humans that consume the water. One set of interventions used to reduce water pollution is the implementation of structural and non-structural best management practices (BMPs). In a world of limited resources it is important that BMPs chosen to address water quality issues be the most cost-effective for the intended purpose in order to use society's resources most efficiently. This thesis outlines a method to assess the most cost-effective set of BMPs to be implemented in an agricultural watershed

Agricultural production contributes to the pollution of water through many different pathways. Some of the main ways water can be degraded are by sedimentation, nutrient loading, atrazine and Escherichia coli (E. coli). Sedimentation arises from erosion; soil is lost from farmland and flows into waterways. Nutrient loading occurs from the loss of fertilizers from farmland into water. Fertilizers high in phosphorus and nitrogen can stimulate excessive algae and aquatic plant growth through eutrophication (Enger, 2000). This high amount of biological activity can reduce dissolved oxygen in the water when dead plant matter and algae decompose. This can cause the dissolved oxygen level to become low enough to negatively affect aquatic life, which can lead to an hypoxic zone, where there is less than 2 mg oxygen per liter of water (Cunningham, 2005). Atrazine is a chemical herbicide that is used for agriculture, which can flow into waterways. It poses health risks to humans. E. coli is a bacterium which may originate from livestock operations, including confined animal feeding operations (CAFOs) and septic system discharge. It can pose a health risk to humans.

When examining issues of water quality, it is important to understand the area of land that is contributing to the water system being examined and also the location at which water quality is being evaluated. All the land which contributes to the water system and the water itself is called the watershed. The point at which water quality is being evaluated is typically referred to as the “receptor site” and may be a water intake or some other critical point in the watershed. In a watershed there are two different methods in which pollutants enter the waterway: point and non-point sources. Point sources are clearly identifiable specific points where the pollution is being emitted. In the case of agricultural production a common point source is a CAFO. An animal operation is considered a CAFO if it surpasses specific animal number amounts, as defined by the EPA. The EPA classifies CAFOs into three groups: small, medium and large. An animal operation that has over 1000 Animal Units (AU) is considered a large

CAFO. An operation with 301 to 1000 AU, which may or may not discharge pollutants into navigable waters, is considered a medium CAFO. An operation that is designated as an animal feeding operation but falls below 300 AU, is a small CAFO. An animal unit is a metric for quantifying the amount of animals in an operation across animal types.

A large amount of pollution resulting from agricultural production is emitted from non-point sources, it is estimated that up to 25 percent of the 52 million tons of fertilizer spread on farmland each year is carried away by runoff (Cunningham, 2005). Non-point sources arise from pollution being emitted across a large area of land in which pollution sources cannot be easily distinguished or are not clearly identifiable. One method for abating these types of agricultural pollution is through the implementation of Best Management Practices.

BMPs are many different types of on-farm practices that reduce the amount of pollution that enters waterways. Each BMP may reduce different pollutants at different rates. The pollution-reducing effects of these BMPs may also vary by location in the watershed. The costs of implementing these BMPs vary by type and may vary by location in the watershed. This makes it important to identify the types of BMPs that are the most cost-effective for the different types of pollutants. One type of BMP is more cost-effective than another if, for a given pollutant, it provides a greater or equal reduction of that pollutant at the receptor site for a lower cost. While water quality at locations between the emission sources and the receptor site may be important, and may differ from that at the receptor site, such issues are not considered in this study.

Location of Study

The empirical portion of this thesis focuses on the Eagle Creek watershed, which is currently experiencing significant amounts of the previously mentioned pollutants (atrazine, nutrient loading, sediment, and E. coli) from point and non-point sources (Tedesco, 2005). The Eagle Creek watershed is located approximately 10 miles to the northwest of the city of Indianapolis, Indiana. The Eagle Creek Watershed is part of the Mississippi River Basin, whose water eventually flows into the Gulf of Mexico. The watershed consists of three main branches of streams: School branch, Fishback Creek and Eagle Creek branch, which flow into the Eagle Creek reservoir. These branches are fed by 8 main tributaries: Dixon Branch, Finely Creek, Kreager Ditch, Mounts Run, Jackson Run, Woodruff Branch, Little Eagle Branch, and Long Branch. The flow apportionments for the three branches are: an average flow 100 ft^3/s for Eagle Creek contributing 79% of the water to the reservoir, an average flow of 37 ft^3/s for Fishback Creek contributing 14% of water to the reservoir, and an average flow of 17 ft^3/s for School Branch contributing 7% of water to the reservoir (Tedesco, 2005).

The approximate area of the watershed is 105,229 acres. The watershed is contained in the four Indiana counties of Boone, Hamilton, Hendricks, and Marion. Table 1.1 indicates the allocation of acreage to different uses in the watershed. Figure 1.1 is a map of land uses in the watershed. The allocation of land to different uses in the watershed is expected to change over time. Tedesco (2005) has predicted likely changes in land uses are to 2040 using the Land Use in Central Indiana (LUCI) model. Results are shown in Table 1.2 below. The total population the watershed as of the 2000 census is 235,142 people. An expected increase in urbanization will lead to an increase in the total population over time.

Table 1.1: Allocation of Land to Specific Uses

Land Cover Type	Total Eagle Creek Watershed *(acres)*	*%*
High Density	1,485	1.4%
Low Density	8,896	8.5%
Excavations	627	0.6%
Forest	14,221	13.5%
Herbaceous	14,579	13.9%
Agriculture	63,219	60.1%
Water	2,202	2.1%
Total Area	**105,229**	

(Source: Tedesco, 2005)

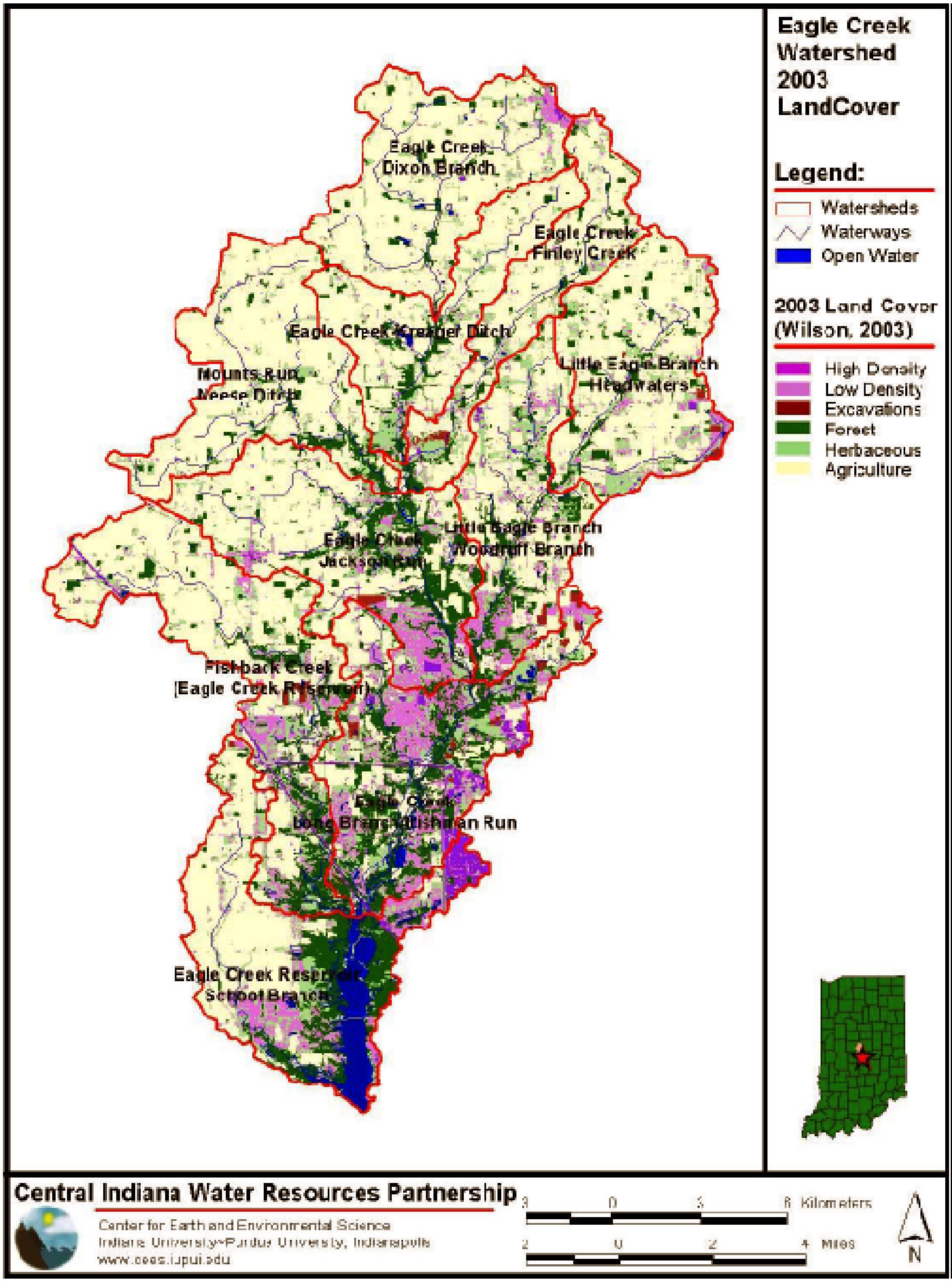

Figure 1.1: Map of Land Use in the Eagle Creek Watershed
(Source: Tedesco, 2005)

Table 1.2: Projected Urbanization in the Eagle Creek Watershed

Subwatershed	%Urban* 2000	%Urban* 2040	Change in % Urbanization
Eagle Creek-Dixon Branch	3%	7%	4%
Eagle Creek-Finley Creek	2%	23%	21%
Eagle Creek-Kreager Ditch	2%	13%	11%
Little Eagle Branch-Headwaters	3%	57%	55%
Mounts Run-Neese Ditch	1%	12%	11%
Little Eagle Branch-Woodruff Branch	10%	75%	66%
Eagle Creek-Jackson Run	15%	64%	49%
Fishback Creek (Eagle Creek Reservoir)	10%	59%	49%
Eagle Creek-Long Branch/Irishman Run	31%	85%	54%
Eagle Creek Reservoir-School Branch	18%	65%	47%

* low and high density land cover
(Source: Tedesco, 2005)

The Eagle Creek reservoir is used for recreational purposes and the water from it is used as a drinking water source for the city of Indianapolis. Accordingly, for this analysis the reservoir is defined as the single receptor site of concern. The drinking water is provided to Indianapolis by Veolia Water Indianapolis, LLC. and is treated in the T.W. Moses water treatment facility, which was constructed in 1976 (Tedesco, 2005). This treatment facility is not technologically equipped to adequately address levels of algal-produced taste and odor compounds historically measured in the reservoir (Tedesco, 2005). Indiana Department of Environmental Management (IDEM) designates the water in Eagle Creek for agricultural use, full body contact recreation, and aquatic life use. However many years of water sampling have shown the quality of water in this watershed is in conflict with IDEM’s designated uses (Turco, 2006).

Problem Statement

Sample data from the watershed show that water impairment in the Eagle Creek watershed frequently exceeds government standards. The acceptable level of E. coli set by the state of Indiana at 235 colonies per 100ml is frequently exceeded. The United States Environmental Protection Agency (USEPA) has set a standard of 3.0 μg/L for atrazine concentration in drinking water. This standard is exceeded in 10% of the samples taken across the watershed and up to 35% of the time samples are taken in the subwatershed of Long Branch/Irishman Run (Tedesco, 2005). While a standard for sedimentation has not been set at a specific level by a government agency, its level in the watershed is high enough to degrade aquatic habitat and to transport large amounts of sediment to the reservoir. Nutrient loading in the reservoir, including nitrogen and phosphorus loading, frequently exceeds the national average for concentrations in similar watersheds (with 50-75% agricultural use) 60% of the time samples are taken (Tedesco, 2006). From these data it is clear that all these pollutants are above acceptable levels in the watershed.

The amount of pollution that is entering the Eagle Creek watershed conflicts with its purposes of providing recreational uses and drinking water, and degrades the natural environment. The problem in the Eagle Creek watershed is that practices are being put into place to prevent water pollution but, it is not clear which BMPs will provide the most cost-effective abatement of this pollution.

Objectives

The objectives of this research are to (1) describe the types of damages that occur from agricultural pollution, (2) to develop an optimization model to study BMP cost-effectiveness, and (3) to use this model to evaluate the cost-effectiveness of a variety of different BMPs implemented at different locations across the watershed.

The main research questions are:

Question 1: Taking the reservoir as a receptor site of concern, how effective are the different BMPs at reducing different types of water pollution in the Eagle Creek watershed?

Question 2: Among these different BMPs, which are most cost-effective?

To answer these research questions, data on BMP cost, BMP efficiency of pollution abatement, and transfer coefficients are utilized in a cost-effectiveness model. This model generates the most cost-effective set of BMPs to achieve a desired water quality. These results allow for construction of a cost curve across the quantity of pollution abatement. A given point on the cost curve will represent the lowest cost option for the desired level of pollution abatement.

Scope of Research

There are some caveats to the scope of this research. Some economic analyses of externalities, such as water pollution, attempt to quantify and value the damages caused from the externality and the costs of abating that pollution. However for this study information necessary to value the damages caused by some of these different pollutants was not available. This limits this research to simply describing what is currently known about the types of damages caused by these different pollutants without attempting to measure the monetary value of these damages.

While the purpose of this study is to determine the cost-effectiveness of different types of BMPs in the watershed, there are some limitations to this approach. One limitation is that in examining BMPs for pollution prevention in the watershed, not all feasible BMPs are considered. There are many different types of BMPs available to farmers and other agricultural producers. In this analysis ten BMPs will be analyzed. The BMPs included in the analysis are:

- Cropland Protection
- Conservation Tillage
- Contour Farming
- Conversion to Forest
- Conversion to Wetland
- Nutrient Management
- Terraces and Diversions
- Vegetative Buffers
- Waste Management
- Runoff Control

Examining a restricted list of BMPs means less cost-effective BMPs might be identified for a particular location than otherwise might have been chosen if the entire population of available BMPs were considered. These ten BMPs have been chosen for this analysis because they are common types of BMPs and the necessary data required for the cost-effectiveness model are available for them. This includes data on cost and effectiveness at reducing five different types of pollutants (atrazine, nitrogen, phosphorus, sediment, and E. coli) as will be discussed in chapter 3.

Summary

The Eagle Creek Watershed is experiencing a significant level of water pollution resulting to some degree from agricultural sources. This level of water pollution conflicts with designated uses of the watershed for recreation and as a source of drinking water. BMPs are being implemented to address the water quality issues, but the available types of BMPs have different levels of effectiveness at abating different pollutants and also have different costs associated with them. As a result, it is important to study the set of cost-effective BMPs to be implemented throughout the watershed to attain the desired water quality. Finding the set of cost-effective BMPs will help promote efforts to attain the desired water quality at least cost. Some of the limitations to this study are that it will not attempt to measure the monetary value of damages caused from pollution and it will not take into consideration other methods besides BMPs for abating agricultural pollution.

CHAPTER II: LITERATURE REVIEW

Overview

This chapter reviews literature relevant to this study. The Literature Review is divided into two main sections. The first section reviews literature on environmental and health damages from the pollutants present in the watershed. This includes examining the damages caused by atrazine, E. coli, sedimentation and nutrient loads. The second section reviews prior studies similar to this study, including Cost-Benefit Analyses (CBAs), Cost-Effectiveness Analyses (CEAs), and construction of cost curves from CEA results.

Literature Review

The types of pollutants studied in this analysis are atrazine, E. coli., nutrient loads (nitrogen and phosphorus), and sedimentation. Although the damages arising from these specific pollutants are not fully quantified and valued, it is important to have an understanding of their relative impact on the environment. Therefore, the characteristics of these pollutants are reviewed briefly below.

Atrazine is the most commonly applied herbicide in the United States with an average of 51 million pounds of active ingredients applied per year (Graziano, 2006). It is commonly applied to corn fields, which make up 31% of the Eagle Creek watershed (Tedesco, 2005). Atrazine is currently regulated under the Safe Drinking Water Act

(SDWA). The USEPA has released reports regarding the health risks of atrazine. In the late 1980s atrazine was originally classified by the EPA as a possible human carcinogen (EPA, 2002). In 1994 the EPA initiated a Special Review of atrazine's potential to cause human cancer through dietary or occupational exposure (EPA, 2002). In 2000 the Federal Insecticide, Fungicide and Rodenticide Act (FIFRA) Scientific Advisory Panel (SAP) determined that atrazine was "not a likely human carcinogen". The EPA has reviewed and accepted this judgment. The current risk assessment of atrazine uses a non-cancer endpoint as the basis for regulating atrazine exposure. A Maximum Contaminate Level (MCL) of 3 parts per billion (ppb) was established in 1991 for drinking water (EPA, 2002) and remains at this level at present. While atrazine has been categorized as "not a likely human carcinogen" by the EPA, it has been found to potentially have some short-term (relatively short period of time of exposure above the MCL) and long-term (lifetime exposure at levels above the MCL) health effects on humans. In the short-term these health effects can include: congestion of the heart, lungs and kidneys, low blood pressure, muscle spasms, weight loss, and damage to adrenal glands. In the long-term these health effects can include: weight loss, cardiovascular damage, retinal and some muscle degeneration, and cancer (EPA, 2005). These potential health risks are not linked to economic damages through any literature, at present.

E. coli is another type of pollutant that is found in the Eagle Creek watershed. E. coli is a coliform bacterium that lives in the intestine of humans and other animals (Cunningham, 2005). Fecal coliform are used as an indicator organism to test for organic pollution (Ritter, 2001). It is usually assumed that if any coliform bacteria are present in are present in a water sample, infectious pathogens (disease causing organisms) are also present (Cunningham, 2005). The acceptable level of E. coli in drinking water is set by the state of Indiana at 235 colonies per 100ml.

Leggett (2000) estimates a portion of the economic cost of water contaminated with fecal coliform bacteria by examining its effect on land prices. In this study fecal coliform is assumed to affect land prices, because its presence will matter to individuals who wish to use the water adjacent to their property for swimming and fishing. Also when coliform levels are high water may appear unsightly and may give off an unpleasant odor, and even moderate levels of fecal coliform can pose a hazard to human health. This economic analysis is performed using data from the Anne Arundel coastline of the Chesapeake Bay region. A hedonic pricing model is used to estimate individual's willingness to pay for an improvement in water quality through a decrease in the amount of fecal coliform present. The hedonic price function is specified in linear form and three different types of logarithmic form. For each of the four specifications two alternate dependent variables are used: market transaction price for the land and market transaction price minus assessed value of the structure on the land. The explanatory variables of the model include lot size, distance from major cities, and of course the median fecal coliform concentration in year of sale, as well as other variables. The results of the hedonic pricing functions are found using ordinary least squares. The coefficient of fecal coliform is found to be negative and significant at the 5% level for seven of the specifications and at the significant at the 10% level for one of the specifications. This negative and significant coefficient indicates that a higher median level of fecal coliform decreases sale price of nearby property. A change of 100 fecal coliform per 100 ml is estimated to produce about a 1.5% change in property prices. The authors conclude that waterfront property owners have a positive willingness to pay for reductions in fecal coliform bacteria concentrations.

Research on the offsite damages from sedimentation (or the offsite benefits of reduction of sediment) has been conducted by Ribaudo and Young (1989). The linkages between soil erosion and offsite damages are formed through a series of models. The first link consists of soil loss on crop land, which is considered to be a function of rainfall erosivity, soil erodibility, slope length, crop management, and conservation practices. The second link consists of the movement of soil from the field edge to the waterway. This consists of such factors as distance, slope, and vegetation amount. The third link is the impact that the eroded soil has on the physical and biological characteristics of the water. This impact is measured by characteristics such as temperature, turbidity, pH, concentrations of applied nutrients and pesticides, and numerous other measures. The fourth link is how the water quality parameters affect the use of the water resources. Recreation, commercial fishing, drinking supplies, and other factors can be affected by poor water quality. The fifth link is the economic damages of these changes in usage of water due to decreased water quality.

Ribaudo and Young (1989), apply the models on a regional level called Farm Production Regions (FPR), with ten FPR in the United States. The damages addressed are: recreation, water storage, navigation, commercial fishing, flooding, water conveyance, water treatment, municipal and industrial use, steam-electric power cooling, and irrigated agriculture. Results suggest that potential benefits aggregated across all FPRs from reduced sediment damages to ditches and canals were $31 million, the benefits to water storage, flooding, navigation, and municipal and industrial withdrawal were $309 million and the benefits to recreation and commercial fishing were zero. The reason recreational and commercial fishing benefits were estimated as zero is that a threshold level was used. The idea of the threshold level is that if the suspended sediment was not reduced below a threshold of 90 mg/L, no improvement for recreation or commercial fishing was made. In the Corn Belt FPR (region containing the Eagle Creek watershed) the total benefit of reductions was $27 million, with 27 million tons reduced, resulting in a benefit per ton reduced of $0.29.

Ribaudo and Young (1989) provide useful information of the economic damages resulting from sedimentation of waterways. However, as acknowledged in the article there are some shortcomings in the measurements of these benefits. For example, the assumption of a threshold level for any economic improvement in recreation and commercial fishing may be too limiting. It is possible that reductions in sediment loads which do not surpass the threshold level would still provide benefits. There is also no measurement of how reduction of sediment may improve the aquatic and surrounding ecosystems, which can provide economic value. Aside from these shortcomings the estimates are still a useful guideline when considering the value of sediment reduction.

Literature specifying actual monetary damages due to increases in nutrient loads is sparse. While it is clear that increase in nitrogen and phosphorus levels can be damaging to aquatic ecosystems through processes such as hypoxia, monetary values have not been placed on these types of damages. In an attempt to place a lower bound on the damage of nutrient runoff from farmland, Buckner (2001) makes an estimate based on market prices of fertilizer. It is reasoned that the damage from runoff of nutrients is at least equal to the price the producer paid for the fertilizer, which once removed from the field provides no crop enhancement. For this estimate the bulk rate for triple super phosphate and anhydrous ammonia fertilizer is determined to be $0.20/kg and $0.27/kg (price as of 2000) respectively. While this method only accounts for on-site damages of nutrient runoff, it does offer a lower bound and some insight into a portion of the value of economic damages.

Several previous studies provide economic analyses using the cost-effectiveness and cost-benefit framework for evaluating agricultural BMPs. These analyses are useful in that they provide methodological assistance as well as insight for this current study. Aust (1996) applies the CBA framework to Forestry BMPs in Virginia. In this study the authors examine the cost and benefits of four different phases of BMP implementation for reducing soil erosion. These four different phases correspond to increasing levels of BMP implementation over time, with the first three levels being an actual program and the fourth phase being hypothetical. Cost estimates for these BMPs include installation and administration components. Installation cost is based on the type of landowner and the physiographic region of installation. Administration costs are taken from the Virginia Department of Forestry records, which show significantly increasing marginal costs at each successive phase of BMP implementation. The benefits of preventing a ton of sediment from entering the streams of Virginia are assumed to be equal to the estimates of Ribaudo (1989) and Ribaudo and Young (1989), which vary for different regions of the country. The results of this CBA show decreasing benefit-to-cost (BC) ratios for each successive phase of BMP implementation.

While Aust (1996) provide a useful example of an economic analysis regarding BMP implementation and a source for an estimation of economic damages for sedimentation, the study does have some shortcomings. These shortcomings include the assumption that full implementation of the BMP program (100%) would eliminate all sedimentation and that the proportion of the total BMP plan implemented at each phase level corresponds directly to the proportion reduction in sedimentation.

Yadav (1998) also used the CBA framework for evaluation of BMPs. In this study the BMPs to be implemented were aimed at controlling nitrate contamination of groundwater. This analysis takes a watershed approach by evaluating these BMPs in the Garvin Brook Watershed in Minnesota. In order to value the benefits of BMP implementation the authors used what would be the foregone costs of providing a low nitrate water supply in the watershed. The method of providing this low nitrate water supply is assumed to be that one third of affected people drill a new well, one third lease a reverse osmosis (RO) system, and one-third buy an RO system. This method is evaluated under the current scenario of contamination and two future scenarios to arrive at the monetized benefits. The first scenario is contamination at its current level of 35% of wells exceed 10 mg/L nitrate, with the two future scenarios exhibiting increasing levels of contamination and correspondingly increasing cost of providing low nitrate water. On the cost side of this analysis there was only one option of adopting a collection of BMPs, which were assumed to reduce nitrate below the level of 10 mg/L. The benefit-cost ratio for the implementation of this collection of BMPs was found to reach one in 6 years under the current scenario and to occur in 5 and 4 years for the progressively worse future scenarios, respectively.

Yadav (1998) is useful for showing methods for quantifying and valuing water quality benefits related to drinking water and watershed level methods for abating this pollution. The CBA does have some limitations, in that it does not attempt to measure BMP efficiency for a single BMP or the entire collection of BMPs implemented as a whole. It is assumed that only the entire collection of BMPs could be implemented to reduce concentration below the 10 mg/L baseline. While it is possible that this collection of BMPs does reduce the concentration below the baseline, it may also bias the CBA analysis towards higher costs by choosing a greater level of BMP implementation than is required to reach the baseline.

A study by Bracmort (2004) uses the CBA framework to analyze agricultural BMPs and uses the Soil and Water Assessment Tool (SWAT) hydrological model to estimate pollution reduction resulting from a BMP implementation. This CBA is conducted ex-post for a project that was implemented in the Black Creek watershed in Indiana from 1973-1984. The CBA is performed only two subwatersheds of the Black Creek watershed. This analysis only takes into account the cost and benefits of reducing sediment and total phosphorus (P). The benefits received from implementation were estimated from the SWAT model which predicted the reduction in pollutants. A monetary value was placed on the benefit of reduced sediment using estimates from Ribaudo (1989) and estimates of the value of reduced dredging from Cangelosi (2001). These estimates were $1.15 per ton of eroded soil from Ribaudo (1989) and $0.87 per ton of eroded soil from Cangelosi (2001), for a total cost of $2.24 per ton. The benefit of reducing nutrient concentration was monetized using the cost of a specific type of phosphate fertilizer, which estimates the money lost to the farmer by the fertilizer not remaining on the field to enhance crop production (Buckner, 2001). This amount was found to be $264/ton. BMP cost included installation and maintenance costs. The CBA shows that the benefits did not exceed the costs with a corresponding BC ratio of 0.470 for the specific subwatershed. It is however mentioned that many benefits to pollution reduction are not accounted for by the analysis.

Bracmort (2004) goes further than other analyses of BMPs, such as Yadav (1998) by using a hydrological model to estimate actual decreases in pollutants due to a specific BMP rather than assuming an amount of decrease. This allows for a more accurate measurement of the costs and benefits of the project. However, these measures of pollutant abatement due to a specific BMP could also be used to measure the cost-effectiveness of a specific BMP, which would have provided a more detailed analysis of how the BMPs perform.

Moving away from the CBA analysis and examining just the cost side of agricultural BMPs is a study by Heatwole (1987). This study is a cost-effectiveness analysis of BMPs in two Florida basins. Models are used to predict the runoff from agricultural land of nitrogen and phosphorus into waterways. BMP efficiency is evaluated for 15 different scenarios of different combinations of BMPs. The authors note that the efficiency of a combination of BMPs cannot be summed because of interactions between BMPs that would make this inaccurate. An interesting result from this analysis is that the overall cost-effectiveness of a scenario decreased with the increase in the level of BMP implementation.

Yuan (2002) presents a study of cost-effectiveness of BMPs. In this study BMPs for sediment reduction in the Mississippi Delta are analyzed. The study is conducted in a monitored 12 hectare (ha) watershed of Deep Hollow Lake. In this analysis the Annualized Agricultural Non-Point Source (AnnAGNPS) pollutant loading model is used to predict BMP efficiency. BMP efficiency is predicted under three scenarios: conventional-till, reduced-till, and no till. BMP efficiency was evaluated for individual practices and combinations of practices. The costs of the BMPs were obtained from USDA Natural Resource Conservation Service (NRCS) data. The possible effect on profitability of the different tillage scenarios was not evaluated in this study. These cost figures were then regressed on their predicted sediment yield reduction for each scenario. This process yielded what are essentially marginal cost curves for sediment abatement. The results of this analysis showed the no-till scenario to reduce a greater amount of sediment at every level of cost compared to the other tillage scenarios.

While the economic analysis by Yuan (2002) does not account for the benefits of sediment reduction in order to offer an optimal level of sediment abatement, it does illustrate the lowest cost method to reach a desired level of sediment abatement. This is useful knowledge to have when selecting a target level or trying to get the greatest increase in water quality from a specific programs budget. The CEA methodology used by Yuan (2002) is similar to what is utilized in this thesis for the analysis performed on BMPs in the Eagle Creek watershed.

Veith (2004) uses an optimization approach to BMP placement through a Genetic Algorithm (GA). The optimization approach enables consideration of spatial variation across multiple variables and, through evaluation of numerous scenarios, incorporating the impacts of BMP interaction and site-dependent characteristics in the assessment of scenario effectiveness. This is compared to the targeting approach, such as that utilized by Heatwole (1987). Conceptually the GA is based on natural selection techniques seen in biological evolution. In this GA a watershed scenario is modeled as a chromosome. Each field in the watershed is represented as a gene and is associated with a selection set of possible management practices. At each iteration of optimization a fitness score is calculated based on non-point source and economic components. This fitness score allows different scenarios to be compared and the “most fit” scenarios selected for implementation. The results of this optimization process provided more cost-effective reduction of sediment than the targeting method. Finally a CBA is performed for an analysis of the cost and benefits of the targeting or optimization approach to deciding how to implement BMPs. The CBA shows that the optimization process is preferred to the targeting approach.

The GA used by Veith (2004) is beyond the scope of the research in this thesis. While it provides a high quality method for obtaining optimal BMP placement in a watershed, it has thus far only been utilized for sediment and nutrient reduction evaluation.

Summary

The existing literature provides knowledge in a range of areas related to this thesis. The literature on the potential damages and risks of atrazine, E. coli, sediment and nutrient loads offers perspective on the relative benefits of reducing levels of these pollutants in a watershed. The articles on CBA and CEA of BMPs provide an overview of the state of economic analysis in this area and a conceptual framework to utilize in this study.

CHAPTER III: METHODS AND DATA

Overview

This chapter contains a description of the methods and data utilized to evaluate the previously stated research questions. The types of data utilized in the model are pollutant emission data, BMP effectiveness data, and BMP cost data. These data provide parameters for a mathematical programming model designed to achieve target levels of pollution abatement at least cost.

Methods

In order to examine the main questions motivating this research a cost-effectiveness model is used. The basic framework of this model is a depiction of the watershed as a finite set of farms and CAFOs which have corresponding emission levels for each type of pollutant. Each of these farm and CAFO sites contribute pollution to a single point of measurement in the watershed called the receptor site, which in this case is the Eagle Creek reservoir. The amount of pollutant contributed to the watershed by each site is determined by the farm/CAFO's initial amount of pollutant output, their distance from the point of measurement, and the effectiveness of implemented BMPs on the site (as chosen through the optimization process). The types of BMPs chosen for implementation are at the watershed level dependent on the target concentration levels and financial penalties accrued for not meeting these target levels.

The cost-effectiveness model is a mathematical programming model in which an objective function is optimized subject to a set of constraints. The mathematical programming model is specified as a mixed-integer linear programming problem with a set of binary choice variables. The model is structured as a total cost function for implementation of BMPs throughout the watershed to be minimized, subject to soft-constraints on a concentration target at a single receptor site, namely the Eagle Creek Reservoir. A soft-constraint differs from a hard-constraint, in that the soft-constraint can be broken, but at a penalty to the objective function. The cost-effectiveness model consists of four equations. Equation 1 is the cost function and equations 2-4 are model constraints. The sets, parameters, and variables included in the model are presented in Tables 3.1 and 3.2.[1] The model is defined as follows:

Choose {θ} to

$$\text{minimize} \qquad C = \sum_{ij} \theta_{ij}\kappa_j S_i + \sum_k (T_k^+ * R_k + T_k^- * P_k) \qquad (1)$$

subject to:

$$N_k = [\sum_i \varepsilon_{ik}\tau_i * (1 - \sum_j \theta_{ij}\beta_{jk})] \qquad (2)$$

$$T_k = N_k + T_k^+ - T_k^- \qquad (3)$$

$$\sum_j \theta_{ij}\beta_{jk} \leq 1 \qquad (4)$$

[1] The entire mathematical program in GAMS is contained in Appendix B

Table 3.1: Description of Sets in the Model

Set Name	# of elements	Description
i	24	A set of farm and CAFO sites within the watershed
j	10	A set of farm and CAFO BMPs
k	5	A set for each type of pollutant

Table 3.2: Parameters and Variables in the Model

Name	**Type**	**Defined over set(s)**	**Description**
κ	Parameter	*j*	Annual cost of the jth type of BMP
τ	Parameter	*i*	Transfer Coefficients for the farm/CAFO sites defined over the set i
T	Parameter	*k*	Target concentration level for pollutant k
P	Parameter	*k*	Monetary penalty for exceedence of the target concentration level
R	Parameter	*k*	Monetary reward for reaching a lower level of pollutant concentration than targeted
ε	Parameter	*i,k*	Emissions of pollutant k from farm site i
β	Parameter	*j,k*	Effectiveness of type j farm BMP towards prevented emissions of pollutant type k
S	Parameter	*i*	Size of farm or CAFO in acres or AU respectively
C	Variable		Annual total project cost
N	Variable	*k*	Concentration of type k pollutant at the Eagle Creek Reservoir
T^+	Variable	*k*	Amount by which the target concentration level for pollutant k was surpassed
T^-	Variable	*k*	Amount by which the target concentration level for pollutant k was deficient
θ	Binary Variable	*i,j*	Choice variable for implementation of type j farm/CAFO BMP at site i

In this model the total cost function (equation 1) is the sum of the cost of the implemented BMPs at every site in the watershed, plus the aggregate monetary penalties arising from deficiencies between observed and target pollutant concentrations, minus monetary rewards for differences between target and observed pollutant concentrations. Implemented BMPs are indicated by the binary choice variable θ_{ij}, where *i* is the set of emission sites (farms and CAFOs) and *j* corresponds to the type of BMP implemented. The choice of θ_{ij} is made in the context of equations 2-4. The implications of this for the model are that the BMPs which reduce the pollutants with the largest penalties in the most cost-effective manner will be chosen at the least stringent levels of concentration constraints, followed by BMPs with decreasing cost-effectiveness relative to the pollutant's penalty as the target concentration level is decreased.

Equation 2 defines the concentration of pollutants in the reservoir as a function of the BMPs selected for implementation. Pollutant concentration is computed by summing the emission level ε_{ik} of each type of pollutant for each farm and CAFO multiplied by its "transfer coefficient" (τ_i) times one minus the sum of the efficiencies[2] of all the implemented BMPs for each pollutant type. The spatial aspects of the watershed are addressed in the model by the parameter τ_i, called the "transfer coefficient". The transfer coefficient accounts for the difference between the on-site pollutant emission amounts and the percentage of that amount which eventually reaches the point of analysis, which is the receptor site. The transfer coefficient is a parameter

[2] The additivity of individual BMP efficiencies within the model is cited as an issue by Heatwole (1987). Equation (2a) provides a possible remedy for this issue.

ranging in value between zero. It indicates the percentage of the pollutant emissions that will contribute to the level of concentration at the receptor site.[3] The implication of the transfer coefficient is that, holding emission level constant, it makes implementation of a BMP on a farm or CAFO site with relatively high transfer coefficient more cost-effective than implementation at sites with relatively low transfer coefficients.

Equation 3 describes how the soft-constraints (formed by T^+ and T^-) are used within the model. In this equation the concentration level for each pollutant must be equal to the target level plus T^+ minus T^-. T^+ is a positive variable. Values of T^+ greater than zero for any pollutant indicate pollutant concentration was lowered by more than is required. T^- is a positive variable. Values of T^- greater than zero indicate pollutant concentration was not lowered by the required amount. The values of the positive variables T^+ and T^- form the soft-constraint. They enter the cost function (Equation 1), where they are multiplied by monetary values and added to or subtracted from the annual total project cost.

Equation 4 is a final constraint that ensures no more than 100% of emissions of a farm or CAFO can be removed by implemented BMPs within the model.

It is also possible and could be necessary to add additional site specific constraints to the model. These site specific constraints would be dependent on spatial and hydrological characteristics of the watershed. These constraints would prevent the model from implementing a BMP that is not practical for implementation at the given

[3] The transfer coefficient is expected to be a function of distance and possibly other factors in the watershed. For the Eagle Creek watershed such spatial data are not currently available. Therefore, in this work the value of the transfer coefficient is set equal to one, having no effect on the BMP implementation decision.

site, due to land characteristics specific to the site. The constraint would be formulated as:

$$\theta_{ij} = 0 \tag{5}$$

where, θ is the binary variable as previously explained and *i* and *j* are set to specific elements in the set. For example, in this equation if *i* were set to”1” and *j* was set to “contour farming”, this would prevent the model from choosing to implement the BMP of contour farming at the farm site number 1.

The solution of this model will generate some important results. These results include annual total cost (C) to reach the desired pollutant concentration level. The resulting estimated concentration level of the receptor site (N_k), which can differ from the desired level specified in the model. The BMP implementation decisions for the different emission areas in the watershed (θ_{ij}). Other results are generated such as, total BMP effectiveness at a site (Equation 4) and the amount of penalties incurred or rewards accrued (T^- and T^+), but will not be reported in this thesis. All the results are a function of the value chosen for the target water quality at the receptor site (T_k).

The intuition of this model is that the solutions generated by the optimization process are the most cost-efficient allocation of BMPs throughout the watershed to achieve the desired goals. The solution traces out a total cost function for pollution abatement within the watershed as the target pollutant levels are increased, where for every level of desired pollutant reduction the least cost method for achieving it is given.

An alternative to the concentration determination equation (equation 2) has also been specified, which could not be utilized due to a lack of necessary computational software. The equation is specified as follows:

$$N_k = \sum_i \varepsilon_{ik} T_i * \prod_j \left(1 - \theta_{ij}\beta_{jk}\right) \qquad (2a)$$

Equation (2a) would replace equation (2) and obviate the need for equation 4 in the model due to the fact that the product of numbers between 0 and 1 can never be greater than 1. Equation (2a) also provides a more interesting definition of the cumulative effectiveness of combinations of different BMPs at one emission site by allowing diminishing marginal productivity of each additional implemented BMP. If this concentration equation were to be utilized in the model it would be expected to increase the slope of the total and marginal cost curve generated by the solution to this model.

Several simplifying assumptions are made in order to implement the model. This includes assumptions regarding BMP implementation across a farm site and the cumulative effect of multiple BMPs implemented at a farm site. In the model BMP implementation is assumed to be implemented on every acre of the farm. So, for example if contour farming is chosen by the model for implementation at farm site 1, every acre of that farm will have contour farming. This assumption may be unrealistic because it may not be possible to implement the same BMP across all acres in farm due to differences in topography within the farm. The cumulative effectiveness of BMPs is added at emission sites where more than one BMP is chosen for implementation. This has the implication that if two BMPs are implemented at one site that both have an effectiveness of 50% their cumulative effect will be 100% and all pollutants will be removed. Related to this idea of cumulative effectiveness, equation (4) is added to the model. This equation limits effectiveness of BMPs at 100%, but also prohibits the implementation of a combination of BMPs that would have a sum of effectiveness greater than 100%. Mathematically, it would be problematic to have a combination of BMPs reducing more than 100% of emissions. Empirically, if these BMPs were implemented they would be unable to remove more emissions than exist. Therefore equation 4 does have a logical role in the model. This assumption may be unrealistic because there may be a diminishing marginal effectiveness of successive BMPs.

Data

Data required to implement the cost-effectiveness model include: pollutant emission data for the different farm and animal operations within the watershed, BMP effectiveness at reducing the different pollutants being considered, average cost data for implementing those BMPs, and spatial data for the watershed. The type of pollutant emission data that are necessary are data which indicates the amount of emissions of specific types of pollutants coming from specific areas in the watershed, in this case agricultural firms. These specific types of data are not currently available, so alternatively site specific pollutant emission data are estimated from pollutant loading data, as is explained in the following section. The ideal type of BMP effectiveness data to utilize in the model would be data which are specific to the Eagle Creek watershed and preferably specific to areas within the watershed, because BMP effectiveness varies widely depending on where it is placed. The type of BMP data utilized in this model is taken from the literature, as is explained in this section and is not specific to the Eagle Creek watershed. The type of spatial data required for this model, which would make up the values of the τ_i parameter, would enable the model to account for the spatial heterogeneity of emission sites in the watershed. These spatial data are not currently available, therefore the τ_i parameter is set equal 1, for all *i*, implying that all emission sites are homogenous in their spatial attributes within this watershed.

Pollutant data for the Eagle Creek watershed come from Tedesco (2005. page 104). The pollutants under consideration are atrazine, nitrogen, phosphorus, sediment, and E. coli. In this study, aggregate pollutant amounts for the entire Eagle Creek watershed are available. The aggregate pollutant amounts are shown in Table 3.3. These aggregate pollution data omit one subwatershed (Long Branch and Irishman Run). In order to adapt to this omission, the average per acre output of pollutant is estimated from the available data. This estimate of average output is then extrapolated onto the excluded acreage of the Long Branch and Irishman Run subwatershed, yielding an estimate of total baseline pollutant loading for the entire watershed. This estimate is then adjusted to create 20 uniform (in pollutants atrazine, sediment, N, and P) representative farms and 4 representative CAFOs. This adjustment is accomplished by dividing atrazine and TSS levels by 20 and dividing N and P by 24. N, P, and E. coli are allocated to the representative CAFOs based on the actual Animal Unit data[4] of four permitted CAFOs in the watershed. Allocation is accomplished by assuming that a CAFO's percentage of AU out of the total in the watershed is perfectly correlated to their percentage of total output of pollutants. Examples of a uniform representative farm and all representative CAFOs are shown in Table 3.4.

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[4] IDEM CAFO data. Data are displayed in Appendix A.

Table 3.3: Aggregate Watershed Emissions

	Atrazine	Sediment	Total N	Total P	E. coli
Extrapolated Total Annual Pollutant Loading	434 (lbs/yr)	28360 (tons/yr)	1636 (tons/yr)	971 (tons/yr)	8726 (mCFU/yr)
Implied baseline concentration level	0.85 μg/L	100 mg/L	7 mg/L	3 mg/L	0.05 mCFU/m^3

Table 3.4: Farm and CAFO Emissions

Type of emission site	Atrazine (lbs/farm/year)	Sediment (lbs/farm/year)	Total N (lbs/farm/year)	Total P (lbs/farm/year)	E. coli (mCFU/yr)
Uniform Farm	22	2835960	136344	80898	0
CAFO 1	0	0	136344	80898	1132
CAFO 2	0	0	136344	80898	2435
CAFO 3	0	0	136344	80898	3947
CAFO 4	0	0	136344	80898	1213

The extrapolated annual pollutant loading data implies specific concentrations of the pollutants for a baseline watershed. These implied concentrations are determined by dividing the total annual pollutant amount by the annual volume of water in the watershed. The estimate annual volume of water in the watershed is found by adding the annual water flow (162,140,562 m^3) and average reservoir volume (21,000,000 m^3) for a result of 183,140,562 m^3. The resulting implied concentrations are shown in Table 3.3. These implied concentrations levels indicate the expected pollutant concentration level at the reservoir assuming the pollutant loading data represents all pollutant emissions in the watershed. These concentration levels are used as a baseline within the model.

BMP effectiveness data are another requisite component of the research model. These data represent the percent of pollutant removed from an emission site due to implementation of the specific BMP. BMP effectiveness for the five pollutants considered in this study has been examined in a variety of studies: In the Pollution Reduction Impact Comparison Tool (PRedICT) User Guide (Evans, 2007), four different sources of BMP efficiencies are reviewed and the median values are presented. Devlin, et al. (2003) offers efficiency data for additional BMPs. These data are listed in Table 3.5. The entries are used as the β_{jk} parameters in the model.

Table 3.5: BMP Effectiveness (% of pollutant emissions prevented)

BMP	Atrazine	Sediment	N	P	E. coli
Cropland Protection	0	35	25	36	0
Conservation Till	20	64	50	38	0
Contour Farming	20	41	23	40	0
Forest Conversion	100	92	95	94	0
Wetland Conversion	100	98	96	98	0
Nutrient Mgmt	0	0	70	28	0
Terrace/Diversion	20	71	44	42	0
Vegetative Buffer	56	58	64	52	70
Waste Mgmt	0	0	75	14	75
Run off Control	0	0	15	15	15

(Source: Evans, 2007 & Devlin, 2003)

The descriptions of farm BMPs directly related to the efficiencies given in Table 3.5 are given by Evans, et al. (2007). The BMP of Cropland Protection consists of the practice of crop rotation and utilization of cover crops. Crop rotation is defined as the use of different crops in a specified sequence on the same farm field. Crop rotations may be as simple as a two-year rotation of corn and soybeans or as complex as a mixture of many crops spread over 6-8 years. Crop rotation can be used for several reasons including an improved soil nutrient balance and improved soil quality, but it is primarily used to reduce sediment and in turn reduces sediment-bound pollutants, such as nitrogen, phosphorus and pesticides. The practice of using cover crops refers to the use of annual or perennial crops to protect soil from erosion during the time period between harvesting and planting of the primary crop. Conservation Tillage can consist of (i) using crop residue to protect the soil, (ii) no-till planting, or (iii) other tillage techniques that leave at least 30% of the soil surface covered with crop residue. Contour Farming is a practice whereby tillage, planting, and harvesting are all conducted perpendicular to the gradient of a hill or slope. The practice is usually most effective on moderate slopes of 3-8%. Forest and Wetland Conversion is the practice of taking agricultural land out of production and letting it revert back to its natural state. This BMP also includes the planting of trees and shrubs dependent on conversion type. Nutrient Management refers to the use of organic and inorganic fertilizer for optimal crop production while protecting the quality of nearby water sources. Nutrient management consists of development of a farm-wide nutrient management plan. Terraces and Diversions are earthen channels that intercept runoff on sloping land parcels. These structures transform long slopes into a series of shorter ones. Vegetative Buffer Strips (also called conservation buffers, buffer zones, or filter strips) are areas of land maintained in some type of permanent vegetation for the purpose of trapping pollutants contained in surface runoff of adjacent land areas.

The descriptions of animal operation BMPs directly related to the efficiencies given in Table 3.5 are given by the Agricultural Waste Management Field Handbook

(USDA-NRCS, 1999) for the waste management BMP and the Pennsylvania Conservation Partnership (2000) for the runoff control BMP. An animal waste management system is a comprehensive system of multiple practices designed to help the producer achieve wise usage of natural resources while protecting the environment. Barnyard Runoff Control reduces the amount of runoff water from a barnyard, feedlot or other animal concentration area and keeps it from affecting clean surface or ground water.

Cost data for these different types of BMPs come from multiple sources. These sources include Evans, et al. (2007), Pennsylvania Conservation Partnership (2000), Indiana NRCS (2006), and Devlin, et al. (2003). However, cost data are not consistent across all sources. To resolve this issue, costs for each BMP type are averaged across the different estimates. In the cost calculations, the BMPs of Agricultural Land Retirement (Forest and Wetland Conversion), Terraces and Diversions, Vegetative Buffer, Animal Waste Management, and Runoff Control are assumed to be structural projects, with a project life of 15 years. The annual cost for these BMPs is determined by amortizing their total cost over the 15 year project life at an interest rate of 5%. The cost calculations are shown in Table 3.6.

Table 3.6: BMP Cost Calculations ($/acre/year)

	Cropland Protection[5]	Conservation Tillage	Contour Farming	AG Land Retirement	Nutrient Mgmt	Terrace Diversion	Vegetative Buffer	Waste Mgmt	Runoff Control
PRedICT[6]	25.00	30.00	10.00	5000.00	110.00	500.00	187.50[7]	1250.00	300.00
Pennsylvania[8]	23.42	n/a	8.78	4039.69[9]	n/a	477.15[10]	351.28	n/a	n/a
Indiana[11]	30.00	n/a	n/a	776.25[12]	1000.00[13]	1092.00[14]	150.00	n/a	n/a
Kansas[15]	n/a	0.00	7.62	n/a	n/a	54.47[16]	112.09	n/a	n/a
Average Amortized Payment[17]	26.14	15.00	8.80	315.23	10.60	51.15	66.90	120.43	28.90
Rental Rate (/ acre)[18]	n/a	n/a	n/a	147.00[19]	n/a	n/a	147.00	n/a	n/a
Average Annual Cost	26.14	15.00	8.80	462.23	10.60	51.15	18.48[20]	120.43	28.90

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5 Cropland Protection is a combination of cover crops and crop rotation as given by Evans (2007).

6 Costs from PRedICT program (Evans, 2007)

7 Converted from cost per mile to cost per acre by assuming that a 1 mile long buffer is approximately 66 ft wide, which equals 348,000 ft^2 of buffer.

8 Cost from Pennsylvania Conservation Catalog (2000)

9 Cost for wetland conversion is the sum of grass, shrubs and pond per acre. Cost for forest conversion is $750. Result is the average of these two values.

10 This cost is the average of gradient terrace and diversion costs. Diversion costs are multiplied by 208 for number of feet on a side of a perimeter of an acre.

11 Costs from Indiana NRCS BMP cost list 2006.

12 This value is the average of costs of planting forest and wetland conversion.

13 This value is based on a fixed amount for the entire farm. It is not used in the calculation.

14 This value is the average of terrace and diversion costs in per foot costs, multiplied by 208 for number of feet of on one side of a perimeter of an acre.

15 Costs from Devlin et al., 2003. Values converted from 2003 to 2006 dollars

16 This value is the average amount of terrace with tile drain and terrace with grass drain.

17 Average of the costs across the literature amortized at 5% interest over 15 years.

18 The average rental rate for an acre of agricultural land in Central Indiana (Purdue Agricultural Economics Report, 2007).

19 This value implies zero farm output on entire acre.

20 Average payment divided by 9 acres, which are protected by one acre of vegetative buffer.

Exploration of Cost-Effectiveness

Figures 3.5-3.8 are scatter-plots with farm BMP[21] effectiveness on the x-axis (from Table 3.5) and cost on the y-axis (from Table 3.6) corresponding to the values of each BMP type.[22] These scatter-plots illustrate how the costs of BMPs relate to their effectiveness for each type of pollutant. A BMP is more cost effective than another if, for a given pollutant, it has a higher effectiveness and an equal or lesser cost, or has a lower cost and an equal or greater effectiveness.

Table 3.7: Definition of Abbreviations

Abbreviation	Description
CP	Cropland Protection
CT	Conservation Till
CF	Contour Farming
FC	Forest Conversion
WC	Wetland Conversion
NM	Nutrient Management
TC	Terraces and Diversions
VB	Vegetative Buffer
WM	Waste Management
RC	Runoff Control

[21] BMPs related to CAFOs are not shown due to a difference in units.
[22] Descriptions of the abbreviations used in the scatter-plot are given in Table 3.5.

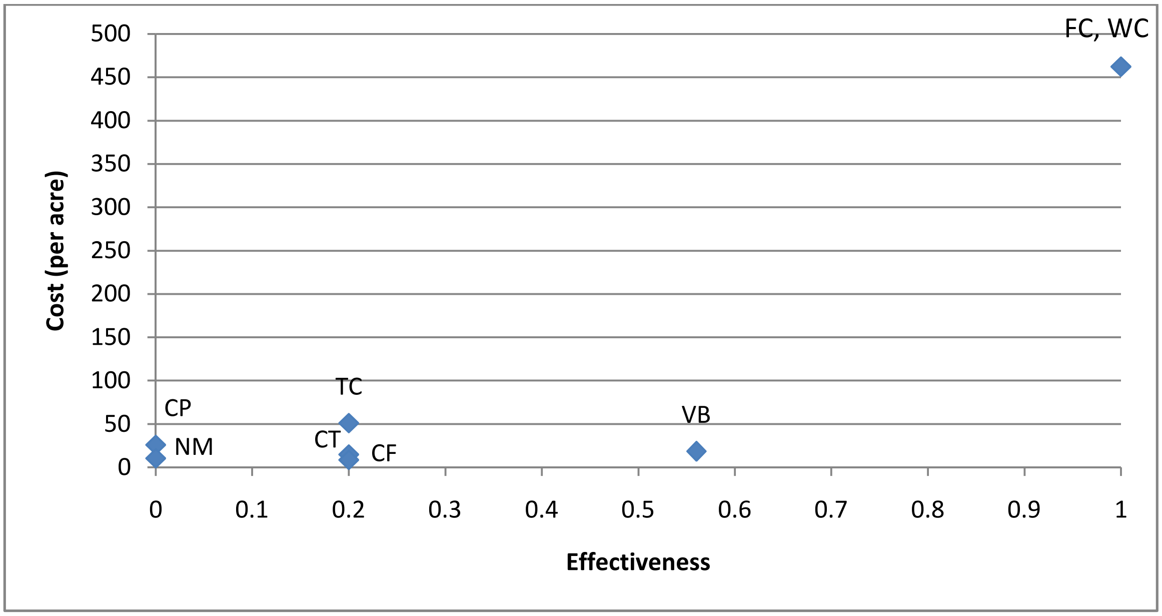

Figure 3.5: Cost-Effectiveness of Farm BMPs for Atrazine

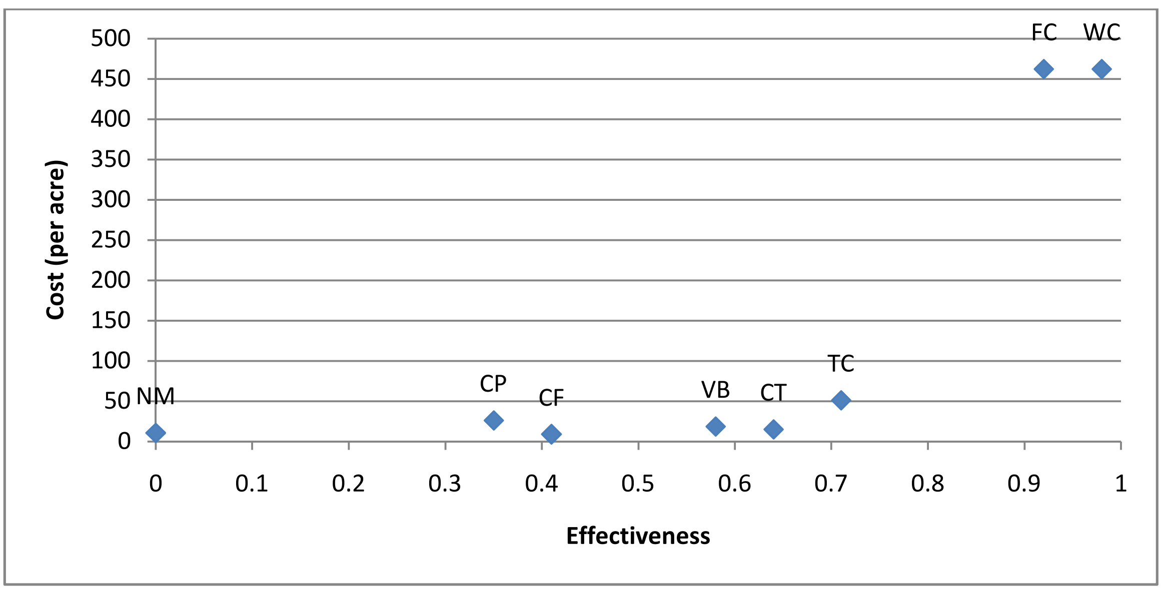

Figure 3.6: Cost-Effectiveness of Farm BMPs for Sediment

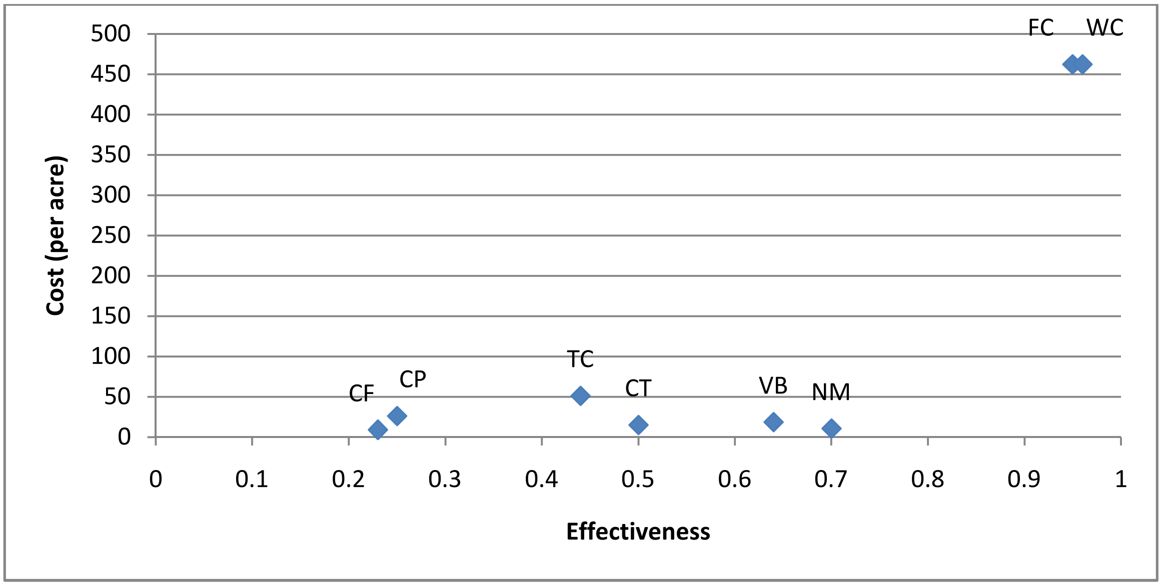

Figure 3.7: Cost-Effectiveness of Farm BMPs for Nitrogen

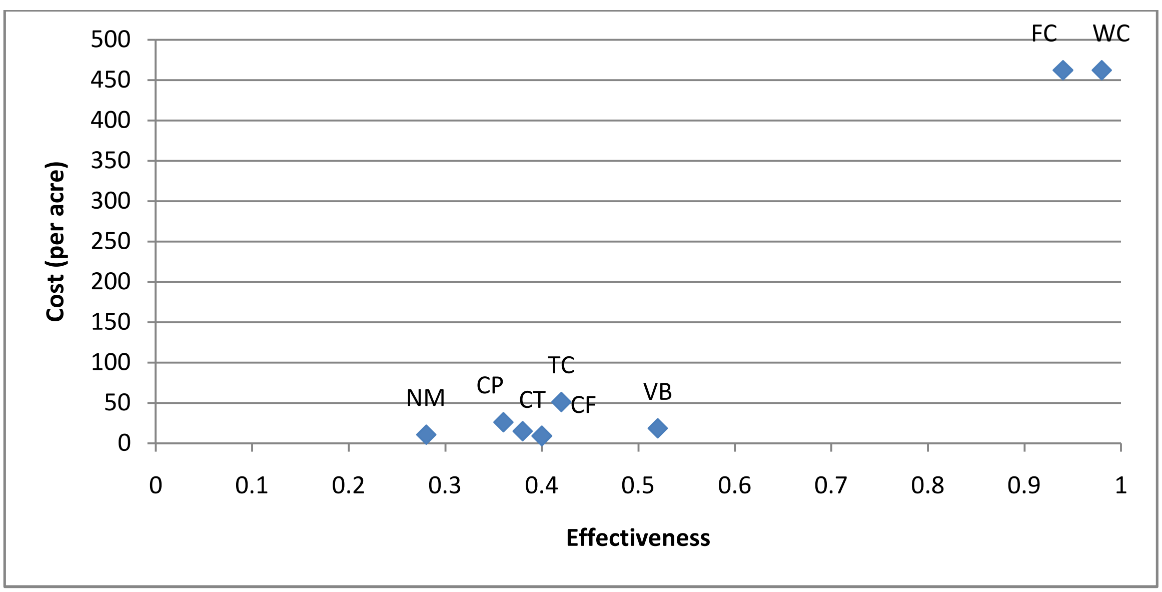

Figure 3.8: Cost-Effectiveness of Farm BMPs for Phosphorus

Another way of understanding these scatter-plots is by examining the cost-effectiveness ratio or the effectiveness-cost ratio of these BMPs. The cost-effectiveness ratio is determined by dividing the cost (from Table 3.6) of a particular BMP by the BMP's corresponding effectiveness (from Table 3.5), relative to a base scenario (Boardman, 2006). Conversely, the effectiveness-cost ratio is determined by dividing the effectiveness of a particular BMP by its corresponding cost, relative to a base scenario (Boardman, 2006). The effectiveness-cost ratio is chosen to be computed here (Table 3.6) due to the fact that some BMPs have an effectiveness of zero for a particular pollutant, which would result in an undefined cost-effectiveness ratio, making it impossible to compute an average ratio across all pollutants. The effectiveness-cost ratio is essentially the reciprocal of the cost-effectiveness ratio, therefore the BMP with the highest effectiveness-cost ratio would also have the lowest cost-effectiveness ratio (most cost-effective). The effectiveness-cost ratio is interpreted as the percentage of effectiveness for a given pollutant per dollar of cost. A BMP with a higher effectiveness-cost ratio for a given pollutant than another BMP is superior. Conversely, for a given pollutant the BMP with the highest effectiveness-cost ratio is also the most cost-effective. The base scenario used for this calculation is no implemented BMPs.

Table 3.8: Effectiveness-Cost Ratio and Average Rank of Considered BMPs

	Effectiveness-Cost Ratio (Percentage Effectiveness per Dollar of Cost)						
Type of BMP	Atrazine	Sediment	Nitrogen	Phosphorus	E. coli	Average	Average Rank
Crop Protection	0.00	1.34	0.96	1.38	0.00	0.73	5
Conservation Tillage	1.33	4.27	3.33	2.53	0.00	2.29	3
Contour Farming	2.27	4.66	2.61	4.55	0.00	2.82	2
Forest Conversion	0.22	0.20	0.21	0.20	0.00	0.16	10
Wetland Conversion	0.22	0.21	0.21	0.21	0.00	0.17	9
Nutrient Management	0.00	0.00	6.60	2.64	0.00	1.85	4
Terraces and Diversions	0.39	1.39	0.86	0.82	0.00	0.69	6
Vegetative Buffer	3.03	3.14	3.46	2.81	3.79	3.25	1
Waste Management	0.00	0.00	0.62	0.12	0.62	0.27	8
Runoff Control	0.00	0.00	0.52	0.52	0.52	0.31	7

As shown in Table 3.8 the most cost-effective BMP for atrazine, nitrogen, and E. coli is a vegetative buffer. The most cost-effective BMP for sediment and phosphorus is contour farming. On average, for all considered pollutants, vegetative buffers are the most cost-effective followed relatively closely by contour farming, conservation tillage, nutrient management. The average ranking may be distorted for BMPs that have a computed effectiveness-cost ratio of 0, even though they may have some effectiveness in practice.

Summary

The general model used in this thesis is designed to depict a watershed as a set of water pollutant emitting sites that contribute to the total concentration of those pollutants at a single receptor site. The model requires data from many aspects of the watershed to form the specific parameters that enable the model to emulate a specific watershed. With the required data included in the model as parameters and a desired pollutant concentration level for the receptor site the model will generate solutions. The solution includes a minimum total cost to achieve the desired pollutant concentration, the recommended cost-effective BMP implementation decisions at specific sites in the watershed, and the resulting concentrations of all pollutants at the receptor site.

The BMP effectiveness and cost data are graphed in a scatter-plot. These scatter-plots provide a graphical understanding of the cost-effectiveness of the considered BMPs. These data are also used to form the effectiveness-cost ratio. The effectiveness-cost ratios provide a general perspective of what BMPs are best suited for what pollutant. This ratio is also average across all pollutant types for an overall perspective of the cost-effectiveness of the considered BMPs. The scatter-plots and effectiveness-cost ratios are used to improve understanding of the data, but are not directly utilized in the model.

CHAPTER IV: RESULTS

Overview

Results from the solutions of the model are generated using six different pollutant reduction scenarios. Each scenario consists of a series of progressive increases of target pollutant reduction levels. The first five of the scenarios are defined by increasing target pollutant reduction levels for each of the five pollutants separately. This is done across ten iterations, where at each iteration the reduction level is increased by ten percent.[23] The final scenario increases the target reduction level in same manner as described above except that all pollutants are reduced simultaneously at each iteration. Table 4.1 displays the numerical values of target pollutant concentration levels used at each of the ten iterations. These numerical values shown in Table 4.1 are entered into the model through the T_k parameter. At each iteration of each scenario the values of T_k are changed to the value shown in Table 4.1. This changes the target water quality level to be obtained by the model.

Six different scenarios are used for analysis in order to assess the effects of abating different types of pollutants by different amounts. Due to the different cost and effectiveness values of the considered BMPs, some pollutants will be more costly to

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[23] Target pollution levels are increased by 10% for the first nine iterations and then increased by 9% for the final iteration, resulting in the final iteration solving for a 99% reduction in the specified pollutant. This is done because it is impossible to decrease some pollutants by 100% in this watershed.

abate than others. Also the targeting of one pollutant for abatement in the watershed can provide the benefit of reducing other pollutants, due to BMPs being effective at removing more than one type of pollutant.

Table 4.1: Target Pollutant Concentration Levels for Model Scenarios

Percentage Reduction	Atrazine (µg/L)	TSS (mg/L)	N (mg/L)	P (mg/L)	E. coli (mCFU/m^3)
0%	1.09	140.48	8.10	4.81	0.0500
10%	0.98	126.43	7.29	4.33	0.0495
20%	0.87	112.38	6.48	3.85	0.0450
30%	0.76	98.34	5.67	3.37	0.0400
40%	0.65	84.29	4.86	2.89	0.0350
50%	0.54	70.24	4.05	2.40	0.0300
60%	0.44	56.19	3.24	1.92	0.0250
70%	0.33	42.14	2.43	1.44	0.0200
80%	0.22	28.10	1.62	0.96	0.0150
90%	0.11	14.05	0.81	0.48	0.0100
99%	0.01	1.40	0.08	0.05	0.0050

The solution results include values of the choice variables, the total cost of the required pollutant reductions, and the actual versus desired pollutant reduction levels. The resulting choice variable values specify the cost-effective types of BMPs to be implemented at specific sites in the watershed for the desired pollutant level. The total cost is the sum of the annualized cost of BMP implementation and the penalties that may have to be paid for not meeting the target reduction level. In these results for the Eagle Creek watershed, monetary penalties will not be considered. The actual versus desired levels of pollutant reduction result from the fact that the pollutant may be reduced more or less than the target level specifies, due to the discrete nature of the model. Also, as the target reduction level of one pollutant is increased above zero an implemented BMP may not only reduce the concentration of that pollutant at the receptor site but also reduce other pollutants, as shown by the BMP effectiveness data in Table 3.5.

The results presented in this chapter are based on the data described in chapter 3. Inherent in these results are the issues associated with that data, as explained in chapter 3. These issues include: no spatial heterogeneity of agricultural sites within the watershed, pollutant emission data are arbitrarily assigned to 24 agricultural sites in the watershed, and the BMP effectiveness data are not watershed or emission site specific. The implications of these data issues for the results presented here are that the BMP implementation decisions shown are not specific to actual farms sites in the watershed and that the types of BMP chosen for implementation may not be very practical in this watershed. The types of BMPs chosen by the model are based on the BMP effectiveness data (β_{jk}), but since these data are not watershed or site specific they may be significantly different than the values in actuality. For example, contour farming is shown as a highly cost-effective practice, but the slopes necessary for this level of effectiveness are not prevalent in the Eagle Creek watershed, which would imply a very low effectiveness value if not zero. This leads the model to select some BMPs that likely would have a lower effectiveness value in the Eagle Creek watershed than is assumed by the model.

Results

The following tables (Tables 4.2-4.7) show the values of the choice variable (θ_{ij}) of the cost-effectiveness model. The choice variable is binary, taking on a value of 0 when no BMP is implemented and 1 when a BMP is implemented. These numbers represent the number of emission sites a given BMP is implemented at in the watershed. If the value of a BMP in the table is 20 that would indicate that the specific BMP was implemented at every farm site in the watershed. The following graphs (Figures 4.2-4.7) illustrate the choice variable results of the model for every iteration of each scenario.

Table 4.2: BMP Implementation Decisions from the Atrazine Scenario (# of sites in which the BMP is implemented)

Type of BMP	10%	20%	30%	40%	50%	60%	70%	80%	90%	100%
Cropland Protection	0	0	0	0	0	0	0	0	0	0
Conservation Till	0	0	0	0	0	0	0	0	0	0
Contour Farming	2	1	2	1	0	4	14	16	8	0
Forest Conversion	0	0	0	0	0	0	0	0	8	17
Wetland Conversion	0	0	0	0	0	0	0	4	4	3
Nutrient Mgmt	0	0	0	0	0	0	0	0	0	0
Terraces and Diversions	0	0	0	0	0	0	0	0	0	0
Vegetative Buffer	3	7	10	14	18	20	20	16	8	0
Waste Mgmt	0	0	0	0	0	0	0	0	0	0
Runoff Control	0	0	0	0	0	0	0	0	0	0

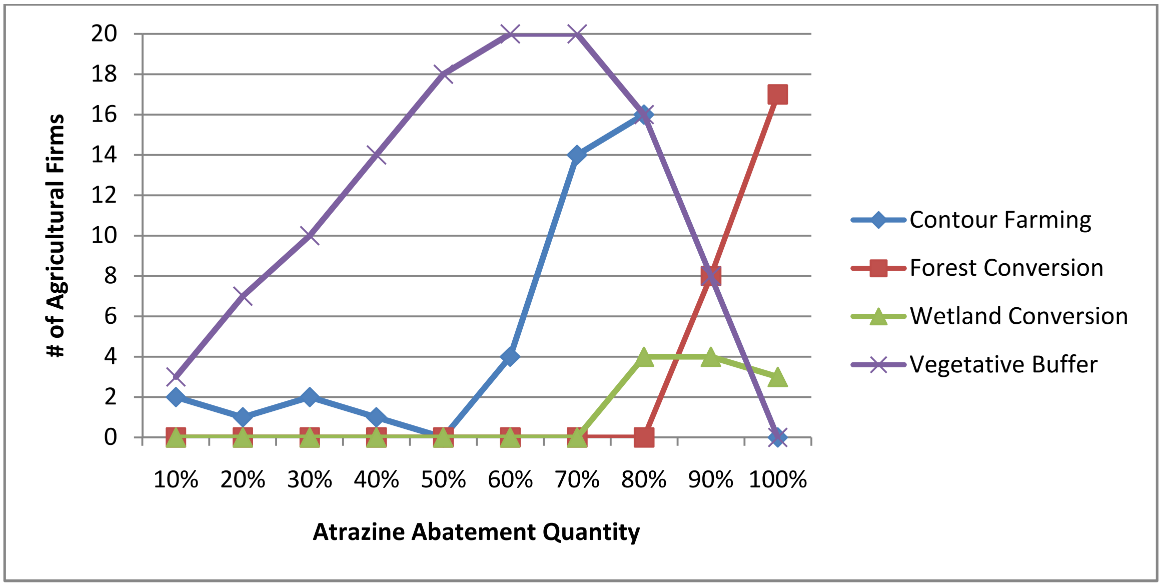

Figure 4.2: BMP Implementation Decision for the Atrazine Scenario

Table 4.3: BMP Implementation Decisions from the Sediment Scenario (# of sites in which the BMP is implemented)

Type of BMP	10%	20%	30%	40%	50%	60%	70%	80%	90%	100%
Cropland Protection	0	0	0	0	0	0	0	0	1	6
Conservation Till	0	0	0	1	8	14	8	9	6	6
Contour Farming	5	10	15	18	12	6	12	11	14	14
Forest Conversion	0	0	0	0	0	0	0	0	0	0
Wetland Conversion	0	0	0	0	0	0	0	0	0	0
Nutrient Mgmt	0	0	0	0	0	0	0	0	0	0
Terraces and Diversions	0	0	0	0	0	0	0	0	0	0
Vegetative Buffer	0	0	0	0	0	1	7	10	14	14
Waste Mgmt	0	0	0	0	0	0	0	0	0	0
Runoff Control	0	0	0	0	0	0	0	0	0	0

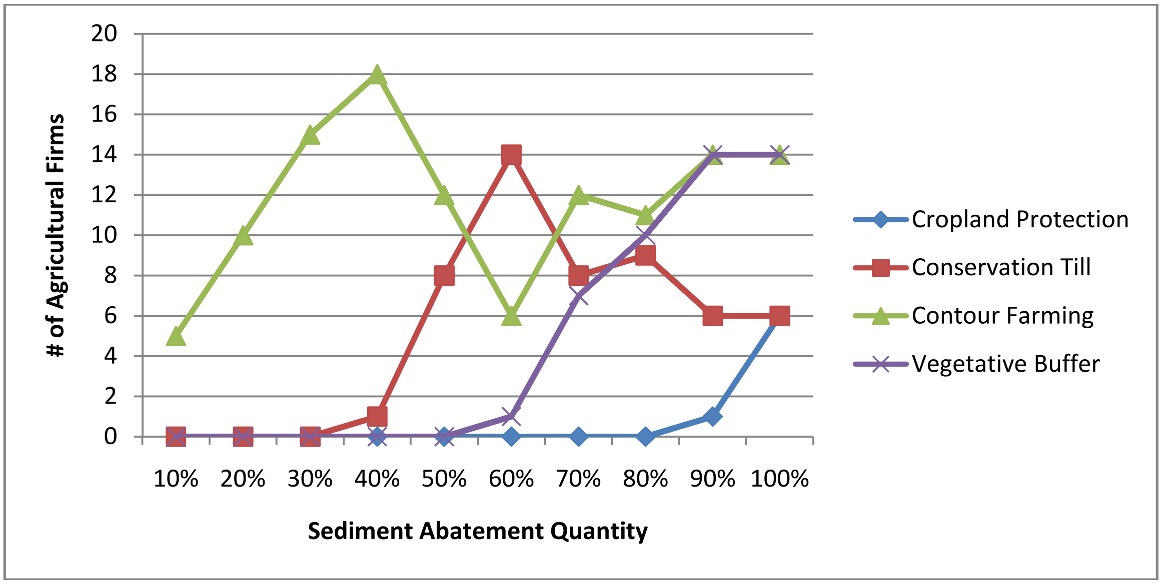

Figure 4.3: BMP Implementation Decision for the Sediment Scenario

Table 4.4: BMP Implementation Decisions from the Nitrogen Scenario (# of sites in which the BMP is implemented)

	10%	20%	30%	40%	50%	60%	70%	80%	90%
Cropland Protection	0	0	0	0	0	0	0	0	0
Conservation Till	0	0	0	0	0	0	0	0	0
Contour Farming	0	0	0	0	0	0	0	11	20
Forest Conversion	0	0	0	0	0	0	0	0	0
Wetland Conversion	0	0	0	0	0	0	0	0	0
Nutrient Mgmt	0	3	7	10	14	17	20	20	20
Terraces and Diversions	0	0	0	0	0	0	0	0	0
Vegetative Buffer	4	4	4	4	3	4	4	4	4
Waste Mgmt	0	0	0	0	0	0	0	0	0
Runoff Control	0	1	0	1	2	0	2	1	3

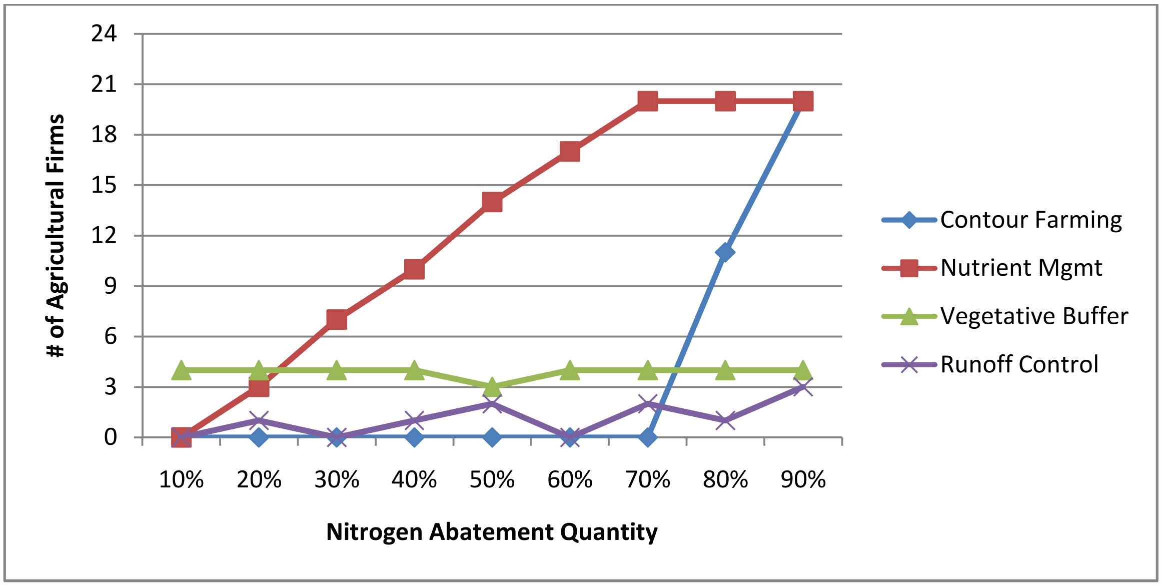

Figure 4.4: BMP Implementation Decision for the Nitrogen Scenario

Table 4.5: BMP Implementation Decisions from the Phosphorus Scenario (# of sites in which the BMP is implemented)

Type of BMP	10%	20%	30%	40%	50%	60%	70%	80%	90%
Cropland Protection	0	0	0	0	0	0	0	0	0
Conservation Till	0	0	0	0	0	0	0	0	0
Contour Farming	1	6	12	19	20	20	20	20	11
Forest Conversion	0	0	0	0	0	0	0	0	0
Wetland Conversion	0	0	0	0	0	0	0	0	9
Nutrient Mgmt	0	0	0	0	4	1	2	0	0
Terraces and Diversions	0	0	0	0	0	0	0	0	0
Vegetative Buffer	4	4	4	4	5	11	15	21	15
Waste Mgmt	0	0	0	0	0	0	0	0	0
Runoff Control	0	3	3	0	2	3	3	2	4

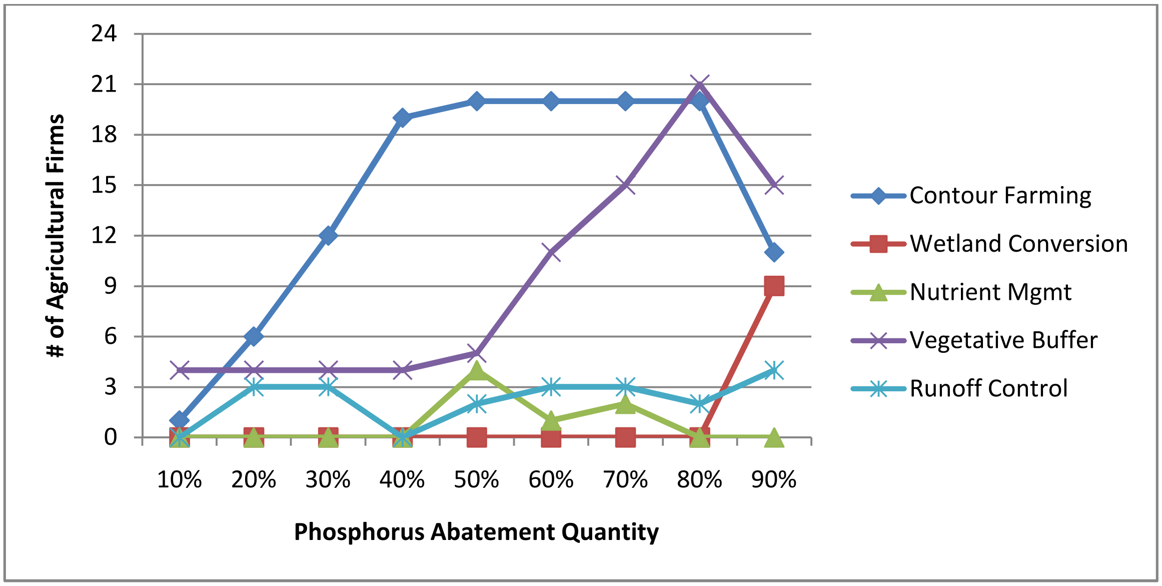

Figure 4.5: BMP Implementation Decision for the Phosphorus Scenario

Table 4.6: BMP Implementation Decisions from the E. coli Scenario (# of sites in which the BMP is implemented)

	10%	20%	30%	40%	50%	60%	70%	80%	90%
Cropland Protection	0	0	0	0	0	0	0	0	0
Conservation Till	0	0	0	0	0	0	0	0	0
Contour Farming	0	0	0	0	0	0	0	0	0
Forest Conversion	0	0	0	0	0	0	0	0	0
Wetland Conversion	0	0	0	0	0	0	0	0	0
Nutrient Mgmt	0	0	0	0	0	0	0	0	0
Terraces and Diversions	0	0	0	0	0	0	0	0	0
Vegetative Buffer	2	2	1	2	3	3	4	4	0
Waste Mgmt	0	0	0	0	0	0	0	0	4
Runoff Control	0	0	0	0	0	0	0	3	4

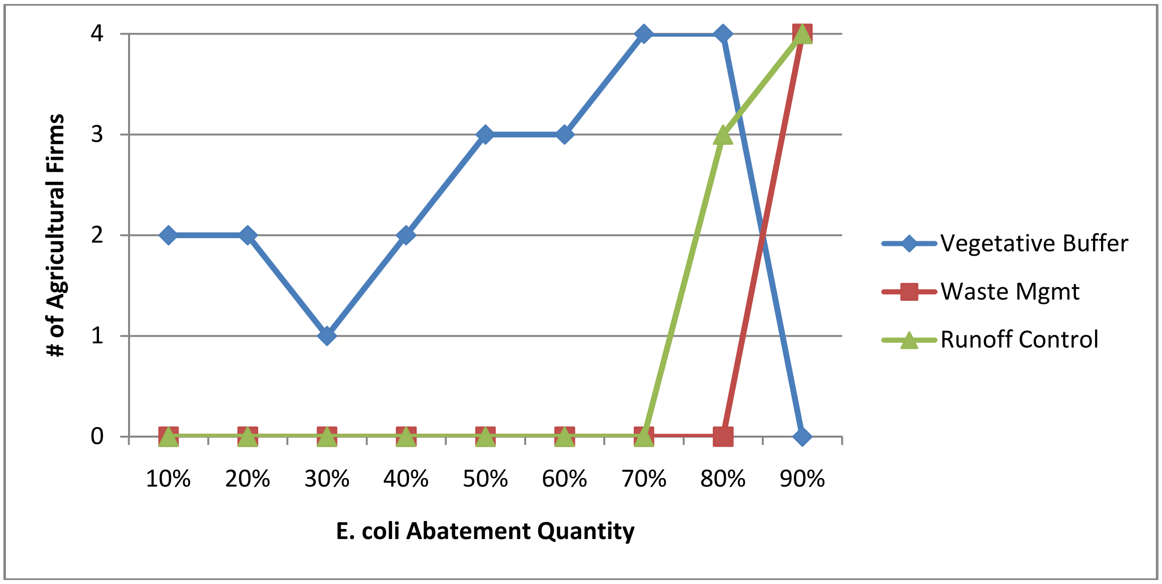

Figure 4.6: BMP Implementation Decision for the E. coli Scenario

Table 4.7: BMP Implementation Decisions from the Aggregate Pollutant Scenario (# of sites in which the BMP is implemented)

Type of BMP	10%	20%	30%	40%	50%	60%	70%	80%
Cropland Protection	0	0	0	0	0	0	0	0
Conservation Till	0	0	0	0	0	0	0	0
Contour Farming	2	1	2	1	0	4	14	16
Forest Conversion	0	0	0	0	0	0	0	0
Wetland Conversion	0	0	0	0	0	0	0	4
Nutrient Mgmt	0	0	0	0	1	0	0	0
Terraces and Diversions	0	0	0	0	0	0	0	0
Vegetative Buffer	5	9	13	18	22	24	24	20
Waste Mgmt	0	0	0	0	0	0	0	0
Runoff Control	0	1	0	0	2	3	0	3

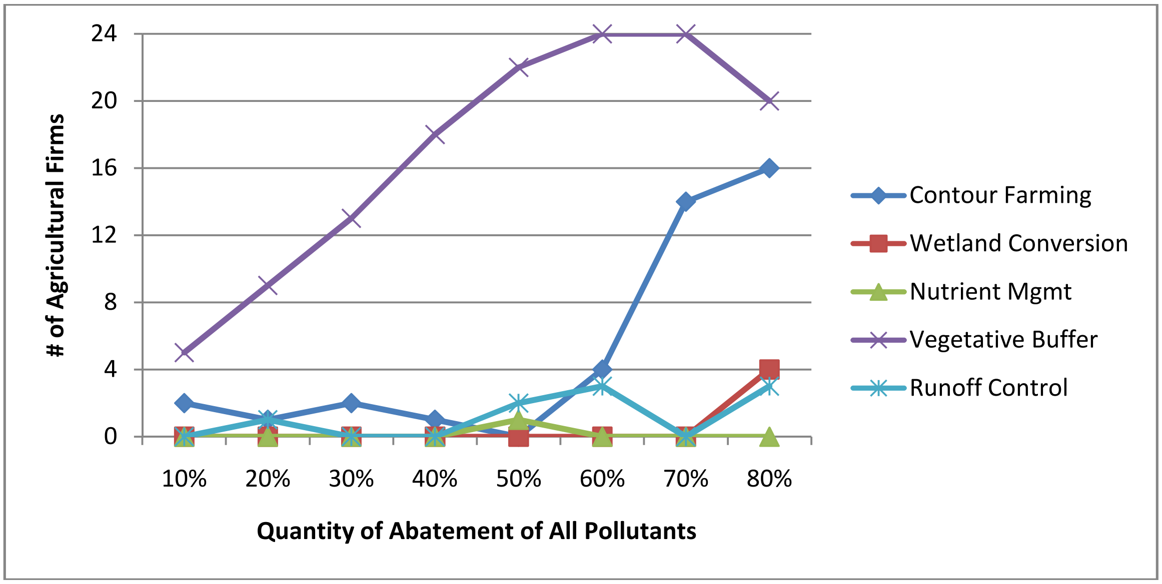

Figure 4.7: BMP Implementation Decision for the Aggregate Pollutant Scenario

In the atrazine scenario (Figure 4.2) vegetative buffers are recommended for the highest level of abatement up to the 70% level, followed by contour farming. At the 90% level forest conversion surpasses vegetative buffers and contour farming on implementation level. In the sediment scenario (Figure 4.3) contour farming is chosen for the highest level of implementation in the watershed up to the 40% abatement level, followed by conservation tillage. Contour farming is surpassed by conservation tillage at the 60% level. At and above the 90% level a mix of cropland protection, conservation tillage, contour farming, and vegetative buffers are chosen for implementation. In the nitrogen scenario (Figure 4.4) nutrient management is chosen for the highest level of implementation above the 10% level. Vegetative buffers are implemented at every level of pollution abatement. At the 90% abatement level contour farming and nutrient management are implemented at all farm sites in the watershed and vegetative buffers and runoff control are implemented at relatively low levels. In the phosphorus scenario

(Figure 4.5) contour farming is chosen for the highest level of implementation up to the 70% level of abatement, followed by vegetative buffers. At the reduction limit of 90%, vegetative buffers are chosen for the highest level of implementation, followed by contour farming, wetland conversion, and runoff control. In the E. coli scenario (Figure 4.6) vegetative buffers are chosen for the highest level of implementation up to the 80% level, followed by runoff control. At the 90% level waste management and runoff control are implemented at the same level. In the scenario where all pollutants are reduced simultaneously (Figure 4.7), vegetative buffers are chosen for the highest level of abatement up to the reduction limit of 80%. The other BMPs implemented along with vegetative buffers vary, but include contour farming, nutrient management, runoff control, and wetland conversion.

The cost results of the six described scenarios are shown in Tables 4.8-4.13. These results are illustrated in Figures 4.8-4.13. Each graph of BMP implementation costs shows the total and marginal cost of abating pollution by the desired quantity. The total cost is defined as the annual total cost of implementing a BMP in the watershed. The marginal cost is defined as the additional cost of each successive unit of pollution abatement. The total and marginal cost graphs are shown on different scales of dollars among the different scenarios due to the fact that the cost of lowering the concentration of some pollutants is much more expensive than others. However, the total costs of each scenario are compared on the same scale of dollars in Figure 4.14. Tables 4.8-4.13, which contain the cost results, also contain the cost-effectiveness ratios computed from these results. The cost-effectiveness ratios are derived by the same concept that is explained in chapter 3, but in this case the cost-effectiveness of an entire set of BMPs implemented throughout the watershed is shown, as opposed to the cost-effectiveness of one type BMP implemented in abstraction.

Table 4.8: Total and Marginal Cost of Abatement (In thousands of dollars) and the Cost-Effectiveness Ratio (thousands of dollars per percentage point of abatement) for the Atrazine Scenario

Actual Reduction Quantity	Total Cost	Marginal Cost	Cost-Effectiveness Ratio
0%	$0	$0	Undefined
10%	$231	$231	22.19
21%	$437	$206	21.19
30%	$640	$203	21.32
40%	$845	$206	21.03
50%	$1,051	$206	20.86
60%	$1,279	$228	21.32
70%	$1,557	$278	22.25
81%	$7,222	$5,665	89.38
90%	$18,217	$10,996	201.52
100%	$29,213	$10,996	292.13

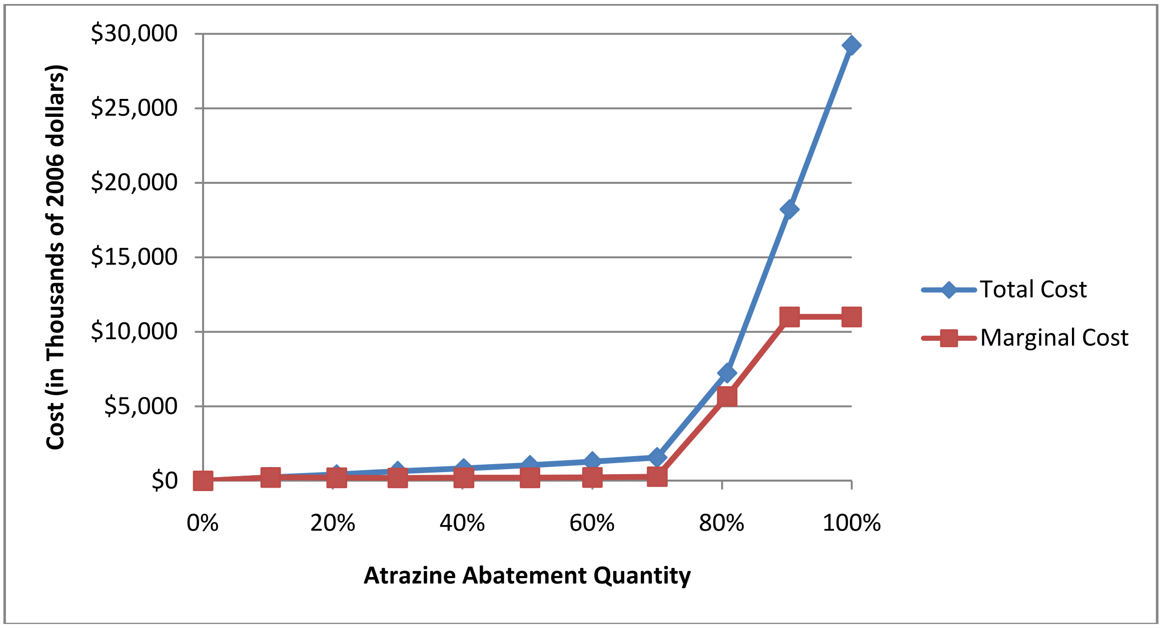

Figure 4.8: Total and Marginal Cost of Abatement for Atrazine Scenario

Figure 4.8 displays the cost of atrazine abatement. As shown in the graph the total cost increases over quantity of atrazine abatement up to the 100% level in the watershed[24]. The marginal cost of atrazine abatement is variable over the rate of reduction. This indicates that in some instances the removal of another 10% of the pollutant concentration is less costly than the previous 10%. This appears to be due to the discrete nature of the model having the effect that the economies of scale are variable. For example, at the 50% abatement level, having a marginal cost less than the 40% abatement level, the least cost method of pollutant abatement is chosen. However, at this level a more effective, albeit more costly BMP (where, β_{jk} at the current level is greater than β_{jk} at the lower level of abatement) can be chosen. This more effective BMP would have a lower average cost for the current abatement quantity than the less

[24] Although the target reduction level for the final constraint is 99%, atrazine is reduced by 100% at this level.

effective BMP would have at the lower abatement quantity. This would result in a decrease in marginal costs. The most cost-effective water quality level (Table 4.8) that is evaluated is at 50%, having a value of $20,860 per percentage point of abatement.

Table 4.9: Total and Marginal Cost of Abatement (In thousands of dollars) and the Cost-Effectiveness Ratio (thousands of dollars per percentage point of abatement) for the Sediment Scenario

Actual Reduction	Total Cost	Marginal Cost	Cost-Effectiveness Ratio
0%	$0	$0	Undefined
10%	$139	$139	13.56
21%	$278	$139	13.56
31%	$417	$139	13.56
40%	$548	$131	13.66
50%	$713	$165	14.20
60%	$889	$176	14.81
71%	$1,122	$233	15.91
80%	$1,316	$195	16.38
90%	$1,574	$257	17.44
99%	$1,987	$413	20.07

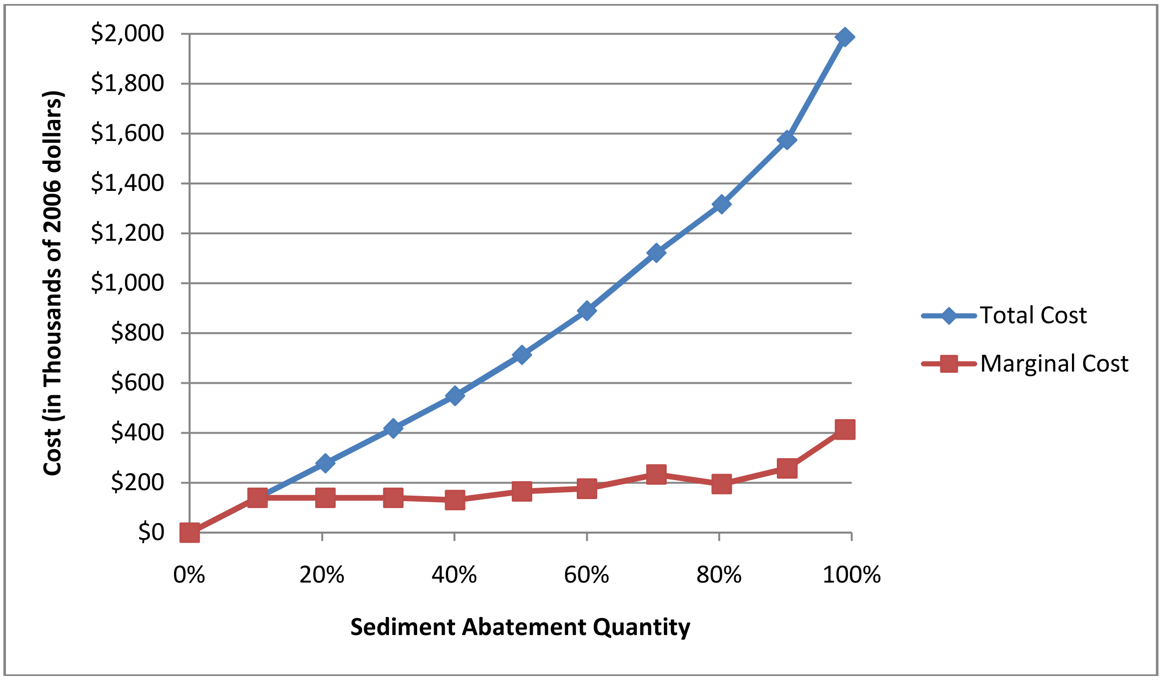

Figure 4.9: Total and Marginal Cost of Abatement for Sediment Scenario

Figures 4.9-4.13 illustrate the cost of sediment, nitrogen, phosphorus, E. coli, and all pollutant abatement scenarios respectively. Consistent with the results from the atrazine reduction scenario they all display increasing total costs and variable marginal costs of abatement.

In the sediment reduction scenario (Figure & Table 4.9) costs increase at a fairly steady rate up to the 90% level. Compared with the atrazine reduction scenario costs are on a much lower scale for sediment at all the levels of abatement. Sediment can exceed the 99% level of pollutant abatement. The most cost-effective water quality level that is evaluated is at 10%-30% each having a value of $13,560 per percentage point of abatement.

Table 4.10: Total and Marginal Cost of Abatement (In thousands of dollars) and the Cost-Effectiveness Ratio (thousands of dollars per percentage point of abatement) for the Nitrogen Scenario

Actual Reduction	Total Cost	Marginal Cost	Cost-Effectiveness Ratio
0%	$0	$0	Undefined
11%	$43	$43	4.037
20%	$152	$109	7.598
31%	$278	$125	8.929
40%	$387	$109	9.559
50%	$511	$124	10.195
60%	$612	$102	10.166
70%	$731	$119	10.407
80%	$1,028	$297	12.818
90%	$1,306	$278	14.505

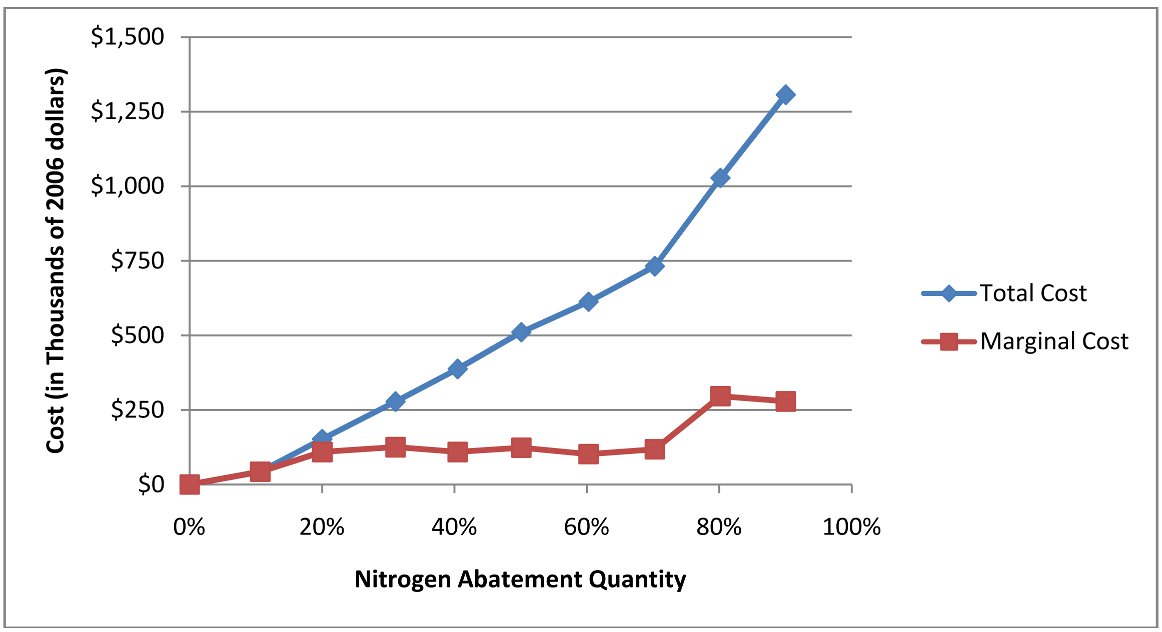

Figure 4.10: Total and Marginal Cost of Abatement for Nitrogen Scenario

In the nitrogen reduction scenario (Figure & Table 4.10) costs increase at a fairly steady rate until the 70% reduction level, where the rate of change (marginal cost) increases. The scale of costs for the nitrogen scenario is lower than the sediment scenario at all levels of reduction. Nitrogen cannot meet the 99% level of reduction in this watershed. The most cost-effective water quality level that is evaluated is at 10%, having a value of $4,037 per percentage point of abatement.

Table 4.11: Total and Marginal Cost of Abatement (In thousands of dollars) and the Cost-Effectiveness Ratio (thousands of dollars per percentage point of abatement) for the Phosphorus Scenario

Actual Reduction	Total Cost	Marginal Cost	Cost-Effectiveness Ratio
0%	$0	$0	Undefined
10%	$181	$181	17.28
22%	$362	$180	16.68
31%	$534	$173	17.14
40%	$733	$199	18.24
50%	$1,013	$280	20.05
61%	$1,314	$301	21.54
70%	$2,281	$967	32.47
80%	$6,435	$4,154	80.27
90%	$20,347	$13,913	225.66

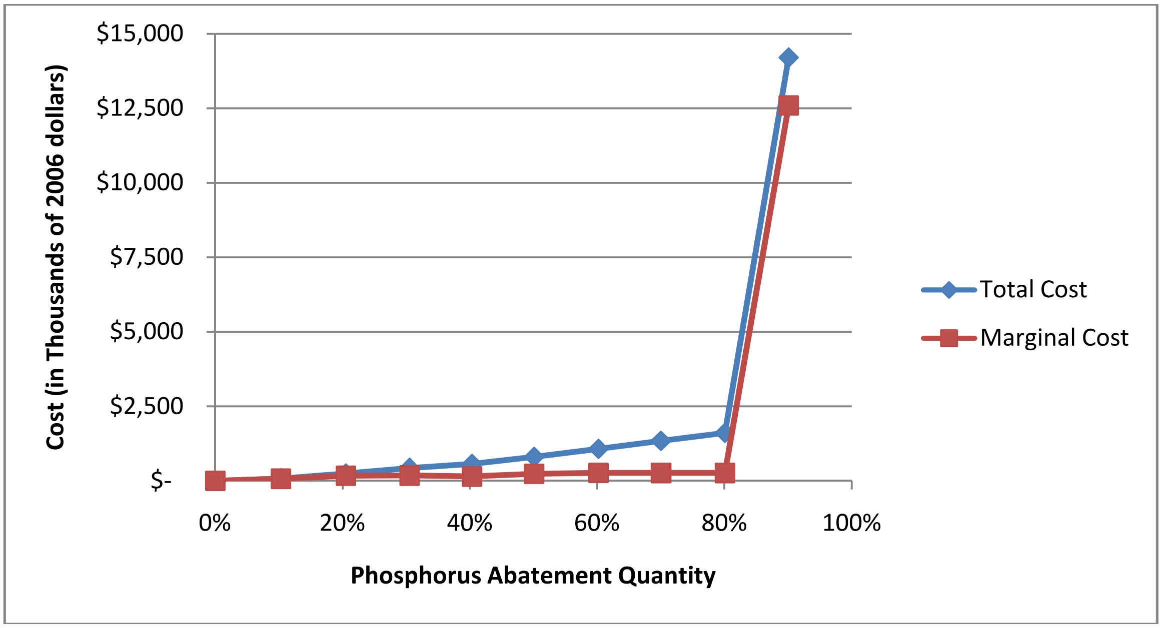

Figure 4.11: Total and Marginal Cost of Abatement for Phosphorus Scenario

In the phosphorus scenario (Figure & Table 4.11) the rate of change of cost remains fairly constant until the 50% level where it increases, then increases sharply at the 90%. Some insight into the reason for this sharp increase is given in Figure 4.5, where at the 90% level much of the agricultural land is taken out of production to meet the strict quality constraint, thereby significantly increasing cost at this point. Phosphorus cannot meet the 99% level of reduction. The most cost-effective water quality level that is evaluated is at 20%, having a value of $16,680 per percentage point of abatement.

Table 4.12: Total and Marginal Cost of Abatement (In thousands of dollars) and the Cost-Effectiveness Ratio (thousands of dollars per percentage point of abatement) for the E. coli Scenario

Actual Reduction	Total Cost	Marginal Cost	Cost-Effectiveness Ratio
0%	$0	$0	Undefined
19%	$12	$12	0.62
29%	$18	$6	0.61
32%	$19	$2	0.62
41%	$25	$6	0.62
50%	$31	$6	0.62
60%	$37	$6	0.62
70%	$43	$6	0.62
81%	$92	$49	1.13
90%	$348	$256	3.87

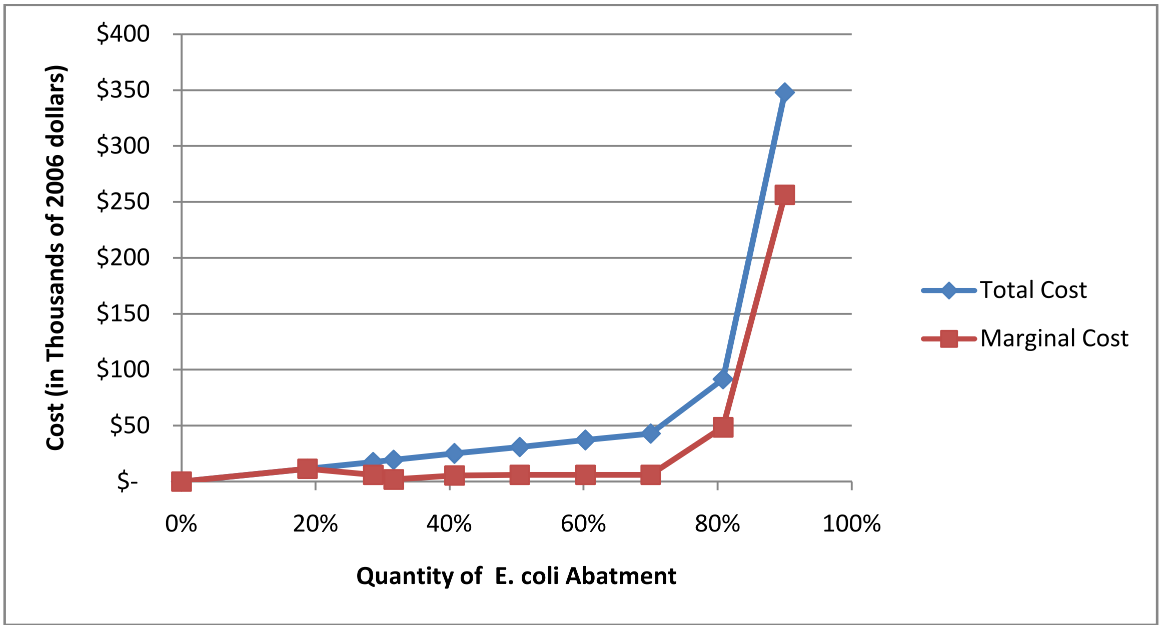

Figure 4.12: Total and Marginal Cost of Abatement for E. coli Scenario

In the E. coli reduction scenario (Figure & Table 4.12) the rate of change of costs remains relatively low up to 80%, at which point it increases sharply. The cost of E. coli abatement remains below $100,000 up to the 80% level for the entire watershed.

E. coli cannot meet the 99% level of reduction. The most cost-effective water quality level that is evaluated is at 30%, having a value of $610 per percentage point of abatement.

Table 4.13: Total and Marginal Cost of Abatement (In thousands of dollars) and the Cost-Effectiveness Ratio (thousands of dollars per percentage point of abatement) for the Aggregate Pollutant Scenario

			Cost-Effectiveness Ratio				
Actual Reduction	Total Cost	Marginal Cost	Atrazine	Sediment	Nitrogen	Phosphorus	E. Coli
0%	$0	$0	Undefined	Undefined	Undefined	Undefined	Undefined
10%	$242	$242	23.31	18.94	15.89	17.11	12.89
20%	$457	$215	22.18	20.44	17.86	20.97	22.01
30%	$663	$206	22.11	20.04	18.13	21.05	17.30
40%	$888	$225	22.10	20.83	18.15	21.85	12.69
50%	$1,155	$267	22.92	22.13	18.39	23.07	15.17
60%	$1,359	$204	22.65	20.53	19.50	22.45	17.38
70%	$1,600	$241	22.86	18.46	20.67	21.24	22.86
80%	$7,313	$5,713	90.51	74.02	84.51	82.91	90.50

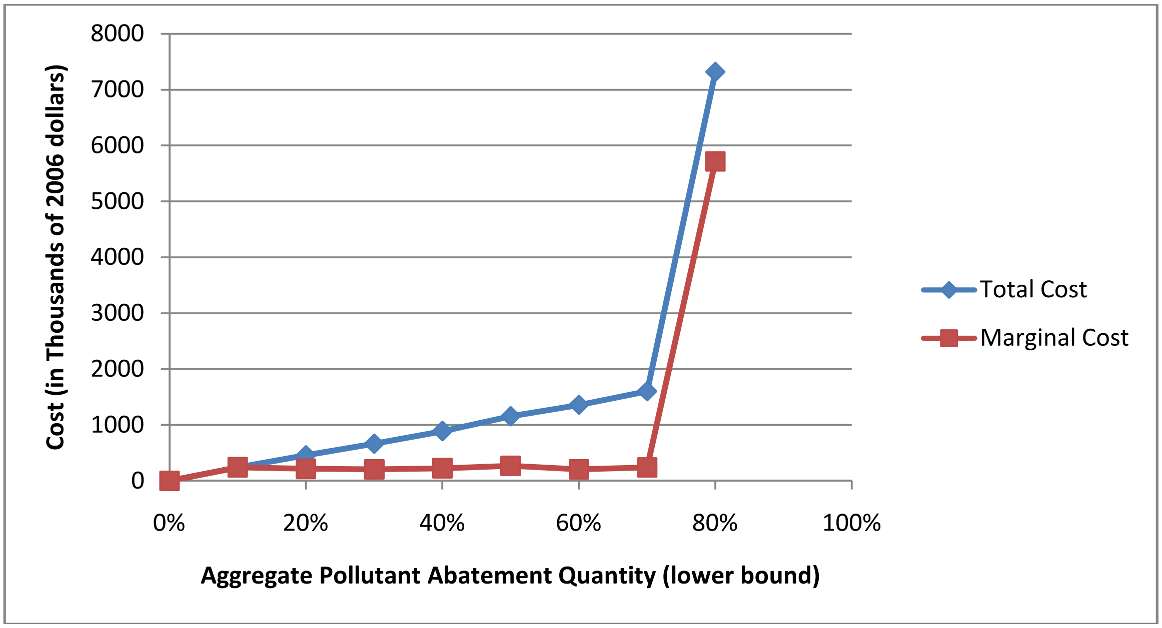

Figure 4.13: Total and Marginal Cost of Abatement for Aggregate Pollutants Scenario

Figure and Table 4.13 display the results for the scenario in which all pollutants are reduced simultaneously. The rate of change of cost for this scenario remains fairly constant up to the 70% level, after which point it increases sharply. Figure 4.7 gives insight into this sharp increase, illustrating that at the 80% level, land is taken out of agricultural production, significantly increasing cost. This scenario is also bounded at 80%, because not all pollutants could be reduced by at least 90% simultaneously. The pollutant reduction level shown on the y-axis in Figure 4.13 represents a lower bound on the amount of all pollutants reduced, meaning that every pollutant is reduced by at least the displayed rate, if not more.

Figure 4.14 illustrates the total cost of pollutant abatement for all six scenarios. As shown, the most expensive removal scenario is that of atrazine at every quantity of pollutant. The least costly scenario is that of E. coli, for which costs are less than all other removal scenarios up to 90% level.

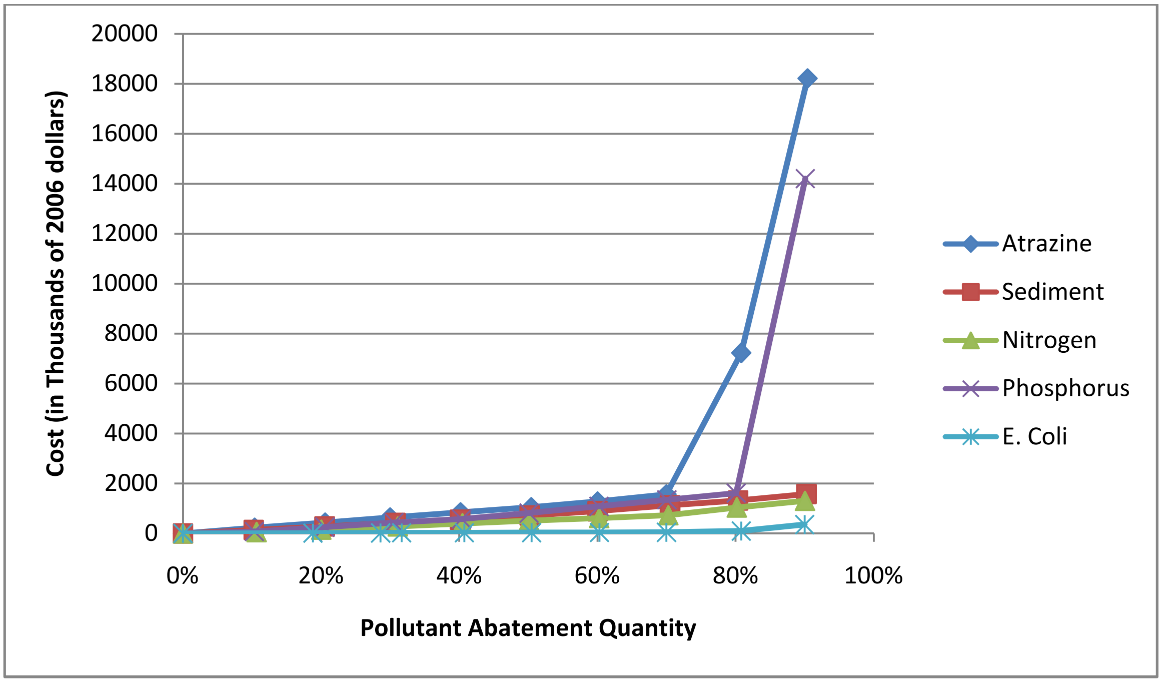

Figure 4.14: Total Cost of Abatement for All Pollutants

Tables 4.15-4.20 display the actual amount of pollutant reduction versus the target amount as specified in the model for each reduction scenario. Figures 4.15-4.20 illustrate these results with graphs. In these graphs the actual amount of pollutant reduction is shown on the y-axis and the target amount as specified in the model is shown on the x-axis. An hypothetical 45 degree line would represent an actual pollutant reduction level exactly equal to the amount specified in the model or a 1:1 reduction relationship. This 45 degree line is not added into the graphs because it would make them more difficult to view. Any point that is above this hypothetical line represents a reduction of more than the required amount for the specific pollutant. Any point that is below this hypothetical line represents a reduction of less than the required amount for the specific pollutant. The pollutant being addressed in a given scenario only is below this hypothetical line when it is cheaper to incur a penalty than to implement a BMP, or at the point where it physically impossible to remove more of the specified pollutant due to the effectiveness of the available BMPs. In this analysis of the Eagle Creek watershed penalties are not being used, therefore a data point occurring below the hypothetical line for the given pollutant only occurs when it is physically impossible to remove any more of the pollutant.

Table 4.15: Actual and Target Abatement Quantity for the Atrazine Scenario

Target Reduction Quantity	Atrazine	Sediment	Nitrogen	Phosphorus	E. Coli
0%	0%	0%	0%	0%	0%
10%	10%	13%	10%	10%	0%
20%	21%	22%	20%	17%	0%
30%	30%	33%	29%	25%	0%
40%	40%	43%	38%	32%	0%
50%	50%	52%	48%	39%	0%
60%	60%	66%	57%	50%	0%
70%	70%	87%	67%	67%	0%
80%	81%	99%	74%	78%	0%
90%	90%	96%	77%	78%	0%
99%	100%	94%	79%	80%	0%

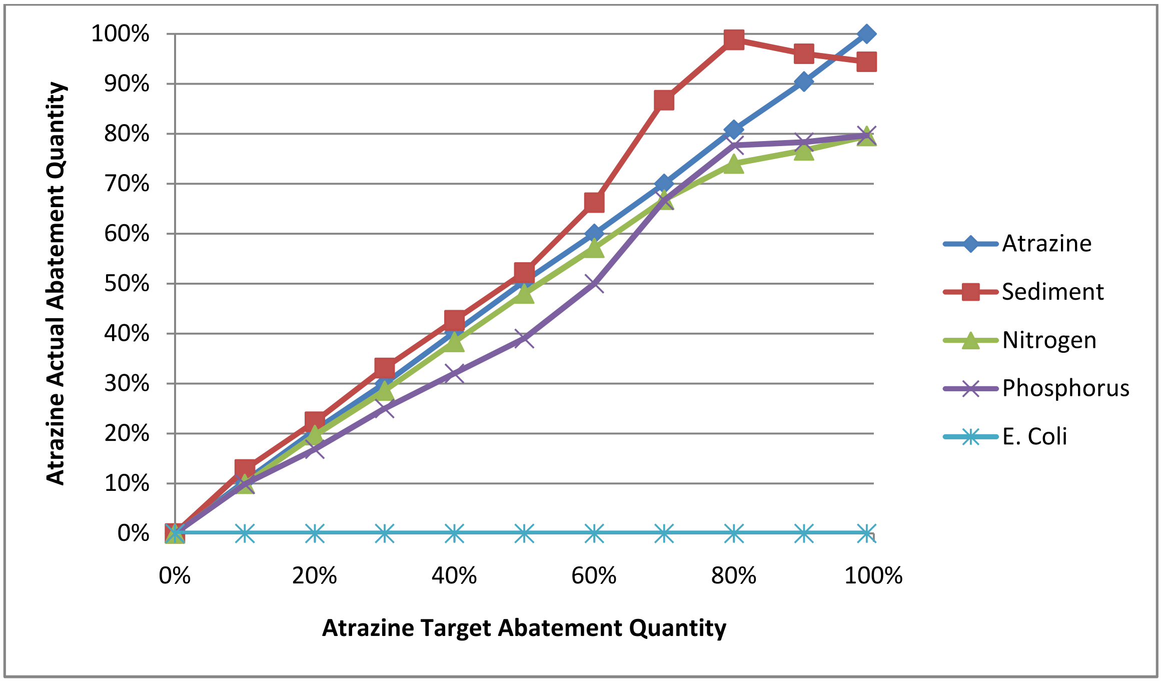

Figure 4.15: Actual versus Target Abatement Quantity for the Atrazine Scenario

Table 4.16: Actual and Target Abatement Quantity for the Sediment Scenario

Target Reduction Quantity	Atrazine	Sediment	Nitrogen	Phosphorus	E. Coli
0%	0%	0%	0%	0%	0%
10%	5%	10%	5%	8%	0%
20%	10%	21%	10%	17%	0%
30%	15%	31%	14%	25%	0%
40%	19%	40%	19%	32%	0%
50%	20%	50%	28%	33%	0%
60%	23%	60%	38%	34%	0%
70%	40%	71%	47%	48%	0%
80%	48%	80%	56%	54%	0%
90%	59%	90%	64%	65%	0%
99%	59%	99%	69%	72%	0%

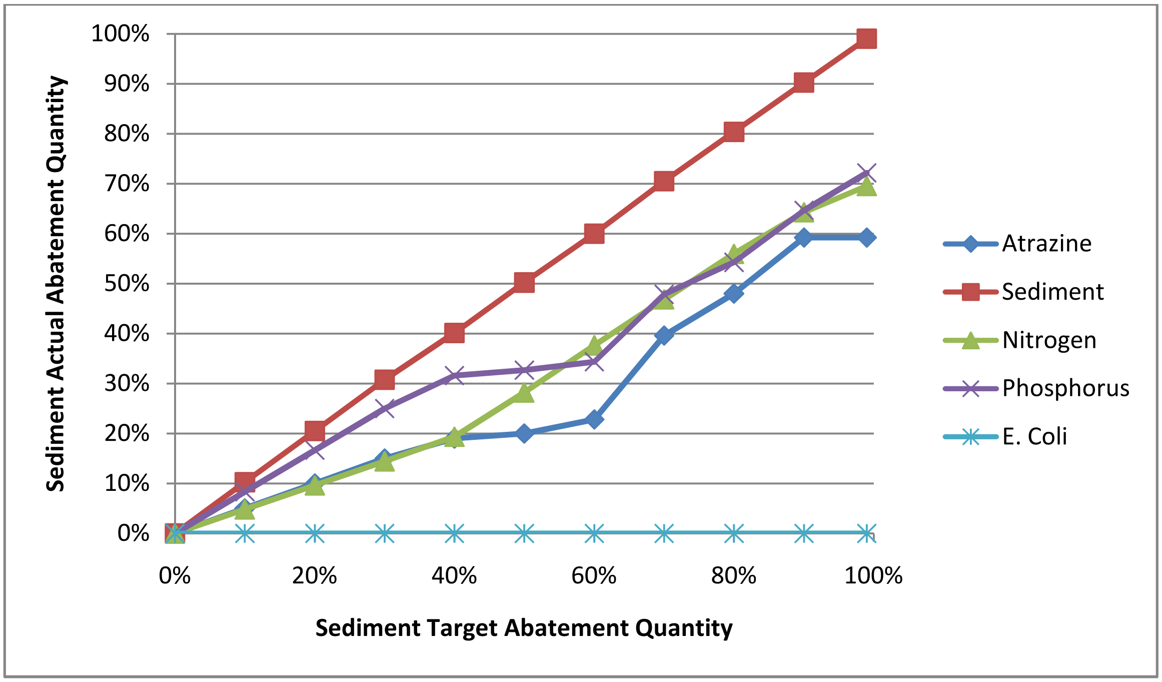

Figure 4.16: Actual versus Target Abatement Quantity for the Sediment Scenario

Table 4.17: Actual and Target Abatement Quantity for the Nitrogen Scenario

Target Reduction Quantity	Atrazine	Sediment	Nitrogen	Phosphorus	E. Coli
0%	0%	0%	0%	0%	0%
10%	0%	0%	11%	9%	70%
20%	0%	0%	20%	13%	72%
30%	0%	0%	31%	17%	70%
40%	0%	0%	40%	21%	72%
50%	0%	0%	50%	24%	42%
60%	0%	0%	60%	28%	70%
70%	0%	0%	70%	33%	74%
80%	11%	23%	80%	51%	72%
90%	20%	41%	90%	67%	78%
99%	100%	98%	95%	86%	90%

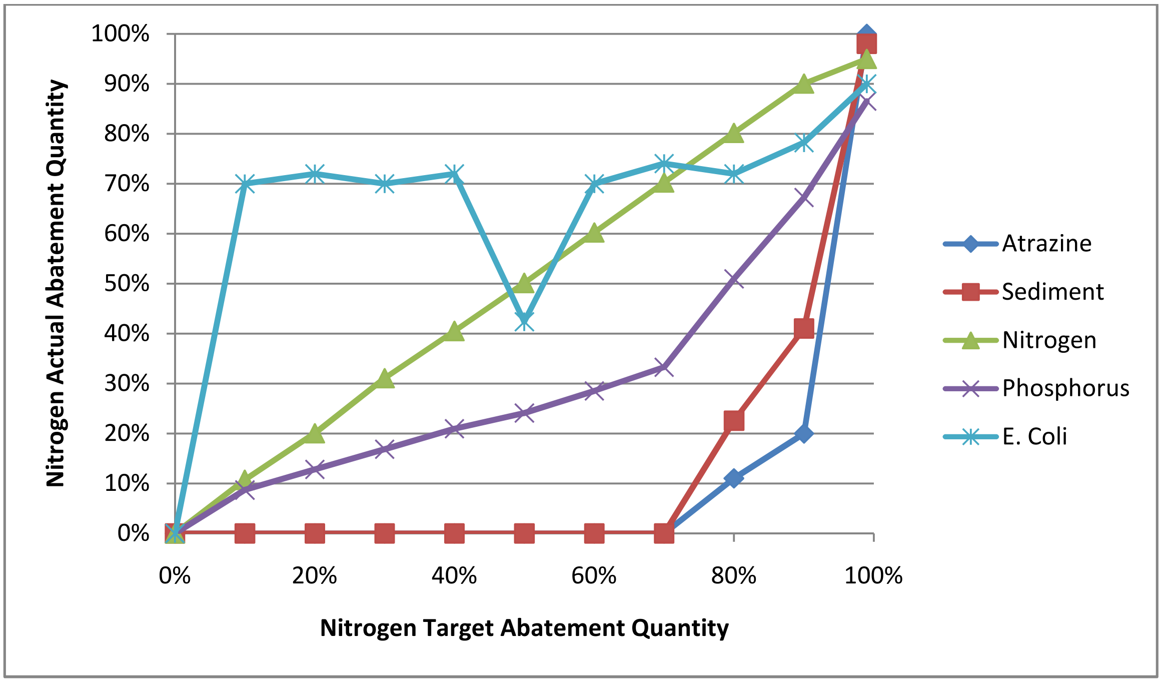

Figure 4.17: Actual versus Target Abatement Quantity for the Nitrogen Scenario

Table 4.18: Actual and Target Abatement Quantity for the Phosphorus Scenario

Target Reduction Quantity	Atrazine	Sediment	Nitrogen	Phosphorus	E. Coli
0%	0%	0%	0%	0%	0%
10%	1%	2%	12%	10%	70%
20%	6%	12%	18%	21%	78%
30%	12%	25%	24%	31%	81%
40%	19%	39%	29%	40%	70%
50%	23%	44%	45%	50%	74%
60%	40%	61%	53%	60%	78%
70%	51%	73%	67%	70%	78%
80%	68%	90%	76%	80%	74%
90%	87%	99%	89%	90%	85%
99%	100%	98%	93%	93%	85%

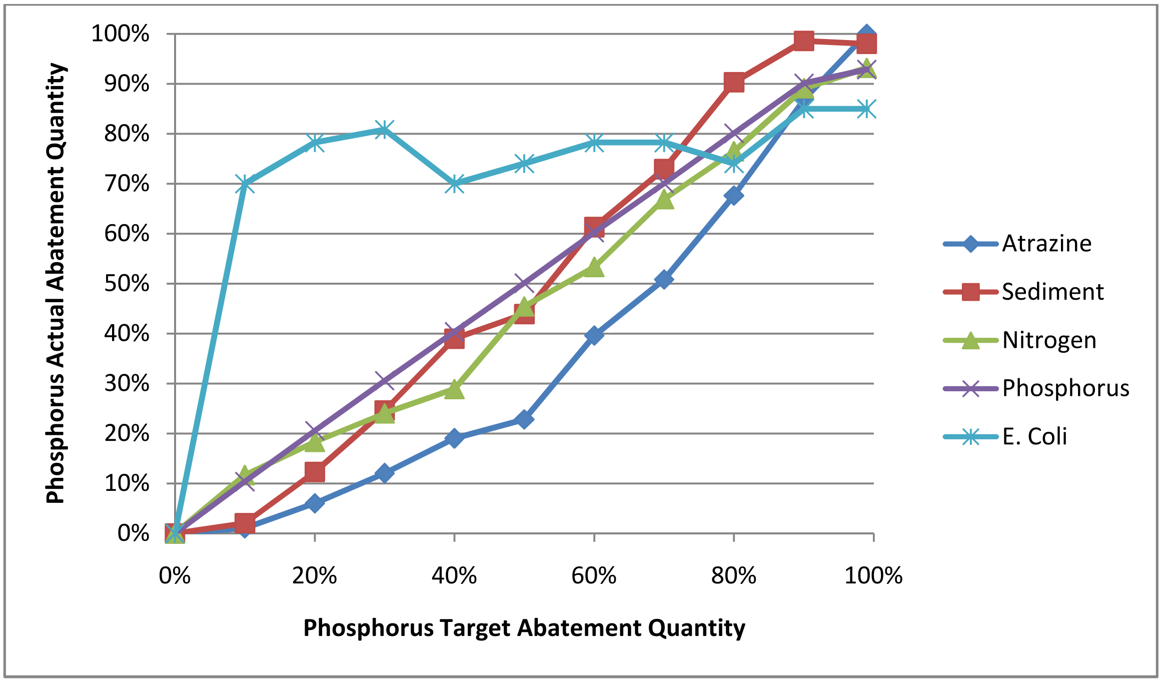

Figure 4.18: Actual versus Target Abatement Quantity for the Phosphorus Scenario

Table 4.19: Actual and Target Abatement Quantity for the E. coli Scenario

Target Reduction Quantity	Atrazine	Sediment	Nitrogen	Phosphorus	E. Coli
0%	0%	0%	0%	0%	0%
10%	0%	0%	5%	4%	19%
20%	0%	0%	5%	4%	29%
30%	0%	0%	3%	2%	32%
40%	0%	0%	5%	4%	41%
50%	0%	0%	8%	6%	50%
60%	0%	0%	8%	6%	60%
70%	0%	0%	11%	9%	70%
80%	0%	0%	13%	11%	81%
90%	0%	0%	15%	5%	90%
99%	0%	0%	15%	5%	90%

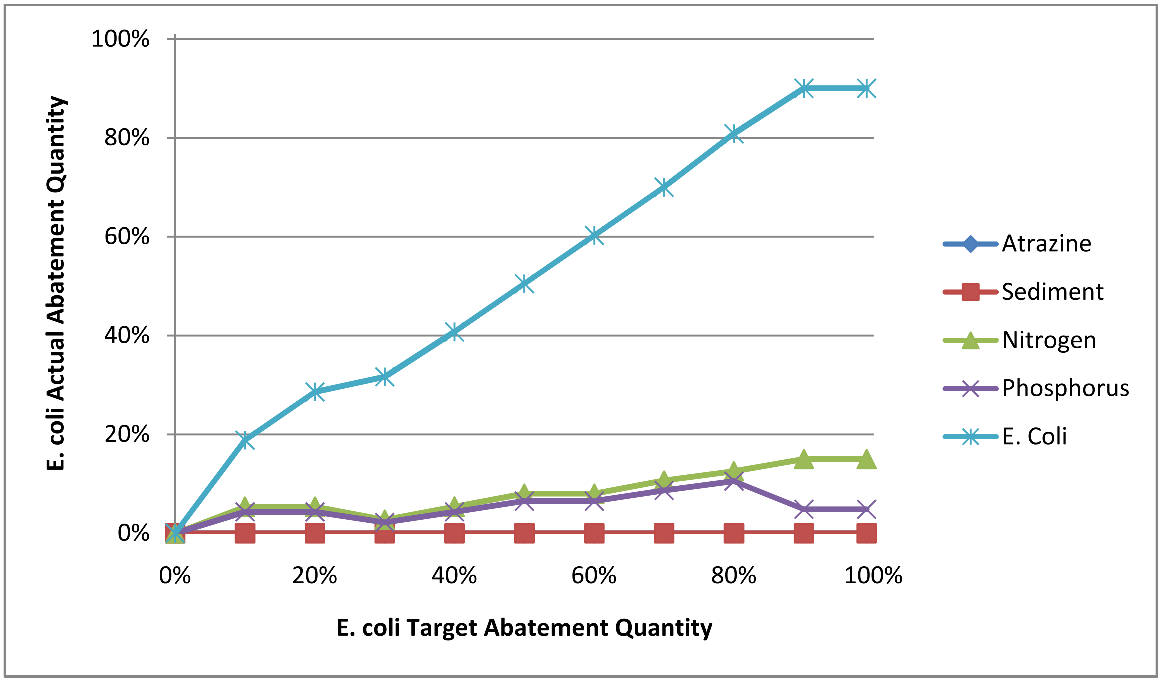

Figure 4.19: Actual versus Target Abatement Quantity for the E. coli Scenario

Table 4.20: Actual and Target Abatement Quantity for the Aggregate Pollutant Scenario

Target Reduction Quantity	Atrazine	Sediment	Nitrogen	Phosphorus	E. Coli
0%	0%	0%	0%	0%	0%
10%	10%	13%	15%	14%	19%
20%	21%	22%	26%	22%	21%
30%	30%	33%	37%	31%	38%
40%	40%	43%	49%	41%	70%
50%	50%	52%	63%	50%	76%
60%	60%	66%	70%	61%	78%
70%	70%	87%	77%	75%	70%
80%	81%	99%	87%	88%	81%
90%	91%	93%	89%	84%	89%
99%	100%	98%	95%	88%	89%

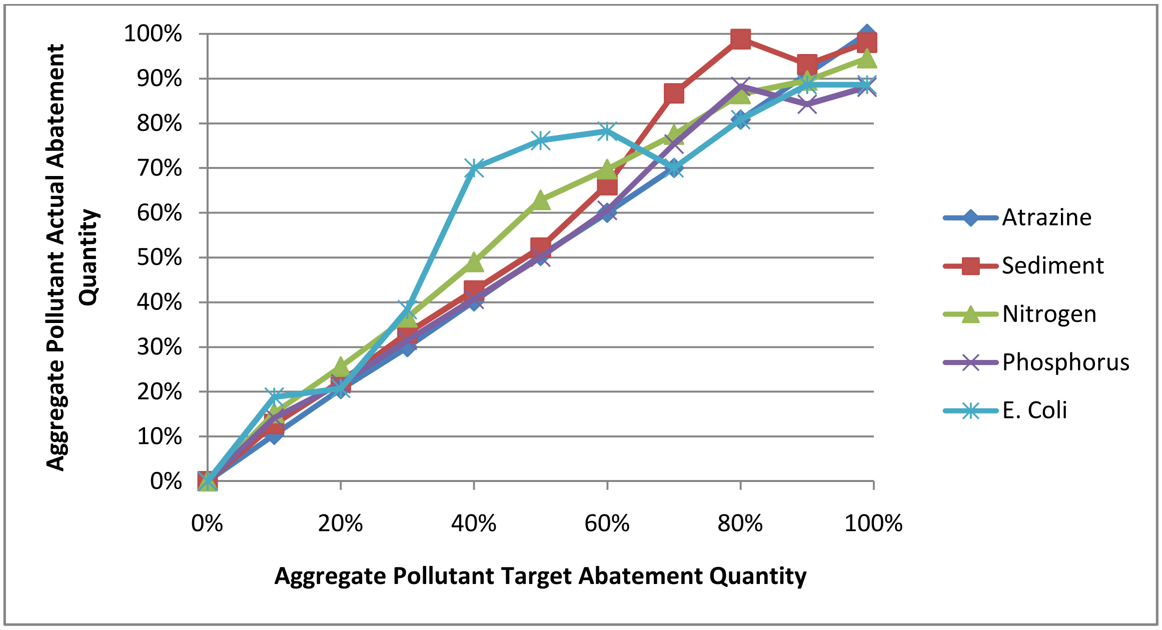

Figure 4.20: Actual versus Target Abatement Quantity for the Aggregate Pollutant Scenario

In the atrazine abatement scenario (Figure & Table 4.15) the quantity of atrazine abated is always greater than or equal to the hypothetical 45 degree line up to 100%. Sediment is reduced at a greater rate than atrazine up to the 90 percent level. In the sediment scenario (Figure & Table 4.16) the amount of sediment reduction is always greater than or equal to the hypothetical 45 degree line up to 100% abatement. All other pollutants are reduced less than sediment at every target level. In the nitrogen scenario (Figure & Table 4.17), nitrogen is reduced by the requisite amount up to the 90% level of abatement. In this case nitrogen cannot be abated at the 100% level due to physical reduction constraints as previously explained. E. coli is reduced by at a higher rate than nitrogen up to the 40% level, where it decreases, then increases at the 60% level. In the phosphorus scenario (Figure & Table 4.18), phosphorus is reduced by the requisite amount up to the 90% level. All other pollutants are highly variable relative to the amount of phosphorus reduction. In the E. coli scenario (Figure & Table 4.19), E. coli is reduced by the requisite amount up to the 90% level. All other pollutants are reduced by a much lower rate than E. coli in this scenario. Atrazine is not reduced at all in this scenario, this has to do with the fact that agricultural sites that are emitting E. coli are not emitting atrazine, so the model will not choose to implement any BMPs at atrazine emitting sites. In the aggregate pollutant reduction scenario (Figure & Table 4.20) all pollutants are reduced by the requisite amount up to the 80% level. It is not possible to reduce all pollutants in the watershed by 90%. While this scenario reduces all pollutants by the greatest rate at each iteration, it is also the most costly scenario at every iteration.

Summary

The results for this model are generated through six scenarios with different water quality constraints. These scenarios are run with ten iterations to generate results for a 10% through 90% pollution reduction in the watershed. The first set of results (Figures & Tables 4.2-4.7) show the number agricultural sites that given type of BMP is implemented at in the watershed. The second set of results show the various costs for each scenario and are illustrated with graphs (Figures & Tables 4.8-4.13). These results are used to compute cost-effectiveness ratios for each iteration of each scenario. These cost-effectiveness ratios display the cost (in thousands of dollars) per percentage point of effectiveness, with a lower value being more cost-effective within a given scenario. The results for all six scenarios display increasing total costs and variable marginal costs over the quantity of pollution abatement. The third set of results (Figures & Tables 4.15-4.20) shown are the actual level of pollutant reduction versus the desired level of pollutant reduction. These results describe how the resulting pollutant concentration at the receptor site compared to the desired pollutant concentration level entered in the model.

When viewing these results it is important to remember that they are a product of the estimated data sets described in chapter 3. The implication of this is that specificity of the cost, reduction quantities, and BMP implementation decisions found for each scenario would vary with the utilization of different and more accurate data from a hydrological model. However, the general framework of analysis used herein could still be applied with different data for Eagle Creek or data from a different watershed.

CHAPTER V: CONCLUSIONS AND IMPLICATIONS

Summary of Pertinent Facts

The Eagle Creek watershed is experiencing a high level of water pollution resulting in some degree from agricultural sources. This level of water pollution conflicts with the designated uses of the watershed and causes some level of economic damages. BMPs are being analyzed by the Conservation Effects Assessment Program to address these water quality issues. This motivates two questions of focus for this research regarding BMPs being considered for implementation in the Eagle Creek watershed:

(1) Taking the reservoir as a receptor site of concern, how effective are the different BMPs at reducing different types of water pollution in the Eagle Creek watershed?

(2) Among these different BMPs, which are more cost-effective?

To answer these questions a review of the relevant literature is undertaken. Literature is reviewed regarding the damages that occur from the different types of pollutants being analyzed in this watershed. Other literature is reviewed on conducting cost analyses on agricultural BMP effectiveness. This literature aids in the development of a watershed-scale BMP cost-effectiveness model.

The model is based on a depiction of the watershed as a set of emission sites distributed throughout the area, emitting a measurable quantity of water pollutants to the receptor site. The concentration of water pollutants in the reservoir is dependent on the emission levels of agricultural sites, the amount of water flowing through the watershed, and the quantity of water pollutants transferred from the emission site to the receptor site. The model can implement BMPs at agricultural sites throughout the watershed in order to obtain a desired level of pollutant concentration at the receptor in the least cost manner. The BMPs chosen by the model are the most cost-effective for the desired outcome.

The data required by the model are obtained from multiple literature sources. This includes BMP effectiveness data, BMP cost data, and pollutant emission data. The BMP effectiveness data consists of the median value of multiple different sources from the literature (Evans, 2007) and additional values from Devlin (2003) for atrazine effectiveness. The cost data that directly relates to the BMP effectiveness data are obtained from multiple sources. These cost data are averaged across all those sources to obtain the BMP costs values used in the model. The BMP cost and effectiveness data are used to compute the effectiveness-cost ratios of the considered BMPs for each type of pollutant. The pollutant emission data are based on the Eagle Creek Watershed Management Plan (Tedesco, 2005) and divided into 20 hypothetical uniform farm sites and 4 different CAFO sites.

The model utilized with the requisite data generates the previously described results. A few of the interesting and pertinent results of the model are the total cost of achieving the desired pollutant concentration level, the resulting concentration level of all the pollutants compared to that which is desired, and the types, amounts, and locations of BMPs throughout the watershed. The results are illustrated in the figures throughout chapter four. One general observation from the results is that as the desired concentration level is reduced (quantity of abatement is increased) the total cost of the achievement of target concentration levels increases. The costs of abatement greatly depend on the type of pollutant(s) targeted and the quantity of that abatement. In the six scenarios analyzed marginal cost of pollutant abatement is variable. The cost results are used to compute a cost-effectiveness ratio at each iteration of the six scenarios. The targeting of one type of pollutant for reduction will also reduce other pollutants, due to the BMP effectiveness for multiple types of BMPs (shown in Table 3.5). The types of BMPs implemented in the watershed vary throughout the six different simulation scenarios. At the 50% level of pollutant abatement the most cost-effective (highest effectiveness-cost ratio) BMP for the given pollutant reduction scenario is chosen for the highest level of implementation in the watershed.

Implications and Recommendations

This study develops a watershed-scale cost-effectiveness model for water pollution abatement. The model provides a general framework for analysis of the Eagle Creek watershed and could possibly be applied to other watersheds where the desire is to increase water quality in the most cost-effective manner. While the model is used to generate results in general for the Eagle Creek watershed, these results are not directly applicable to the actual watershed, due to some shortcomings in the available data. These issues with the data necessitate some assumptions to be used, in order to allow the data to fit the framework of the model. There is also some data that with increased specificity could increase the accuracy of the results.

One assumption to note is that the amount of pollutant output from emissions sites is determined by using the watershed-wide pollutant loading data and attributing it uniformly to 20 identical farm sites.[25] One of the implications of this is that the actual agricultural sites in the watershed are not being analyzed, and therefore the BMP implementation results from the model do not apply to any actual farm site. Another implication of this is that, as the agricultural sites used in this analysis do not actually exist in the watershed, there is not spatial data available for them. If spatial data were available for actual agricultural sites in the watershed it would be possible to introduce realistic values of the transfer coefficient (τ_i) in the model.

Another assumption to note is how the cumulative effectiveness for multiple BMPs at one site is handled by the model. In the model the effectiveness of multiple BMPs implemented at one agricultural site is added, then limited at a value of 1 (100% effectiveness). This may not be a realistic view of the effectiveness of multiple BMPs. As an alternative, Equation 2a models the effectiveness of multiple BMPs as the product of the effectiveness those BMPs. This alternative exhibits diminishing marginal productivity of each successive BMP. It is also possible that the cumulative effectiveness of multiple BMPs is synergistic, where the combined effectiveness of all the BMPs implemented at one site is greater than their sum. This possibility would exhibit increasing marginal productivity of each successive BMP. A better

[25] This process is described in Chapter 3.

understanding of the effectiveness of multiple BMPs could be provided by using a hydrological model of the watershed.

Data that are not specific to the Eagle Creek watershed are BMP effectiveness (shown in Table 3.5). These data are based on a literature review of many different studies of BMP effectiveness. However, if BMP effectiveness data specific to the Eagle Creek watershed and possibly specific to individual agricultural sites in the watershed were available, the accuracy of the model results could be increased. The current issues with the data are that BMPs which are not highly applicable to the Eagle Creek watershed, such as contour farming are shown as highly cost-effective and therefore chosen for a high level of implementation. If the effectiveness data for this type of practice more accurately reflected the viability of this practice in the watershed, its resulting cost-effectiveness would be very poor, and would therefore not be chosen for implementation in the watershed.

There are a few possibilities for relaxing some of the assumptions of the model, in order to improve its validity. Regarding the assumption within the functional form of the model that when a BMP is chosen for implementation, it is implemented on every acre of that agricultural site, a different method of grouping land area in the model may be necessary. It may be preferable to instead of using the area of agricultural site to make up an emission site (*i*) in the model, to use topographically similar land areas. If the sites in the model where made up of topographically similar, contiguous land areas, with similar hydrological characteristics, it would be less problematic that a BMP chosen for implementation at that site was implemented on all acres of the site. This also relates to the issue regarding the precision of BMP effectiveness data used in the model. If areas of similar land are used to form the set *i*, it would make more sense to have BMP effectiveness, not only vary by type of pollutant, but by site in the watershed. This would imply changing the β_{jk} parameter to β_{ijk} in the model. If enough data were available for this proposed β_{ijk} parameter, it would obviate the need for using equation 5 to set site specific BMP implementation constraints for a BMP that would not be effective at a specific site, because a BMP which would be ineffective at a specific site in the watershed, could have its corresponding β_{ijk} value set to zero and the model would never implement it.

If some of these drawbacks in this analysis were remedied it would be possible to present more realistic and reliable results for the Eagle Creek watershed. The more accurate results would show which BMPs should be implemented at actual emission sites in the watershed, with the resulting concentration levels of the receptor site and the annual total cost of the project. These results could then be used to aid institutions which desire to increase the water quality in the Eagle Creek watershed. These institutions could utilize these results to target cost-share dollars and other incentives towards implementing the recommended cost-effective BMPs, thereby ensuring the most efficient use of their resources.

LIST OF REFERENCES

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Aust, W. M., Shaffer, R.M., & Burger, J. A. (1996). Benefits and Costs of Forestry Best Management Practices in Virginia. Southern Journal of Applied Forestry 20(1):23-27.

Boardman, A. E., Greenberg, D. H., Vining, D. H. & Weimer, D. L. (2006). Cost-Benefit Analysis: Concepts and Practice. Third Edition. New Jersey: Pearson Education.

Bracmort, K. Lee, J. G., Frankenberger, J. R., & Engel, B. A. (2004). Estimating the Long-Term Benefits and Costs of BMPs in an Agricultural Watershed. An ASAE/CSAE meeting presentation. Paper No. 042174. 1- 4.

Buckner, E. R. (2001). An Evaluation of Alternative Vegetative Filter Strip Models for Use on Agricultural Lands of the Upper Wabash River Watershed. Ph.D. Thesis, Purdue University, West Lafayette, IN.

Cangelosi A., Wether, R., Taverna, J., & Cicero, P. (2001). Revealing the Economic Value of Protecting the Great Lakes. Northeast-Midwest Institute and the National Oceanic and Atmospheric Administration. Washington, DC.

Cunningham, W. P., Cunningham, M. A., Siago, B.(2005). Environmental Science: A Global Concern. Eigth Edition. New York: Mcgraw-Hill.

Devlin, Daniel, et al. (2003). Water Quality Best Management Practices, Effectiveness, and Cost for Reducing Contaminant Losses from Cropland. Kansas State University, February 2003.

Dobbins, C. & Cook, K. (2007). Indiana Farmland Values & Cash Rents Jump Upward. Purdue Agricultural Economics Report (August 2007). Purdue University.

Enger, E. D., Smith, B. F. (2000). Environmental Science: A Study of Interrelationships. Seventh Edition. New York: Mcgraw-Hill.

Evans, B. M., Lehning, D. W., & Corradini, K. J. (June 2003, Revised November 2007) Users Guide for the Pollution Reduction Comparison Tool. Penn State Institutes of Energy and the Environment. The Pennsylvania State University.

Graziano, N., Mcguire, M. J., Roberson, A., Adams, C., Jiang, H., & Blute, N. (2006). 2004 National Atrazine Occurrence Monitoring Program Using the Abraxis ELISA Method. Environmental Science & Technology 40(4):1163-1171.

Heatwole, C. D., Bottcher, A. B., & Baldwin, L. B. (1987). Modeling Cost-Effectiveness of Agricultural Nonpoint Pollution Abatement programs on Two Florida Basins. Water Resources Bulletin 23(1):127-131.

Leggett, C. G. & Bockstael, N. E. (2000). Evidence of the Effects of Water Quality on Residential Land Prices. Journal of Environmental Economics and Management 39, 121-144.

Pennsylvania Conservation Partnership. (2000). A Conservation Catalog: Practices for the Conservation of Pennsylvania's Natural Resources.

Ribaudo, M. O., Young, C. E. (1989). Estimating the Water Quality Benefits From Soil Erosion Control. Water Resources Bulletin 25(1)71-788.

Ribaudo, M. O., Colacicco, D., Barbarika, A., & Young, C. E. (1989). The Economic Efficiency of Voluntary Soil Conservation Programs. Journal of Soil and Water Conservation 44(1):40-43.

Ritter, W. F. & Shirmohammadi, A. (2001). Agricultural Non-point Source Pollution: Watershed Management and Hydrology. Lewis Publishers, New York.

Tedesco, L.P., Pascual, D.L., Shrake, L.K., Hall, R.E., Casey, L.R., Vidon, P.G.F., Hernly, F.V., Salazar, K.A., Barr, R.C., Ulmer, J., Pershing, D. 2005 Eagle Creek Watershed Management Plan: An Integrated Approach to Improved Water Quality. Eagle Creek Watershed Alliance, CEES Publication 2005-07, IUPUI, Indianapolis, 182p. http://www.cees.iupui.edu

United States Department of Agriculture, NRCS. (2006). Indiana Environmental Quality Incentives Program BMP Cost List.

United States Department of Agriculture, Natural Resource Conservation Service. National Engineering Handbook Part 651. Agricultural Waste Management Field Handbook. June 1999.

United States Environmental Protection Agency: Washington, DC, 2005. 2005 Consumer Factsheet on: Atrazine. http://www.epa.gov/safewater/dwh/c-soc/atrazine.html

United States Environmental Protection Agency: Washington, DC. May 2, 2002. Overview of Atrazine Risk Assessment.

Veith, T. L., Wolfe, M. L., & Heatwole, C. D. (2004). Cost-Effective BMP Placement: Optimization versus Targeting. Transactions of the ASAE 47, no. 5.

Yadav, S. N. & Wall D. B. (1998). Benefit-cost Analysis of Best Management Practices Implemented to Control Nitrate Contamination of Groundwater. Water Resources Research 34(3): 497-504.

Yuan, Y., Dabney, S. M., & Bingner, R.L. (2002). Cost effectiveness of Agricultural BMPs for Sediment Reduction in the Mississippi Delta. Journal of Soil and Water Conservation 57(5): 259-267.

APPENDICES

Appendix A

Indiana Department of Environmental Management CAFO Data for the Eagle Creek Watershed

CAFO Name	Nursery Pigs	Finishers	Sows	Turkeys	Total AU
KOUN'S FARMS, INC	54	640	62	0	302.4
HOME PLACE	600	1000	26	0	650.4
TOM'S PLACE	600	1970	66	0	1054.4
DOUBLE BRIDGE FARM	0	0	0	18000	324.0

Appendix B

Mathematical Program in GAMS

*4 different sets are considered in this model:
*(I) Farm emission sites (which are farm units emitting Atarazine, TSS, N, and P)
*(J) BMP systems for reduction of the types of pollutants considered
*(K) Type of Pollutant (Atrazine, TSS, N, P, and E. coli)
*(L)CAFO emission sites (which are concentrated animal operations emitting N, P, and E. coli)

SETS
I Farm emission sites / 1*20 /
J Type of BMP / CropProtection, ConTill, ContourFarming, Forest_conv, Wetland_conv, NutrientMgmt, Terrace_Diversion, VegBuffer, VegBuffer2, WasteMgmt, RunoffControl /
K Type of pollutant / Atrazine, TSS, N, P, EColi /
L CAFO emission sites /1*4 /

*E(I,K) represents the level of emissions attributed to farm i of pollutant type k.
*Estimates for emission levels for 20 uniform farms are based on aggregate pollutants loading data for the entire Eagle Creek watershed from the 2005 ECWP.
*This aggregate pollutant loading data is then dividing by the number of emission sites (20 for atrazine and TSS and 24 for N and P, due to the 4 CAFO sites also being considered).

Table

E(I,K) Level of emissions at site i for pollutant k

	Atrazine	TSS	N	P	Ecoli
1	22	2835960	136344	80898	0
2	22	2835960	136344	80898	0
3	22	2835960	136344	80898	0
4	22	2835960	136344	80898	0
5	22	2835960	136344	80898	0
6	22	2835960	136344	80898	0
7	22	2835960	136344	80898	0
8	22	2835960	136344	80898	0
9	22	2835960	136344	80898	0
10	22	2835960	136344	80898	0
11	22	2835960	136344	80898	0
12	22	2835960	136344	80898	0
13	22	2835960	136344	80898	0
14	22	2835960	136344	80898	0
15	22	2835960	136344	80898	0
16	22	2835960	136344	80898	0
17	22	2835960	136344	80898	0
18	22	2835960	136344	80898	0
19	22	2835960	136344	80898	0
20	22	2835960	136344	80898	0 ;

*CAFO(L,K) represents the level of emissions attributed to CAFO l of pollutant type k.
*Estimates for emission levels of N and P for 4 CAFOs are based on aggregate pollutant loading data for the entire Eagle Creek watershed divided by the number of emission sites (25).

*Estimates for emission levels of E. coli are based on aggregate pollutant loading data multiplied by the proportion of animal units out of the total in the watershed that a given CAFO has.

Table

CAFO(L,K) Level of emissions from CAFOs

	Atrazine	TSS	N	P	Ecoli
1	0	0	136344	80898	1131924502
2	0	0	136344	80898	2434536033
3	0	0	136344	80898	3946763212
4	0	0	136344	80898	1212776253 ;

*Beta(J,K) Effectiveness of type j BMP for pollutant k on farm emission sites.
*These proportions represent the percentage reduction in a given pollutant from a given BMP.
*Pollutant reduction effectiveness estimates are based on data utilized by PRedICT, 2007, Mickelson, 2003, and Devlin et al., 2003.

TABLE

BETA(J,K) Effectiveness of type j BMP for pollutant k

	Atrazine	TSS	N	P	Ecoli
CropProtection	0	.35	.25	.36	0
ConTill	.20	.64	.50	.38	0
ContourFarming	.20	.41	.23	.40	0
Forest_Conv	1	.92	.95	.94	0
Wetland_Conv	1	.98	.96	.98	0
NutrientMgmt	0	0	.70	.28	0
Terrace_Diversion	.20	.71	.44	.42	0
VegBuffer	.56	.58	.64	.52	.70
VegBuffer2	0	0	0	0	0
WasteMgmt	0	0	0	0	0
RunoffControl	0	0	0	0	0 ;

*Gamma(J,K) Effectiveness of type j BMP for pollutant k on CAFO emission sites.
*These proportions represent the percentage reduction in a given pollutant from a given BMP.
*Pollutant reduction effectiveness estimates are based on data utilized by PRedICT, 2007.

TABLE

GAMMA(J,K) Effectiveness of type j BMP for Pollutant k CAFO

	Atrazine	TSS	N	P	Ecoli
CropProtection	0	0	0	0	0
ConTill	0	0	0	0	0
ContourFarming	0	0	0	0	0
Forest_Conv	0	0	0	0	0
Wetland_Conv	0	0	0	0	0
NutrientMgmt	0	0	0	0	0
Terrace_Diversion	0	0	0	0	0
VegBuffer	0	0	0	0	0
VegBuffer2	0	0	.64	.52	.70
WasteMgmt	0	0	.75	.14	.75
RunoffControl	0	0	.15	.15	.15 ;

PARAMETER

*C(J) These represent the annual costs for implementation of type j BMP.
*These costs estimates are the sum annualized cost of implementation and Opportunity costs (value of land taken out of production) amortized over 15 years at 5% interest rate.
*Initial implementation cost data is based on estimates utilized by PRedICT (2007), EQIP (2006), Pennsylvania Conservation (2000), and Kansas State University (2003). .
*Opportuntity costs are based on estimates of Indiana agricultural land rental rates from Dobbins, 2007.
*Costs are amortized over a 15 year time horizon at an interest rate of 5%.

```
C(J) Cost of type j BMP
    /CropProtection     26.14
    ConTill             15.00
    ContourFarming      8.80
    Forest_Conv         462.23
    Wetland_Conv        462.23
    NutrientMgmt        10.60
    Terrace_Diversion   51.15
    VegBuffer           18.48
    VegBuffer2          18.48
    WasteMgmt           120.43
    RunoffControl       28.90/
```

*TF(I) Transfer Coefficient for farm site i.
*This value represents the proportion of emissions from farm site i in the E(I,K) table that gets transmitted to the receptor site.

```
   TF(I) Transfer coefficient for farm i
    /1     1
    2      1
    3      1
    4      1
    5      1
    6      1
    7      1
    8      1
    9      1
    10     1
    11     1
    12     1
    13     1
    14     1
    15     1
    16     1
    17     1
    18     1
    19     1
    20     1   /
```

*TC(L) Transfer Coefficient for farm site i.
*This value represents the proportion of emissions from CAFO site i in the CAFO(L,K) table that gets transmitted to the receptor site.

```
    TC(L) Transfer coefficient for CAFO l
```

/1 1
2 1
3 1
4 1 /

*Target(K) This represent a desired target level for pollutant concentration within the watershed.
*The target level is measured in micrograms/L for Atrazine, mg/L for TSS, N, and P, and mCFU/cubic meter for E. coli.
*This parameter, when set to a numerical value, represents the desired water quality at the receptor site.
Target(K) Target concentration of pollutant
/
Atrazine 1.089767557
TSS 140.4790
N 8.1045
P 4.8087
Ecoli 47.6465
/

*Penalty(K) This represents a monetary penalty in dollars for exceedence of the target pollutant concentration level.

Penalty(K) Penalty for limit exceedence for pollutant K

/ Atrazine x
TSS x
N x
P x
Ecoli x /

*Reward(K) This represents a monetary reward in dollars for having a lower concentration level than the target.

Reward(K) Null matrix
/ Atrazine 0
TSS 0
N 0
P 0
Ecoli 0 /

*Unit(K) This matrix converts the pollutant output from farms in E(I,K) from lbs/L to micrograms/L for Atrazine.
*It converts pollutant outputs from farms and CAFOs in E(I,K) and CAFO(L,K) from lbs/L to milligrams/L for TSS, N, and P.

Unit(K) Unit Conversion matrix
/ Atrazine 453592370
TSS 453592.37
N 453592.37
P 453592.37
Ecoli 1000 /

AU(L) Animal Units
/ 1 302
2 650

```
        3      1054
        4      324  /;

Scalar

*Farm (Scalar) This is the size in acres of the 20 uniform farms in this model.

Size Farm Size in acres / 3160/

*Volume (Scalar) This is the volume in cubic meters of the total amount of water that annually passes
through the watershed.
*This value is attained from adding the average volume of the Eagle Creek reservoir (21,000,000 m3) and
the amount of annual waterflow into the reservoir (162,140,562 m3).

Volume Annual volume of water in the watershed in cubic meters /183140562/;

Variables
        COST cost
        Cn Concentration
        CnC Concentration Converted to appropriate units

Positive Variables
        T_plus       Target sufficient
        T_minus      Target deficient

BINARY VARIABLES
              THETA(I,J) Ag BMP implementation decision
              IOTA(L,J)  CAFO BMP implementaion decision ;

Equations
Objective         Total Cost
Cnformula(K)      Concentration Formula
UnitConv(K)       Unit Conversion
Defgoal(K)        Definition of Goal
Limit(I,K)        Physical reduction limit
Limit2(L,K)       Physical reduction limit ;

Objective..          SUM((I,J), THETA(I,J)*C(J)*SIZE)+SUM((L,J), IOTA(L,J)*C(J)*AU(L)) =E= COST
;
Cnformula(K)..       SUM(I, (E(I,K)*TF(I))*(1-SUM(J,THETA(I,J)*BETA(J,K))))+ SUM(L,
(CAFO(L,K)*TC(L))*(1-SUM(J,IOTA(L,J)*GAMMA(J,K)))) =E= Cn(K);
UnitConv(K)..        (Cn(K)/(Volume*1000))*Unit(K)=E= CnC(K);
Defgoal(K)..         CnC(K) =L= Target(K);
Limit(I,K)..         SUM(J,THETA(I,J)*BETA(J,K)) =L= 1 ;
Limit2(L,K)..        SUM(J,IOTA(L,J)*GAMMA(J,K)) =L= 1 ;


MODEL Watershed /ALL/;
option MIP=COINBONMIN;
Solve Watershed USING MIP MINIMIZATION COST;
```