Sector-Targeting for Controlling Nutrient Loadings:
A Case Study of the North Fork of the Shenandoah River Watershed

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Bibek B. Singh

Abstract

The main purpose of Total Maximum Daily Loads (TMDL) is to achieve a water quality standard. The economic costs of reducing nutrient loadings are often not taken into account during development. In this study, sector targeting is used to minimize the total cost of nutrient reduction by targeting sectors with lower costs per unit of pollution reduction. This study focuses on targeting nitrogen (N) and phosphorus (P) loading reductions from three sectors: agricultural, point source, and urban non-point source, in the North Fork watershed. Linear programming optimization models were created to determine an optimal solution that minimized total compliance cost to implement BMPs subject to targeted loading reductions in N and P in the watershed. The optimal solution for each sector using uniform allocation and sector targeting were compared for N and P loading reductions separately and N and P reductions simultaneously. The difference between sector targeting and uniform allocation showed the sector targeting was the more cost effective approach to achieve the desired nutrient reduction compared to uniform allocation. From the agricultural sector, cropland and hayland buffers provided the best options for reducing both N and P. Urban BMPs are least efficient in term of nutrient reduction and cost. Similarly, for point source upgrade, Broadway has the lowest cost of upgrade per unit of N or P reduction. This study implies that both stakeholders and policymakers can use targeting to achieve nutrient reduction goals at lower costs. The policymakers can incorporate economic considerations in the TMDL planning process which can help in developing a cost-effective tributary strategy and cost-share program.

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CHAPTER 1: INTRODUCTION

1. 1. Background

Chesapeake Bay is the largest estuary in the United States (167,000km^2) extending over six states (New York, Pennsylvania, Delaware, Maryland, West Virginia and Virginia) and the District of Columbia and includes a human population of over 17 million. It also has the highest watershed land area per volume of water of any estuary in the United States, making runoff from the land surface critically important in determining the nutrient status of the estuary (Roberts et al., 2009). Environmental degradation of Chesapeake Bay is occurring due to nutrient over enrichment or eutrophication from municipal and industrial wastes directly discharged into tidal water as well as discharge of non-point source pollution (NPS) into the watershed (Roberts et al., 2009). Various steps and policies have been implemented at both the federal and state level to control this problem.

Through the Federal Water Pollution Control Act (FWPC) of 1972 and the Clean Water Act (CWA) of 1977, the primary focus has been on restoring the water quality of the Chesapeake Bay by reducing nutrient pollution. In 1998, major portions of Chesapeake Bay and its tidal tributaries within Virginia, Maryland, Delaware and the District of Columbia were identified as not meeting water quality standards and listed as impaired. As these Bay waters remained impaired in 2008, the six Chesapeake Bay Watershed States and the District of Columbia are required to develop a Total Maximum Daily Load (TMDL) for nutrients (nitrogen and phosphorus) entering the Chesapeake Bay and its tributaries (Chesapeake Bay TMDL, 2010).

1.1.1. Sources of Pollution

In the early stage of the Clean Water Act, water quality improvement has been achieved mainly through technology based performance standards on municipal and industrial point sources (Economic Research Service, 2010). Despite tremendous improvement in point source pollution reduction, serious water quality problems persist as EPA has shifted its focus to addressing nonpoint source pollution. Nonpoint sources of pollution have been identified as the major contributors to water nutrient enrichment problems (Chesapeake Bay Program, 2010a). This study will focus on point source pollution and agricultural and urban nonpoint sources to achieve cost-effective nutrient allocation.

- **Point sources*:*** Point source of nutrients can be attributed to a single location, such as wastewater discharge pipes from municipal and industrial areas. The Chesapeake Bay Program estimates that 21 percent of the P loading and 20 percent of the N loading in the Bay comes from municipal and industrial wastewater facilities (USEPA, 2010). Nutrient loading is the total amount of N or P entering the water during a given time. Municipal point sources contribute pollution resulting from sewage treatment. Industrial point sources can contribute pollution in the form of toxic chemicals and heavy metals. The Clean Water Act gives the EPA the authority to establish effluent limits on point sources. Effluent is the outflow from a municipal or industrial treatment plant. The EPA manages effluent limits in two ways: technology-based controls and water quality-based controls (Economic Research Service, 2010). The minimum standards are based on available treatment technology and pollution prevention measures.

  Wastewater treatment plants are designed to remove harmful chemicals from residential, commercial and industrial wastewaters before they are released back into water bodies. Removal processes focus on the reduction of total suspended solids, five-day biological oxygen demand, total P, total N, ammonia nitrogen, and oil and grease. State and local governments have increasingly supported consolidation of treatment plants and the use of more effective technology in treatment of wastewater, including biological nutrient removal (Belval and Sprague, 1999).

- **Agriculture Non-Point Source:** Non-point source pollution resulting from agricultural activities has been identified as a major source of water-quality pollution in the United States. Agriculture is estimated to contribute 41% of nitrogen and 47% of phosphorus entering the Bay (Bonham et al., 2006). Agricultural activities with potential to contribute nutrient loadings to water bodies include manure disposal, fertilizer use, poultry litter and cropping practices.

Agricultural sources can be divided into those associated with crop cultivation and those associated with livestock management. The process of crop cultivation disturbs the soil surface with the removal of natural vegetative cover. Tillage practices and crop rotations can affect the sediment runoff to water bodies. The frequency of soil tillage and resultant disturbances of the soil surface increases the chance of soil erosion. Nutrients applied to enhance crop production such as phosphorus, nitrogen, and potassium in the form of fertilizers, manure, sludge, legumes, and crop residues affect the amount of nutrients leaving the field. The unutilized nutrients either accumulate in the soil or are removed by runoff or infiltration to ground water.

Livestock operations are the other major sources of nutrients from agriculture. Within the Shenandoah sub-basin, the major types of livestock operations are dairy farms, poultry operations, cow-calf farms and stocker cattle operations (Faulkner and Trott, 1994). Without an appropriate waste management system, animal waste can be a significant source of nutrients that end up in the Bay. Runoff from livestock operations and fields receiving animal manure can carry a high concentration of nutrients and pathogens (bacteria and viruses) causing water quality problems. Another issue can be overgrazing of pasture which increases erosion and surface runoff.

- **Urban Non Point Source:** Urban expansion is inevitable as population continues to increase and people migrate from rural areas to cities. Urbanization is a primary form of land cover/land use change that is accelerating and has significant influence on watershed-wide environmental conditions (Roberts et al., 2009). The urbanized area attracts more people resulting in higher demand for water and an increase in the volume of wastewater to be treated. The construction process affects the ability of the land to retain precipitation and results in surface runoff. The Chesapeake Bay Program estimates that 31 percent of the P loading is from urban/suburban runoff and in-stream sediment (Chesapeake Bay Program, 2010b).

Impervious surfaces are created as a result of conversion of croplands, forests, grasslands, pastures, wetlands, and other cover types to residential and transportation uses (the majority) and also commercial and industrial uses (Tsegaye et al., 2006). As a result, the incidence of non-point source nutrients flowing to streams such as stormwater runoff from impervious surface has risen significantly. Experts predict that the population will increase to nearly 20 million from 17 million by 2030 (The Chesapeake Bay Program

2010c). Thus, with the projected future urban growth around the coastal region, it is important to mitigate the impact of nutrients loading to the watershed.

1.1.2. Total Maximum Daily Load

The objective of the 1972 Clean Water Act (CWA) was to achieve water quality to restore the biological, chemical and physical integrity of the nation's waters and make them "fishable and swimmable." The CWA addressed both point and nonpoint sources of pollution and water quality. However the Act does not require the EPA or the States to control nonpoint sources of a pollutant. The initial efforts were geared toward implementing Best Available Technology to control discharges from point sources. The principal regulatory tool for achieving this goal was the National Pollution Discharge Elimination System (NPDES) permit. The NPDES permits were issued by the regulators to point sources such as municipal and industrial dischargers which led to the upgrade of wastewater treatment plants. For most of the first two decades of CWA enforcement, water quality was not incorporated into the criteria and nonpoint sources were rarely evaluated. Despite tremendous improvements in point source pollution reduction, serious water quality problems persisted. This led to a push for total maximum daily load (TMDL), increasing the scope of water quality management to address both point and nonpoint source pollution on a watershed basis (Copeland, 2008).

Under Section 303(d) of the CWA, States are required to establish water quality standards for water bodies, consisting of the designated uses of a water body and the water quality criteria which are necessary to protect the uses. After identifying impaired water bodies, the states must determine the daily allowable loadings for specific pollutants that the water body can receive and still attain water quality standards. This is known as a TMDL. The states must then develop and implement policies to improve the health of the water bodies. TMDLs identify the maximum level of pollutant discharge necessary to meet water quality standard and support the designated uses of a water body. Once a TMDL is set, the total load reduction is allocated among all existing sources. The allocation is divided into two portions - a load allocation representing natural and non-point sources and a waste load allocation representing NPDES permitted point source discharges. Although the EPA provides national minimum water quality guidelines and is required to review and approve all state standards, water quality standards are established by each state independently (Copeland, 2008). If a state fails to do this, the EPA is required to develop a priority list for the state and make its own TMDL determination. The TMDL program serves as the primary mechanism to provide the attainment of water quality standards for impaired water bodies.

The EPA has primary responsibility for administration of TMDLs (Copeland, 2008). However, it generally delegates this responsibility to the state or the tribal department charged with protecting environmental quality, while it oversees the process (Jarell 1999). Developing a TMDL for an estuary requires delineating watersheds, analyzing nutrient sources, and collecting comprehensive water quality and land use data (USEPA 1997). In the process of developing a TMDL, there is much emphasis on including mathematical modeling and data centric approaches to characterize nutrient loadings but not required by CWA to give emphasis to the economic cost of reducing loadings.

Once nutrient reduction targets are set, a number of issues related to the implementation of projects and activities arise. These issues include identifying the sources, evaluating the source control measures and assessing the costs associated with the use of these measures. Often nutrient reduction strategies are designed without a clear idea of the cost for implementing solutions (Schleich et al, 1996). Allocation of load reductions must include an evaluation of the most cost-effective approach; however, specific guidelines set by the EPA do not address how this can be accomplished (Zaidi et al, 2003). Unfortunately, the economic analyses are often performed at a later stage once the loads have been allocated and the implementation strategies are being evaluated (Zaidi et al, 2008). The estimated $1.1 billion annual cost of achieving water quality protection goals for the Chesapeake Bay would accrue primarily to Virginia, Pennsylvania, and Maryland (Blankenship, 2003). Economic analysis plays an indispensable role in dealing with the two primary issues that arise in TMDL development and implementation: efficiency and equity (Keplinger, 2003). The economic analysis suggests that this cost could be reduced by selecting more cost effective treatments, trading pollution reduction responsibilities, and/or developing new, lower-cost treatment technologies (Blankenship, 2003). Thus, incorporating economic considerations in the TMDL planning process can help in developing a cost-effective tributary strategy and cost-share program. In addition, economic models are vital tools for assessing the benefits, challenges, and progress of TMDL implementation (Bosch et al, 2006a).

TMDL allocation is central to the overall TMDL process because it creates a technically feasible and reasonably fair division of the allowable load among sources (Zhang, 2008). TMDL allocation process is a method of analyzing pollution sources and allocating responsibility among those sources. Point sources apply a technology standard to assign allocation. They also get large reduction because they are under regulation. With non-point sources allocation is sensitive to political forces. The determination of control measure allocations among the urban and agricultural sectors is complex. The urban sector may get a higher allocation of the reduction despite higher cost if it has less political power in the negotiations. The TMDL allocation is a complex process due to both technical and political issues. In order to simplify this complex process uniform percentage allocation among sources is used to represent the TMDL allocation under the baseline. With uniform allocation, there is a constant percentage reduction required for each source of pollution without considering differences in pollution reduction costs.

1.1.3. Nutrient Reduction Goal

In the Chesapeake Bay agreement of 1987, the cooperating states and Washington, DC agreed to reduce nutrient loadings to the Bay by 40% from the 1985 baseline (Chesapeake Bay Agreement, 1987). Recent model simulations indicate that only 58% of P, 41% of the N and 54% of the sediment reduction goals necessary to assure water quality of the Bay's living resources have been achieved (Chesapeake Bay Program, 2010d). The 2010 goals of the Program include removal of the Bay and its tidal waters from the CWA 303(d) impaired waters list through achievement of established Tributary Strategies (Chesapeake Bay Program, undated).

The EPA issued the draft Chesapeake Bay TMDL on Friday, September 24, 2010. The TMDL has been called a "pollution diet" for the Bay portion, which extends across portions of 6 states and the District of Columbia (Chesapeake Bay TMDL 2010). The EPA estimates that in the year 2009, N and P loadings to the bay were 247.5m lbs/yr and 16.6m lbs/yr respectively. The EPA Bay-wide plan is to have practices in place to reduce N loading by 24 percent to 187.4m lbs/yr and P loading by 25 percent to 12.5m lbs/yr by year 2025 through the TMDL Program (Chesapeake Bay TMDL 2010). Virginia, like other states in the Chesapeake Bay watershed, has already developed a draft Phase 1 Watershed Implementation Plan (WIP). The draft Phase 1 WIP details two implementation periods, one from 2011-2017 and the other from

2018-2025. According to the draft, pollution control practices that achieve 60% of the needed nutrient and sediment load reductions (based on model predictions) must be in place by 2017and have practices in place to achieve the remaining 40% of the required load reductions from 2018-2025 (WIP 2010). Based on the draft Chesapeake Bay TMDL, the reduction goals for this study is 24 percent and 25 percent for N and P respectively.

1.1.4. North Fork Shenandoah Watershed

This study focuses on the North Fork of the Shenandoah River Watershed. The North Fork of the Shenandoah River Watershed is a largely rural 661,821 acre basin located in the Shenandoah Valley of northwest Virginia and eastern West Virginia (Figure 1.1). The watershed includes all of Shenandoah County, Virginia, and parts of Rockingham, Page, Warren, and Frederick Counties in Virginia, and Hardy County, West Virginia (Figure 1.2).

Figure 1.1 North Fork of the Shenandoah River Watershed

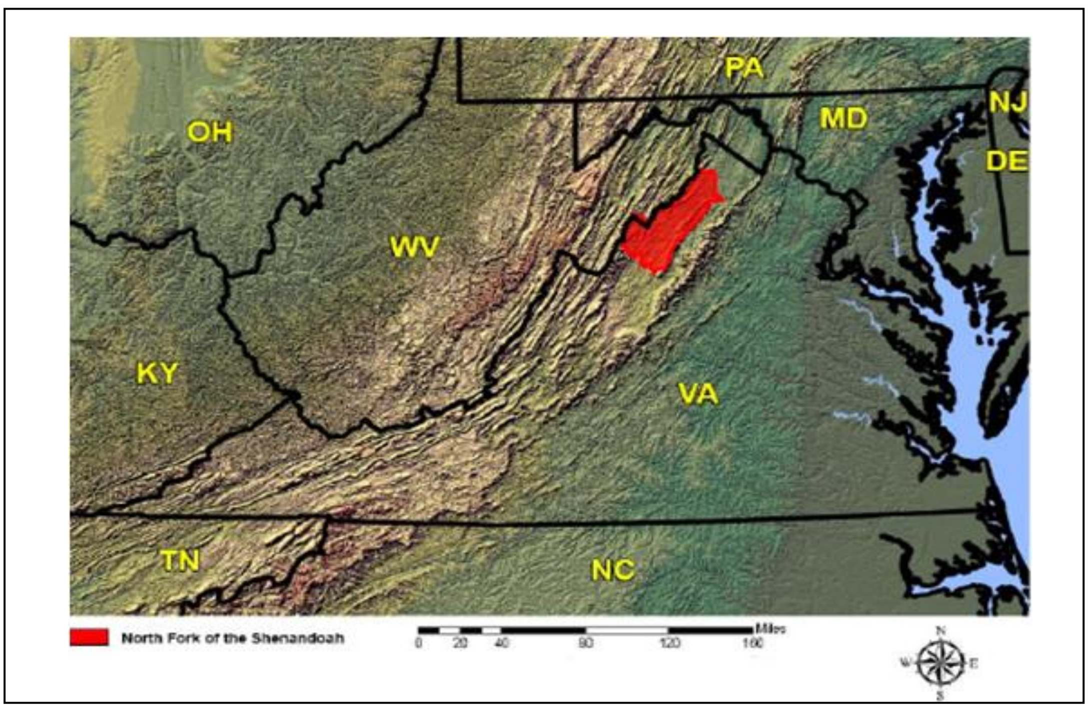
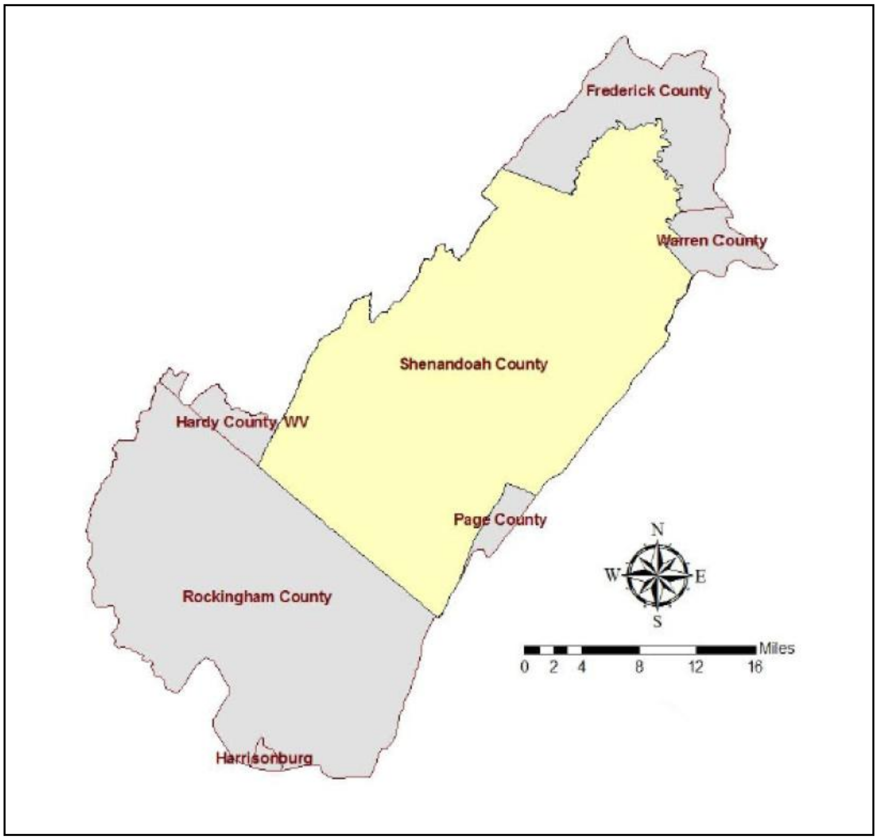


Figure 1.2 Counties within the North Fork of the Shenandoah River Watershed



According to the USDA's North Fork Watershed Assessment, the primary concerns in the North Fork watershed are the decline in water quality, the loss of agricultural land to urbanization, the projected inability to meet future water quantity demand, and the perception that farmers are the primary source of water quality impairments (USDA 2008). The number of urban acres in the watershed has increased rapidly with most of the converted acreage coming from agricultural land. Shenandoah County's population has nearly doubled since 1970 –from 20,000 then to over 37,000 in 2004 (Comprehensive Plan 2010).

There are 2,606 miles of perennial and intermittent streams in the watershed. Of these, 272.48 miles are impaired to the point where aquatic organisms are harmed or where recreational use of the water is restricted as determined by the Department of Environmental Quality (DEQ)

(USDA 2008). To address the identified impairments, numerous TMDL studies are planned for each impaired stream segment which is important in development of a Tributary Strategy report for Chesapeake Bay. Tributary Strategy is a river-specific cleanup strategy that details the "on-the-ground" actions needed to reduce the amount of nutrients and sediment flowing into the Chesapeake Bay (Chesapeake Bay Program, 2010e).

1.2. Effectiveness of Pollution Control Measures

The most widely used approach to solve increasing problems in nutrient runoff and necessary non-point-source pollution control is to implement best management practices (BMPs). BMPs are structural or management practices found to be most effective and practical for reducing nonpoint source pollution (LID Guidance Manual for Maine Communities, 2007). Each BMP may reduce different pollutants at different rates which vary depending on the location of BMPs in the watershed. Similarly the cost of implementing BMPs varies by type and location in the watershed.

This research focuses on reducing compliance costs borne by farmers, developers and local agencies tasked for reducing point or nonpoint source of pollution. For farmers, compliance costs include the costs of switching their production systems in order to achieve their pollution reduction responsibility (Carpenter et.al. 1998). Similarly, developers and/or municipalities incur costs for implementing urban BMPs and municipalities incur costs to upgrade wastewater treatment plants. The involvement of stakeholders including landowners, developers, and municipalities throughout this process is critical since they make management decisions on their property that affect water quality. These stakeholders participate through implementation of agricultural, forestry, and urban BMPs as well as point source treatment upgrades. Stakeholder participation in selection and implementation of BMPs and treatment plant upgrades will assist in developing and implementing TMDLs that achieve nutrient reductions at least cost.

1.2.1. Cost Share Programs

Government agencies promote water quality improvement through BMP implementation by playing a pivotal role in controlling non-point source pollution. The agencies offer cost-share assistance as an incentive to carry out construction or implementation of selected BMPs. The basis of the program is to encourage the voluntary installation of agricultural BMPs to meet non-point source pollution water quality objectives (Virginia Department of Conservation and Recreation, 2011a).

Cost-share programs may result in reduction of NPS pollution but they may not be the most cost effective approach. Using cost-share criteria to recommend management practices does not include the effects of the practices on water quality in the watershed. For example, with a no till corn cost-share program, all farmers growing suitable crops may be equally encouraged to participate regardless of differing NPS pollution impacts to the watershed from different fields. Additionally, farmer participation in the program may depend heavily on economic or regulatory factors. Therefore just using cost-share BMPs on farms contributing significant quantities of NPS pollution is not always the most cost effective approach. Similar arguments can be made for cost sharing urban BMPs and subsidizing upgrades to point source treatment plants.

1.2.2 Targeting

Targeting is increasingly considered as a method to reduce the cost of controlling nonpoint source pollution. Braden et al. (1989) stressed that NPS pollution control through targeting is likely to be cheaper and less disruptive overall than applying the same control measures across the watershed. Targeting increases social cost-effectiveness by allocating more control responsibility to sources with low compliance costs and large loadings reductions and by reducing the number of sources that must be included (Carpentier et.al. 1998). Targeting means maximizing the environmental benefits of every dollar spent by considering both costs and pollution reduction of implementing particular control measures.

If the goal is maximization of cost effectiveness (maximum reduction per dollar of compliance cost), strategic targeting and prioritization of areas for implementation of BMPs is conceptually preferable to a “voluntary” basis, which has no guarantee of resulting in better pollution abatement than a random distribution of practices within a watershed (Diebel et al., 2008). Targeting allows areas with high pollution potential to be identified and treated accordingly. This strategy would be a more efficient way to allocate available resources and control NPS pollution compared to uniform allocation. With uniform allocation, there is a constant reduction set for each source of pollution without considering the costs of pollution reduction of each pollution source. Allocating available resources to reduce pollution from a source with lowest costs of nutrient reductions helps in achieving maximum reduction per dollar of compliance cost.

Targeting is often based on physical characteristics or cropping practices, focusing on variables factors such as slope, soil type, proximity to stream, and crop and tillage practices (Veith et al, 2004). In this study we are focusing on targeting for three sectors: agricultural, point source and urban non-point source. Sector targeting is minimizing the total cost to achieve a load reduction target across sectors by considering the differential costs of measures within each sector. Sectors with lower costs per unit of pollution reduction are targeted for higher reductions.

1.3. Problem Statement

In an effort to comply with the Environment Protection Agency's (EPA) Total Maximum Daily Load (TMDL) regulatory program, the state of Virginia is trying to reduce its annual load of N and P discharged into the Chesapeake Bay. Policymakers would like to achieve the mandated reduction in the TMDL allocation in the most cost effective manner. The TMDL program is viewed by many as a legislative mandate for a singular and definitive determination of the precise loading limit for a water body (Freedman et.al 2004). The level of uncertainty in TMDL determination is rarely well defined and often exceedingly large (Freedman et.al 2004). Allocation of TMDL reduction often lacks economic analysis. Due to the complexity associated with pollutant load modeling and allocation, economic considerations are traditionally not included (Zaidi et al, 2008). The unit costs for load reductions vary considerably depending on the control strategy and the location. With targeting, a highly polluted area can be identified and treated accordingly. Sector targeting minimizes the total cost by targeting sectors with lower costs per unit of pollution reduction to get higher reductions for a given cost. Thus with sector targeting, economic considerations can be incorporated in the TMDL planning process.

As part of determining minimum cost of achieving nutrient reduction goals, the principal sources of N and P are identified along with the potential control options for each source. As effective measures for controlling pollution are identified, there is a tendency to want to implement it to the greatest extent possible by uniformly establishing those measures across the landscape (Veith et al 2004). However, soil erosion and nutrient runoff do not happen uniformly across the landscape. The land use, soils and topography makes certain locations critical in terms of generating nutrients load. Similarly, within sub-watersheds, a particular sector might contribute higher amount of nutrient loading. For example, if a sub-watershed is intensively devoted to poultry farming, we can expect agriculture to be the main contributor for nutrient loading. Therefore, targeting along the sectors will be used to identify the least cost combination of BMPs to reduce nutrient loading.

With sector targeting, both policymakers and stakeholders in Virginia would benefit from determining the combination of pollution control measures that will achieve nutrient reduction goals at lower cost. Research is needed to demonstrate the benefits of sector targeting in order to give policymakers incentives to pursue such strategies for meeting TMDL reduction goals as well as other water quality improvement programs.

1. 4. Objectives

The main objective of this research project is to determine potential cost savings in meeting N or P reduction goals by sector targeting in the North Fork Watershed. Specific nutrient loading reductions considered include:

i. Reduce N loading by 24 percent
ii. Reduce P loading by 25 percent
iii. Simultaneously reduce N & P loading by 24 and 25 percent, respectively, to achieve desired allocation at minimum cost

Achievement of these objectives can help in developing a cost-effective watershed management plan that can be used in developing and implementing TMDL allocation and also used as guideline for allocating funds to achieve reductions.

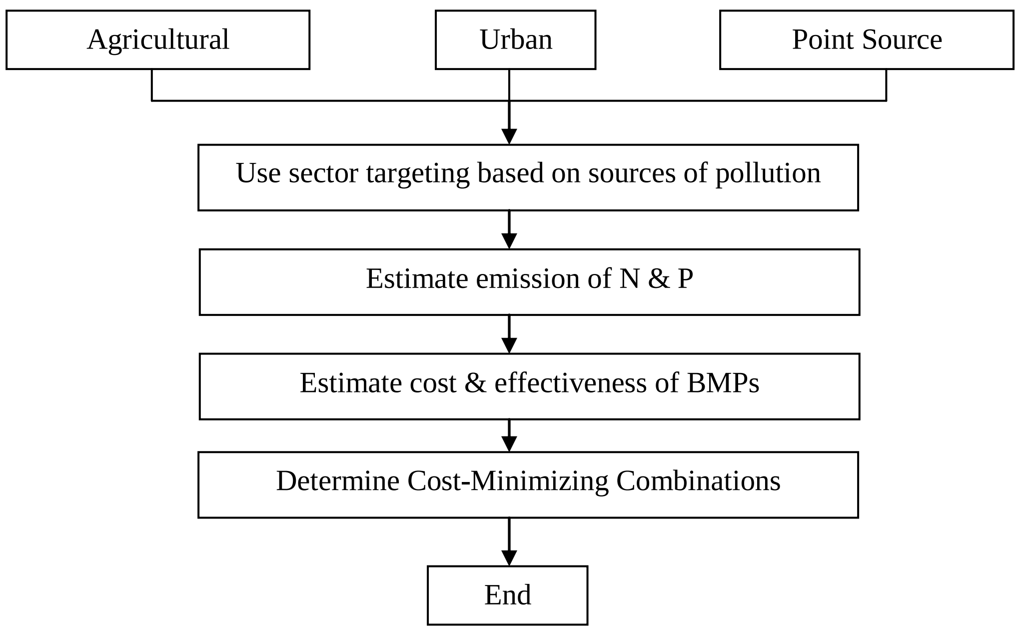
1.5. Research Methods and Procedures

A framework is designed to come up with a cost effective way to manage the watershed. This cost-minimization problem can be viewed as a case of constrained optimization. The farmer, developers and local agencies want to minimize their total costs, subject to the requirement to meet annual targeted inflow reductions in N and/or P into North Fork watershed. The optimal load reduction targets are carried out separately for N and P and then simultaneously. There are multiple sources and potential solutions to the nutrient loading problem. These sources are categorized into respective sectors – point, agricultural non-point and urban non-point. The model focuses on minimizing compliance cost borne by the farmers, developers and local agencies associated with pollutant sources.

The BMPs that are analyzed for the agricultural sector are no-till, cropland buffers, pasture buffers and hayland buffers. Urban BMPs include bioretention filters using sandy soils and clay soils and urban buffers. Five treatment plants are included and analyzed for potential point source upgrades. The cost saving from sector targeting is realized by reducing the compliance cost by implementing cost effective BMPs i.e. BMPs with higher nutrient reductions per dollar of cost. Cost is based on total cost to stakeholders and taxpayers of implementing BMPs or treatment plant upgrades. Costs are not reduced to reflect government subsidies or cost share of BMPs. The least cost best management practice approach meets nutrient inflow reduction goals at least cost to stakeholders and taxpayers.

The basic framework of this model is a depiction of the watershed based on sources of pollution: agricultural non-point, point, and urban non-point. Each of these sectors has corresponding loading for each type of nutrient. The amount of nutrients contributed to the watershed from respective sectors is calculated. In determining the optimal solution, the performance of each BMP in reducing nutrient loadings and the annual cost per unit of P and N loading reductions are computed. Each BMP is an alternative available to the decision makers, which has costs based on constraints such as initial investment capital, annual operating requirements, and possible losses of revenues (opportunity cost). Thus, an optimal solution is created that minimizes the cost to implement BMPs subject to targeted loading reductions in N and P into the watershed. Figure 1.3, shows the work flow.

Figure 1.3 Steps Involved in Achieving Water Quality Standard at Least Cost



In order to quantify the cost-effectiveness of sector targeting, costs of achieving a reduction in loadings are compared with uniform allocation along the sectors. In the case of sector targeting, the nutrient reduction is achieved at lowest overall cost by allocating higher reductions to sectors with lower costs. With uniform allocation, there is a stringent constraint requiring equal percentage reductions per each sector. Sector targeting provides flexibility to the model and helps to determine the least cost combinations. Table 1.1, shows the 24 percent reduction in N using uniform allocation and sector targeting.

Table 1.1 Measuring Cost Saving

Sectors	Uniform Allocation (constrained)	Sector Targeting (unconstrained)
Agricultural	24%	↓
Urban	24%	24%
Point	24%	↑

1.5.1. Hypothesis Testing

The two testable hypotheses for this study are:

- **Urban BMPS are least Cost-Effective:** Urban BMPs are not very cost efficient when compared with agricultural and point source BMPs. The Chesapeake Bay Program estimates that the standard average cost of removing one pound of P from urban discharges is $15,875 compared to an estimated $644 per pound for P removal from agricultural discharges (Chesapeake Bay Program, 2010d).

- **With sector targeting, proportionately more reduction will come from agriculture:** Residential development is complex and implementing residential or urban BMPs can be complicated and costly. For example, according to the National Association of Home Builders, the average single-family lot size in 2002 was 0.38 acres, whereas, the average Virginia farm is 181 acres (Chesapeake Bay Program, 2010d). A program administrator would need to identify, coordinate, and verify BMP installation on 476 single-family residences to match the acreage of one farm if the program followed the same patterned as the current Agricultural BMP Cost Share Program.

1.5.2. Data

The types of data utilized in the model are pollution emission data and BMP efficiency in reducing nutrients and cost data. These data provide parameters for a mathematical programming model designed to achieve targeted levels of nutrient reduction at least cost. Daily mass loading of nutrients from agricultural sites to North Folk Watershed is calculated using GLEAMS (Groundwater Loading Effects of Agricultural Management Systems) which simulates nonpoint source loading. The GLEAMS model simulates overland and subsurface loadings of nutrients to all tributaries in the watershed. GLEAMS is a mathematical model developed for field size areas to evaluate the effects of agricultural management systems on the movement of agricultural chemicals within and through the plant root zone (Leonard et al., 1987). The GWLF (Generalized Watershed Loading Function) is used to simulate the nutrient loading from urban sector. It is a mid-range watershed loading model developed to assess non-point source flow and sediment and nutrient loading from urban and rural watersheds (Haith et al 1987). The GWLF model provides the ability to simulate runoff, sediment, and nutrient loadings (N and P) from a watershed given variable-size source areas. The allowable discharge from point source sector and estimated reductions from source upgrades were obtained from respective treatment plants. These models are used to predict potential N and P runoff which can be used to interpret or predict possible changes in the water quality. This is used to assess nutrient inflows reduction for each BMP.

To identify and enable implementation of cost-efficient strategies, the efficiency and financial cost analyses for each of the BMPs is carried out. The following information for each BMP and point source control is required:

- Baseline data on nutrient loading at the outlet of North Fork Watershed
- Initial investment costs for BMPs and treatment plant upgrades
- Annual operating and maintenance costs for BMPs and treatment plant upgrades
- Opportunity cost of land
- Efficiency of BMPs and point source upgrades in terms of nutrient reduction

These data will be used in assessing nutrient inflow reduction performance of each BMP. The data will be used to calculate the annual costs per unit of P and N reduction toward meeting the North Folk watershed targeted objective. The above data are used to build a linear programming model to minimize costs of reducing nutrient loadings. In addition, these data are used to prepare a narrative and numeric descriptive summary of the respective optimal solutions associated with the baseline situation and other sensitivity scenarios.

1.5. Summary

This thesis is organized to reflect the use of sector targeting to achieve nutrient reduction in a least cost way in the North Fork Watershed. Chapter Two presents the conceptual framework and supporting assumptions and conditions. The comprehensive description of data used in the model is discussed in the Chapter Three. Chapter Four gives the general overview of the structure of the linear programming optimization model. Chapter Five presents the LP results of three sectors and their BMP combinations, thus comparing the costs between uniform allocation and sector targeting. In Chapter Six, the summary, conclusions, limitations and opportunity for further research are presented.

CHAPTER 2: CONCEPTUAL FRAMEWORK

2.1. Introduction

The N and P load reduction were carried out separately and jointly with uniform allocation and sector targeting for North Fork watershed in Virginia. The study was carried out at the watershed level to provide relevant watershed management information for local farmers, developers and local agencies. The nutrient runoffs were categorized based on sources into respective sectors: agricultural, urban and point source. Both agricultural and urban sectors have a number of BMPs as control alternatives and similarly there are a number of treatment plant upgrades for point sources. With number of pollution sources and control alternatives, linear programming was used to create an optimal solution for BMP implementation while minimizing the cost. The combinations of BMPs were used to evaluate the effect on cost savings and nutrient reductions at the watershed level.

2.2. Reducing Cost by Targeting

Targeting is a plan-based method that focuses pollution control towards critical areas that are anticipated to contribute most heavily to NPS pollution (Veith et al, 2004). It helps in identifying areas with high pollution potential which can be treated accordingly with available resources. Batie (1994) defines targeting as investing in regions, and in enterprises within these regions, that contribute to the problem, where economic benefits from achieving the goals per dollar invested are greatest. The costs of nutrient reduction can be reduced by selectively choosing and placing site-specific BMPs.

Spatial information is critical to determining the appropriate application of agricultural BMPs in order to maximize their effectiveness and minimize farm costs (Carpentier, et al., 1998). Spatial information is equally important for urban BMPs. In this study, the nutrient loadings were calculated using soil type, slope and land use for the flow path over which nutrients travel and leach through to the nearest water body in the North Fork watershed. The choice of landuse determines the BMPs that can be implemented on the land. For example, pasture buffer can be implemented on pasture not in hayland.

Carpentier et al. (1998) conducted a study to determine the difference in the control cost of agricultural NPS control between uniformly applied pollution reduction policies and spatially targeted pollution reduction policies. With uniform allocation, a particular set of BMPs was implemented throughout the watershed to achieve the nutrient reduction goal. With targeting, BMPs were applied based on spatial characteristics of each farm to minimize both compliance and transaction costs. The study concluded that BMP implementation based on spatial characterization of farms reduces the cost of BMP implementation to both farmers and tax payers.

Veith (2004) used an optimization approach to BMP placement through evaluation of numerous scenarios by incorporating the impact of BMP interaction and site-dependent characteristics. This approach provided more cost-effective reduction of sediment compared to single BMP scenario based on a set of targeting criteria. The optimal solutions provide more BMP selection to farmers, and therefore increase the probability of adoption, leading to a more cost effective solution at the watershed level.

For this study, sector targeting is used in implementation of BMPs based on sources of pollution and landuse within the sectors, and an optimization approach is used to determine the cost-effective strategy.

2.3. Optimization

A linear programming model was created to calculate the cost-effective reduction of N and P using sector targeting by taking into consideration the differential costs and effectiveness of BMPs within each sector. At the watershed level, the farmer, developers, and urban agencies have decisions to make in terms of assigning unique pollution control to every pollution source to achieve the water quality goals with the available resources. The number of pollution sources and control alternatives determines the complexity of the decision problem. The watershed-scale optimization enables decision makers to consider all feasible alternatives implicitly, exploiting rather than restricting the complexity of the feasible choice set (Schwartz 2009). It provides more effective and desirable management options.

2.4. Control Alternatives

The agricultural and urban sectors have a number of BMPs that can be used as alternatives to control nonpoint source runoff throughout the watershed. Similarly, the upgrades to five wastewater treatment plants technologies give control over point source discharges. Each of these control measures is calculated in terms of its unit cost and nutrient reductions which, together define cost-effectiveness.

- *Agricultural BMPs*: No till- corn silage, cropland buffer, pasture buffer, hayland buffer
- *Urban BMPs*: Bioretention filters using sandy soils and clay soils; urban buffer
- *Point Source*: Upgrades to five wastewater treatment plants

2.5. Costs

In this study it is assumed that both local government and stakeholders will make rational choices and they will minimize the total cost of achieving nutrient reduction goal. The main focus is minimizing the compliance costs borne by the farmers, developers and local agencies. The analysis does not consider transaction costs. Transaction costs include information, contracting, and enforcement costs (Carpentier, et al., 1998). The compliance cost can reduce the net revenue through direct costs (installation of BMPs), as well as through opportunity cost (revenues foregone by installing the buffer). The cost-share subsidies and tax credit programs for BMP adoption are not included in the calculation of costs. The compliance costs of reducing both N and P vary within the same sector and across the watershed depending upon the practice and landuse. Thus, it is important to evaluate compliance cost accurately in order to measure the economic effects of BMP implementation.

2.6. Generalized Structure

The optimal load reductions are carried out separately for both N and P. The reduction goal for N and P are 24 percent and 25 percent respectively based on 2010 drafted Chesapeake Bay TMDL. The pollution reduction costs will increase at an increasing rate with the amount of reduction. The linear programming model is generalized below in the following sections:

2.6. 1. Uniform Allocation

The cost-effectiveness of sector targeting (T_A) is measured based on the difference between the total cost of control measures using sector targeting (CM_S) and cost of control measures uniformly applied to the entire watershed (CM_U).

$$T_A = CM_U - CM_S \quad (2.1)$$

With uniform allocation, there is a constant constraint per each sector, 24 percent reduction in N and 25 percent reduction in P from the baseline. The cost of implementing control measures using uniform allocation for each sector was calculated separately and is generalized below.

Agricultural Sector

$$\text{Min } CAg_{UN} = \sum_{i} [C_{NAgi} * BMP_{Agi}] \quad (2.2)$$

Subject to,

Nitrogen Loading: $[(N_C * C + N_P * P + N_H * H) - \sum_i (N_{Agi} * BMP_{Agi})] \leq 0.76e_{Ag}$ (2.3)

Cropland Acres: C = b_C (2.4)

Pasture Acres: P = b_P (2.5)

Hayland Acres: H = b_H (2.6)

Maximum BMPs: $BMP_{Agi} \leq b_{BMPi}$ (2.7)

CAg_{UN}, represents the cost of control measures for reducing N loading from the agricultural sector using uniform allocation. It is calculated using the number of implemented agricultural BMPs, BMP_{Agi}, and unit cost of implementing them, C_{NAgi}. Equation 2.3 represents the constraint that N loading should meet the reduction at 24 percent of the agriculture base loading, e_{Ag}. The first part of equation 2.3, gives the baseline loading which is calculated using the N loading per acre from cropland, N_C, and total acres of cropland, C, and similarly from pasture and hayland. The second part, $\sum_i (N_{Agi} * BMP_{Agi})$, calculates the N loading with BMP implementation. In the above equations, b_C, b_P and b_H represents the total resource availability of cropland, pasture and hayland. Equations 2.4, 2.5 and 2.6 are total acres of cropland, pasture and hayland. Equation 2.7 represents the maximum number of agricultural BMPs that can be implemented based on landuse activities.

Urban Sector

$$\text{Min } CUb_{UN} = \sum_{i} [C_{NUbi} * BMP_{Ubi}] \quad (2.8)$$

Subject to,

Nitrogen Loading: $[(N_{Ub} * Ub) - \sum_i (N_{Ubi} * BMP_{Ubi})] \leq 0.76e_{Ub}$ (2.9)

Urban Acres: Ub = b_{Ub} (2.10)

Maximum BMPs: $\text{BMP}_{Ubi} \leq b_{BMPi}$ (2.11)

CUb_{UN}, represents the cost of implementing control measures for reducing N using uniform allocation for the urban sector. In equation 2.8, C_{NUbi} is the unit cost of implementing urban BMPs and BMP_{Ubi} is the number of implemented BMPs. Equation 2.9 represents the constraint that the N loading should meet the reduction at 24 percent of the urban base loading, e_{Ub}. The first part of the equation, $(N_{Ub} * Ub)$, calculates the baseline loading using the N loading per acre from urban land use, Nu_{Ub}, and total urban acres, Ub. The second part, $\sum_i (Nu_{Ubi} * BMP_{Ubi})$, calculates the reduced N loading with urban BMP implementation. Equation 2.10 shows the total urban acres at North Fork watershed. Equation 2.11 represents the maximum number of urban BMPs that can be implemented.

Point Source

$$\text{Min } CPs_{UN} = \sum_{i} [C_{Ni} * WWTP_i] \quad (2.12)$$

Subject to,

Nitrogen Loading: $\left[(\sum WWTP_{base}) - \sum_i WWTP_{Upgrade})\right] \leq 0.76e_{Ps}$ (2.13)

WWTP Baseline: $WWTP_{Basei} = b_N$ (2.14)

WWTP Upgrade: $WWTP_{Upgradei} \leq b_P$ (2.15)

In equation 2.12, CPs_{UN}, represents the cost of upgrading the wastewater treatment plants which is calculated using the total pounds of N reduced and per unit costs for reducing N. Equation 2.13, represents the constraint that the N loading should meet the reduction at 24 percent of the point source base loading, e_{PS} . Equation 2.14 represents the N baseline loading at the respective treatment plants. Similarly, equation 2.15 shows the maximum units of N that can be reduced from the respective treatment plants after upgrade.

Therefore, combining equation 2.2, 2.8 and 2.12 gives the total cost of control measures used to reduce N using uniform allocation along the three sectors.

$$\textbf{Min } \boldsymbol{CM_{UN}} = \sum_{\boldsymbol{i}} [\boldsymbol{CAg_{UNi}} + \boldsymbol{CPs_{UNi}} + \boldsymbol{CUb_{UNi}}] \qquad (\mathbf{2.16})$$

2.6.2. Sector Targeting

Sector targeting is likely to meet the nutrient reduction goal with lower compliance cost. Sector targeting minimizes the total cost necessary to achieve a load reduction target level across sectors by considering the differential costs of BMPs within each sector. In the case of sector targeting, the constraint on nutrient reduction is an overall reduction from the baseline, so one sector can have a greater contribution in load reduction.

$$\textbf{Min } \boldsymbol{CM_{SN}} = \sum_{\boldsymbol{i}} \left[\boldsymbol{C_{NAgi}} * \boldsymbol{BMP_{Agi}} + \boldsymbol{C_{NUbi}} * \boldsymbol{BMP_{Ubi}} + \boldsymbol{C_{Ni}} * \boldsymbol{WWTP_i}\right] \qquad (\mathbf{2.17})$$

Subject to,

Nutrient Loading: $\left[(Ag_{base} + Ub_{base} + WWTP_{base}) - \sum_i (Nu_{Agi} * BMP_{Agi}) - \sum_i (Nu_{Ubi} * BMP_{Ubi}) - \sum_i WWTP_{Upgrade})\right] \leq 0.76e$ (2.18)

Agriculture Acres:	C = b_C	(2.19)
Urban Acres:	Ub = b_{Ub}	(2.20)
WWTP Baseline:	$WWTP_{Basei} = b_N$	(2.21)
Maximum Agricultural BMPs:	BMP$_{Agi} \leq b_{BMPi}$	(2.22)
Maximum Urban BMPs:	BMP$_{Ubi} \leq b_{BMPi}$	(2.23)
WWTP Upgrade:	$WWTP_{Upgradei} \leq b_P$	(2.24)

The cost of control measures using sector targeting is calculated similarly to uniform allocation using the number of implemented BMPs and unit cost of implementing them as shown in equation 2.17. Equation 2.18 represents the constraint that the N loading should meet the reduction at 24 percent of base loading, $e,$ as compared to fixed reduction rate per each sector in uniform allocation. In the above equations, b represents the total resource availability. Equations 2.19 represents total acres agriculture land which is further divided based on landuse activities and similarly equation 2.20 shows the total urban acres in North Fork watershed. Equation 2.21 represents the N baseline loading at the respective treatment plants. Equations 2.22 and 2.23 show the maximum number of agricultural BMPs and urban BMPs, respectively, that can be implemented. Equation 2.24 demonstrates the maximum units of N that can be reduced from the respective treatment plants after upgrade.

Similarly, the nutrient reduction cost using uniform allocation and sector targeting was calculated for P.

2.6.3. Nitrogen and Phosphorus Combined

The cost of reducing N and P jointly was calculated using uniform allocation for each sector and by sector targeting for the watershed.

<u>Agricultural Sector</u>

Min $CAg_U = \sum_i [C_{Agi} * BMP_{Agi}]$ (2.25)

Subject to,

Nitrogen Loading: $[(N_C * C + N_P * P + N_H * H) - \sum_i (N_{Agi} * BMP_{Agi})] \leq 0.76e_{Ag}$ (2.26)

Phosphorus Loading: $[(P_C * C + P_P * P + P_H * H) - \sum_i (P_{Agi} * BMP_{Agi})] \leq 0.75e_{Ag}$ (2.27)

Cropland Acres: C = b_C (2.28)

Pasture Acres: P = b_P (2.29)

Hayland Acres: H = b_H (2.30)

Maximum BMPs: BMP$_{Agi} \leq b_{BMPi}$ (2.31)

CAg_U, represents the cost of control measures for reducing both N and P loading from the agricultural sector using uniform allocation. C_{NAgi} is the cost of implementing agricultural BMPs and BMP_{Agi} represents the implemented agricultural BMPs. The unit of implementing agricultural BMPs for N and P are same. Equations 2.26 and 2.27 represent the constraints that N and P loading should meet the reduction of 24 percent and 25 percent, respectively, from the agriculture base loading, e_{Ag}. The first part of the equation 2.26, $(N_C * C + N_P * P + N_H * H)$, gives the baseline nutrient loading which is calculated using the N loading per acre from cropland, pasture and hayland. The second part of the equations, $\sum_i (N_{Agi} * BMP_{Agi})$, calculates the N loading with BMP implementation. Similar calculation for P loading is carried out in equation 2.27. Equations 2.28, 2.29 and 2.30 are total acres of cropland, pasture and hayland.

Equation 2.31 represents the maximum number of agricultural BMPs that can be implemented based on landuse activities.

<u>Urban Sector</u>

Min $CUb_U = \sum_i [C_{Ubi} * BMP_{Ubi}]$ (2.32)

Subject to,

Nitrogen Loading: $[(N_{Ub} * Ub) - \sum_i(N_{Ubi} * BMP_{Ubi})] \leq 0.76e_{Ub}$ (2.33)

Phosphorus Loading: $[(P_{Ub} * Ub) - \sum_i(P_{Ubi} * BMP_{Ubi})] \leq 0.75e_{Ub}$ (2.34)

Urban Acres: Ub = b_{Ub} (2.35)

Maximum BMPs: BMP$_{Ubi} \leq b_{BMPi}$ (2.36)

CUb_U, represents the cost of implementing control measures for reducing N and P using uniform allocation for the urban sector. In equation 2.32, C_{Ubi} is the unit cost of implementing urban BMPs and BMP_{Ubi} is the number of implemented BMPs. Equations 2.33 and 2.34 represent the constraints that the N and P loadings should meet the reduction of 24 and 25 percent, respectively, of the urban base loading, e_{Ub}. The first part of the equation 2.33, $(N_{Ub} * Ub)$, calculates the baseline loading using the N loading per acre from urban, Nu_{Ub}, and total urban acres, Ub. The second part, $\sum_i(N_{Ubi} * BMP_{Ubi})$, calculates the reduced N loading with urban BMP implementation. Similar calculation for P loading is carried out in equation 2.24. Equation 2.35 shows the total urban acres at North Fork watershed. Equation 2.36 represents the maximum number of urban BMPs that can be implemented.

Point Source

$$\text{Min } CPs_U = \sum_i [TC_i * WWTP_i] \quad (2.37)$$

Subject to,

Nitrogen Loading: $\left[(\sum WWTP_{Nbase}) - \sum_i WWTP_{NUpgrade})\right] \leq 0.76e_{Ps}$ (2.38)

Phosphorus Loading: $\left[(\sum WWTP_{Pbase}) - \sum_i WWTP_{PUpgrade})\right] \leq 0.75e_{Ps}$ (2.39)

WWTP N_Baseline: $WWTP_{Basei} = b_N$ (2.40)

WWTP P_Baseline: $WWTP_{Basei} = b_P$ (2.41)

WWTP N_Upgrade: $WWTP_{Upgradei} \leq b_{RN}$ (2.42)

WWTP P_Upgrade: $WWTP_{Upgradei} \leq b_{RP}$ (2.43)

In equation 2.37, CPs_U, represents the cost of upgrading the wastewater treatment plants summed over the treatment plants that are utilized to achieve nutrient reductions.. The per unit costs of reducing N and P are different at each treatment plant so the combination of upgrades that minimized the total cost of upgrades, TC_i, was used. Equations 2.38 and 2.39, represents the constraint that the N and P loading should meet the reduction at 24 and 25 percent of the point source base loading, e_{Ps} . Equations 2.40 and 2.41 represent the N and P baseline loading at the respective treatment plants. Similarly, equations 2.42 and 2.43 show the maximum units of N and P that can be reduced from the respective treatment plants after upgrade.

Therefore, combining equation 2.25, 2.32 and 2.37 gives the total cost of control measures used to reduce N and P using uniform allocation along the three sectors.

$$\textbf{Min } \boldsymbol{CM_{UN}} = \sum_{\boldsymbol{i}} [\boldsymbol{CAg_{Ui}} + \boldsymbol{CUb_{Ui}} + \boldsymbol{CPs_{Ui}}] \quad (\mathbf{2.45})$$

Sector Targeting

$$\textbf{Min } CM_S = \sum_i \left[C_{Agi} * BMP_{Agi} + C_{Ubi} * BMP_{Ubi} + C_i * WWTP_i \right] \qquad (2.46)$$

Subject to,

Nitrogen Loading: $\left[(Ag_{Nbase} + Ub_{Nbase} + WWTP_{Nbase}) - \sum_i (N_{Agi} * BMP_{Agi}) - \sum_i (N_{Ubi} * BMP_{Ubi}) - \sum_i WWTP_{NUpgrade}) \right] \leq 0.76e$ (2.47)

Phosphorus Loading: $\left[(Ag_{Pbase} + Ub_{Pbase} + WWTP_{Pbase}) - \sum_i (P_{Agi} * BMP_{Agi}) - \sum_i (P_{Ubi} * BMP_{Ubi}) - \sum_i WWTP_{PUpgrade}) \right] \leq 0.75e$ (2.48)

Agriculture Acres:	C = b_C	(2.49)
Urban Acres:	Ub = b_{Ub}	(2.50)
WWTP N_Baseline:	$WWTP_{Basei} = b_N$	(2.51)
WWTP P_Baseline:	$WWTP_{Basei} = b_P$	(2.52)
Maximum Agricultural BMPs:	$\text{BMP}_{Agi} \leq b_{BMPi}$	(2.53)
Maximum Urban BMPs:	$\text{BMP}_{Ubi} \leq b_{BMPi}$	(2.54)
WWTP N_Upgrade:	$WWTP_{Upgradei} \leq b_{RN}$	(2.55)
WWTP P_Upgrade:	$WWTP_{Upgradei} \leq b_{RN}$	(2.55)

The cost of control measures using sector targeting is calculated similarly to uniform allocation using the number of implemented BMPs and unit cost of implementing them as shown in equation 2.46. Equations 2.47 and 2.48 represent the constraints that the nutrient loading should meet the reduction at 24 percent and 25 percent for N and P, respectively, of base loading, e, as compared to fixed reduction rate per each sector in uniform allocation. In the above equations, b represents the total resource availability. Equation 2.49 represents total acres agriculture land which is further divided based on landuse activities and similarly equation 2.50 shows the total urban acres in North Fork watershed. Equations 2.51 and 2.52 represent the N and P baseline loading at the respective treatment plants. Equations 2.53 and 2.54 show the maximum number of agricultural BMPs and urban BMPs, respectively, that can be implemented. Equations 2.55 and 2.56 demonstrate the maximum units of N and P that can be reduced from the respective treatment plants after upgrade.

2.7. Summary

A uniform allocation and a sector targeting allocation are used in implementation of BMPs based on sources of pollution and landuse within the sectors. A linear programming model was created to calculate the cost-effective reduction of N and P. The solutions generated by the optimization process are the most cost-efficient allocation of control measures throughout the North Fork watershed to achieve the desired goals based on sector targeting or uniform allocation among sectors. The difference between sector targeting and uniform allocation costs represents the cost saving from sector targeting.

CHAPTER 3: NUTRIENT CONTROL MEASURES AND COST

3.1. Introduction

This chapter focuses on data used to implement the cost-minimization model: baseline loading for the watershed, BMP effectiveness in reducing nutrients and annual cost data for implementing those BMPs. The task of determining the lowest cost for meeting the nutrient loading is determined by examining the sources of nutrients, the control practices for reducing them, and the costs associated with the use of each practice. The costs can be divided into startup costs, annual operating and maintenance costs, and land opportunity cost. The nutrient emission from agricultural sectors is calculated using GLEAMS (Knisel et al 1999). The nutrient runoff from urban sectors was calculated based on Generalized Watershed Loading Function (GWLF) (Haith et al 1987). The BMP implementation cost was estimated using numbers found in the literature.

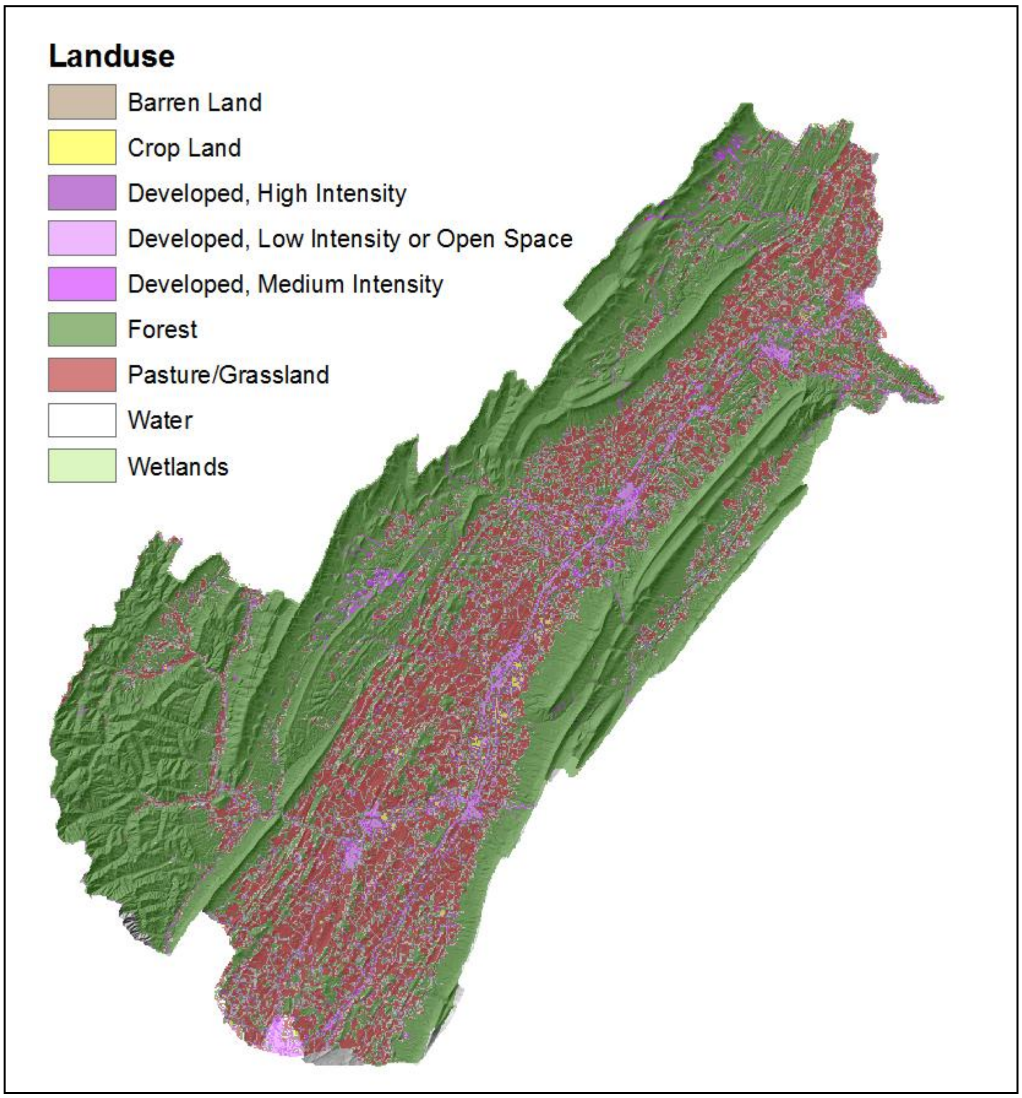
3.2 Spatial Characterization

The North Fork watershed of the Shenandoah River can further divided into 30 sub-watersheds which are unique from each other. In terms of land use, about 62 percent is forest, 28 percent is pasture, 6 percent is urban and the rest cropland, barren, wetland, and water (Table 3.1). Figure 3.1 shows landuse map of the watershed.

Table 23.1 Landuse Area of North Fork Watershed

Landuse	Acres	%
Forest	406,629	62.28
Pasture	185,796	28.46
Urban	41,050	6.29
Crop	14,399	2.21
Water	4,453	0.68
Barren	493	0.08
Wetlands	70	0.01
Total Area	**652,890**	**100.00**

Figure 3.1 Landuse Map of North Fork Watershed



The baseline loadings at the outlet of the North Fork watershed for N and P are shown in Table 3.2. The agriculture loading was obtained using GLEAMS, urban loading using GWLF and point source loading from authority at each treatment plant. The agricultural sector is composed of a total of 201,423 acres including cropland, pasture and hayland. The nutrient runoff for both N and P are similar for agricultural sector. Out of three activities, hayland is the largest source of nutrients. The urban sector is classified into low, medium and high intensity developed regions based on the area of impervious surface. However the implementation of urban BMPs is independent of this classification. The N runoff from the urban sector is larger compared to P. The nutrient loadings from wastewater treatment plants (WWTP) were obtained contacting the local authorities at each plant. In point source sector N runoff is greater than P.

Table 3.2 Nutrient Loading at the Outlet of North Fork Watershed

Landuse	Area (acre)	Nitrogen (lbs)	Phosphorus (lbs)
Agriculture			
Crops	14,602	5,834	3,678
Pasture	110,091	2,907	452
Hayland	76,730	7,586	10,140
	201,423	16,328	14,271
Urban			
Developed, Low Intensity	40,193	15,611	2,484
Developed, Medium Intensity	1,899	762	138
Developed, High Intensity	618	272	46
	42,710	16,645	2,667
Point sources	-	189,111	31,716
Total	**244,133**	**222,084**	**48,654**

3.3. Best Management Practices

Best management practices are structures, systems, and procedures that are recognized by federal and state governments to manage operations and in many cases reduce non-point source (NPS) pollution, such as nutrients, sediment, bacteria, and chemicals. Each BMP differs with the land use, climate, or terrain within the water bodies. The average cost of a BMP implemented at North Fork may vary considerably from the average cost of the same BMP implemented in another state. The selection, design and implementation of appropriate BMPs require evaluation of the resources involved, and the potential impacts on them. BMPs can either complement each other – erosion control on a site typically increases the effectiveness and reduces the size and maintenance requirements of the site's sediment controls – or undermine each other – armoring a straight stretch of channel or stream bank may increase flow velocity and channel erosion downstream (USEPA, 2009). Thus, for optimum effectiveness it is important to understand the use and characteristics of each of the BMPs. They can be categorized based on the primary nonpoint source of pollution, in this case agriculture and urban BMPs.

Each BMP has several important characteristics which are considered along with estimated startup and maintenance costs. These characteristics are (USEPA, 2009):

- ***Efficiency:*** BMP removal efficiencies for pollutant loading is an important characteristic to consider. Efficiency can be measured in terms of average percentage of nutrient reduction with the implementation of the BMP. The efficiency coupled with estimated cost is used to determine cost effectiveness.

- ***Durability:*** This refers to how the rate of effectiveness is expected to change over the lifespan of a BMP. The durability of a BMP affects the maintenance cost as equipment used for the management practice will wear out and need to be replaced.
- ***Reliability*****:** This refers to the failure rate of a BMP. The reliability of a BMP can impact the maintenance cost. BMP failure can occur due to improper selection and implementation or due to unforeseen circumstances.

Although this information is critical in implementing BMPs, it may not be available for every BMP. Along with compliance costs, transaction costs such as information and enforcement costs may also be important in the formation of costs assessments for using the BMP. Due to lack of information and difficulties associated with estimating these costs, transaction costs are not included in this study.

In this study the following costs associated with each BMP are calculated:

- ***Startup Costs***: There is a startup cost associated with implementing BMPs. Such cost typically takes into account the purchase of new equipment, installation and labor costs needed for construction. Some BMPs may require significant capital cost, trained personnel or land space.
- ***Operation and Maintenance Costs*****:** Most BMPs require operational costs such as labor and energy inputs, namely fuel and electricity. Similarly, an additional maintenance cost is required for the replacement of damaged or broken equipment. Most of the BMPs do not require daily labor inputs with the exception of wastewater treatment plants. However they all require periodic maintenance to lengthen their lifespan.

- ***Land Opportunity Costs*:** The opportunity cost is an alternative that must be forgone when choosing between two or more mutually exclusive alternatives. It is important to include any expected changes in revenue or expenses as a result of implementing a BMP. For example when implementing riparian buffers adjacent to drainage channels, streams, or river, the land is removed from agricultural production. Here the opportunity costs include income given up, which may vary depending on the productivity of the land used for buffer and other aspects of the farm operations.

3.4. BMPs Description and Cost

In the following section, BMPs used in the study are described in detail with the cost associated with them and also their efficiency to reduce nutrients. These BMPs are designed to reduce nutrients from the field due to runoff or leaching. The costs are converted to 2009 dollars using the National Agricultural Statistics Services (US department of Agriculture) Index of Prices Paid for Commodities and Services, Interest, Taxes and Wages rates. The practices selected for this study are those that are judged to be potentially cost effective and have the potential to be further extended in the watershed. The individual practices used in each sector are described below.

3.4. 1. Agricultural BMPs

Agricultural activities have been identified as a major source of water quality pollution for the Bay. Agricultural BMPs can be divided into those for crop production and for raising livestock. There are numerous BMPs available for both crop cultivation and livestock management. The following were selected for this study:

- **Continuous no-till** involves the planting, growing and harvesting of crops with minimal disturbance to the soil surface. No-till involves no seedbed preparation other than a small slit punched into the soil to place the seed (Bosch and Wolfe, 1998). This practice helps in reducing erosion and runoff by maintaining residue on the soil. No-till is the most effective practice for decreasing soil erosion, but it can also lead to formation of macropores within the soil which allow more nutrients to reach groundwater (Novotny and Olem, 1994). No-till costs or corn grain were estimated by comparing corn enterprise budgets on Productivity Group 2 soils for minimum tillage and conventional tillage (Virginia Cooperative Extension, 2007). The corn silage cost, $31.56, is the difference in silage net receipts on Productivity Group 2 soils for conventional vs. minimum-till corn silage. A detailed breakdown of costs is provided in Appendix A.

- **Vegetative Riparian Buffer** is an area of trees, shrubs or other vegetation placed adjacent to water body (drainage channels, streams or rivers) to maintain the integrity of stream channels and shorelines. Riparian buffers help improve water quality by filtering or retaining sediment particles and chemicals, such as nutrients and toxics, preventing them from reaching the waterways. Roots of buffer vegetation create breaches in the soil, promoting rainwater infiltration and groundwater recharge while moderating peak runoff flows in adjacent streams and subsequent erosion. Roots also stabilize stream banks, further preventing bank erosion. At North Fork watershed, 35 foot wide buffers were simulated for cropland, hayland and pasture using GLEAMS and a nutrient routing algorithms (Personal Communication, Dr. Mary Leigh Wolfe, March 2011). A minimum width of 35 foot buffers are required to qualify for Virginia cost-share program (Virginia Department of

Conservation and Recreation. 2011b). The buffers were amortized over a 10 year lifetime with a 7 percent interest rate. The cost of implementing cropland and hayland buffers were $181.11 and $135.08 per acre respectively. The difference in the costs was attributed due to the higher land opportunity cost for cropland. In case of pasture land, fencing was placed along with the buffer on either side of the stream in order to keep the livestock out. The fencing creates an area for buffer that is installed as an additional BMP. The total annual cost of fencing and 35 foot wide buffer is $746.45 per acre. Table 3.3, shows the estimated cost of agricultural BMPs. Further detail on buffer costs is provided in Appendix A.

Table 3.3 Estimated costs of Agricultural Best Management Practices

	Urban Best Management Practices	BMP units	Annualized Capital Construction Costs ($)	Land Opportunity Cost ($)	Annual Operating & Maintenance Costs ($)	Total Annual Costs ($)
1	*Corn silage no till- corn silage*	acre	0.00	32.00	0.00	32.00
	Winter Cover Crop	acre	0.00	0.00	55.56	55.56
2	*Buffers 35 ft wide on cropland*	acre	40.98	131.50	8.63	181.11
3	*Buffers 35 ft wide on hayland*	acre	40.98	85.47	8.63	135.08
4	*Fences + 35 ft wide Buffer on pasture*	acre				746.45
	Buffers 35 ft wide on pasture	acre	40.98	32.87	8.63	82.49
	Fencing (4 strand barbed wire)	foot	0.29	0.00	0.24	0.53

3.4. 2. Urban BMPs

Urbanization increases the incidence of non-point source nutrients in streams from impervious surfaces. In urban settings, there is a higher percentage of impervious material resulting in a lower rate of infiltration. Runoff entering water bodies is untreated and carries a heavy pollutant load such as oils, fertilizers, and metals contaminating surface water. The main sources of nutrient loadings include construction and development sites as well as residential and commercial sites and associated landscaping. Impervious materials, such as pavement, rapidly channel runoff to a storm sewer conveyance. The following urban BMPs were selected for evaluation in North Fork watershed:

- **Bioretention** systems are stormwater best management practices that use filtration to treat stormwater runoff. Trees and other vegetation are planted in shallow landscaped depressions containing a high percentage of sand and lesser amounts of clay and other organic matter (Wossink and Hunt, 2003). The runoff's velocity is reduced by passing over or through a buffer strip and subsequently distributed evenly along a pond area. Bioretention in clay soils is much more expensive than in sandy soils due to the need to replace existing clay with sand and other organic matter. Estimated construction cost (2003 dollars) in clay soil = $\$10{,}162X^{1.088}$ where X is size of the area draining into the bioretention filter in acres. Construction cost in sandy soil = $\$2{,}861X^{0.438}$. Cumulative (20-year) maintenance and operating costs for both soils are estimated by $3{,}437X^{0.152}$. The opportunity costs are estimated assuming 2.5 percent of area draining into the filter is occupied by bioretention areas (Wossink and Hunt, 2003). These filters were placed so as to filter the drainage from an area of 5 acres. The annual costs of implementing bioretention filters with sandy soils and clay soils are $1,514 and $8,508 per unit of 5-acre drainage capacity. Further detail is provided in Table 3.4 and Appendix A.

- **Urban Buffers** work in a very similar manner to those used in agriculture and the descriptions used in the agricultural section above, for vegetative riparian buffers, are applicable to their use in urban areas. The total annual cost of 35 foot wide urban buffer is $3,550 per acre. The land opportunity cost for urban areas varies depending upon areas.

The used land opportunity cost is not specific to North Fork region it is an estimation based on literature (Wossink and Hunt, 2003). Table 3.3, shows the estimated cost of urban BMPs. Further detail is provided in Table 3.4 and Appendix A.

Table 3.4 Estimated costs of Urban Best Management Practices

	Urban Best Management Practices	BMP units	Annualized Capital Construction Costs ($)	Land Opportunity Cost ($)	Annual Operating & Maintenance Costs ($)	Total Annual Costs ($)
1	*Bioretention filters Sandy soils*	5 acre	768.0	438.0	308.0	1,514.0
2	*Bioretention filters Clay soils*	5 acre	7,762.0	438.0	308.0	8,508.0
3	*Buffers 35 foot wide on urban*	acre	41.0	3,500.0	9.0	3,550.0

3.4. 3 Point Source Upgrades

Municipal and industrial wastewater treatment facilities treat wastewater to reduce the amount of nutrients that are discharged into the Bay's tributaries. Nutrient removal comes at a cost to municipal wastewater treatment facilities and their ratepayers. The Clean Water State Revolving Fund (CWSRF) is available to fund a portion of this upgrade. The wastewater treatment process is a multi-stage process to restore wastewater before it reenters a water body, is applied to the land, or is reused. The goal is to reduce or remove organic matter, solids, nutrients, disease-causing organisms, and other pollutants from wastewater. The basic wastewater treatment process has several stages (Nutrient Control Design Manual 2009):

- **Preliminary Treatment:** The wastewater is sent through a bar screen, which removes large solid objects such as rags and large debris. Leaving the bar screen, the wastewater flow is slowed down entering the grit tank. This allows sand, gravel, and other heavy material that was small enough not to be caught by the bar screen to settle to the bottom which is disposed of at a sanitary landfill or recycled.

- **Primary Treatment:** Primary treatment is the second step in wastewater treatment. It allows for the physical separation of solids and greases from the wastewater. The screened wastewater flows into a primary settling tank where it is held for several hours. This allows solid particles to settle to the bottom of the tank and oils and greases to float to the top. These settled solids, called primary sludge, are removed along with floating scum and grease and pumped to anaerobic digesters for further treatment.

- **Secondary treatment:** The CWA requires that all municipal wastewater treatment plant discharges meet a minimum of secondary treatment. In this stage a biological process is employed to remove colloidal and soluble organic matter. Grease, oil, and other floatables are also removed here. This stage is also known as biological stage. Here, the wastewater is mixed with a controlled population of bacteria and an ample supply of oxygen. The microorganisms digest the fine suspended and soluble organic materials, thereby removing them from the wastewater. There are several variations of secondary treatment such as activated sludge, lagoons and ponds and trickling filtration.

- **Tertiary Treatment:** This stage is also known as advanced treatment. EPA classifies advanced treatment as "a level of treatment that is more stringent than secondary or produces a significant reduction in conventional, non‐conventional, or toxic pollutants present in the wastewater" (U.S. Public Health Service and USEPA, 2008). Effluent filtration and nutrient removal are the most common tertiary treatment processes. Tertiary treatment may be accomplished using a variety of physical, chemical, or biological treatment processes to remove the targeted pollutants. Advanced treatment may be used to remove such things as color, metals, organic chemicals, and nutrients such as P and N.

- **Disinfection:** This is the final step to remove any disease-causing microorganism before the final effluent is released into the receiving water. The most common processes use chlorine gas or a chlorine-based disinfectant such as sodium hypochlorite at controlled level. Other disinfection options include ultraviolet light and ozone.

The eight treatment plants in North Fork watershed are mainly using three types of biological nutrient removal process: Oxidation Pond, Activated Sludge and Aerated Lagoons. Oxidation Ponds are also known as stabilization ponds or lagoons. Within an oxidation pond, heterotrophic bacteria degrade organic matter in the sewage which results in production of cellular material and minerals. The production of these materials supports the growth of algae in the oxidation pond. Growth of algal populations allows further decomposition of the organic matter by producing oxygen. Activated sludge is a process in which air or oxygen is forced into sewage liquor to develop a biological floc which reduces the organic content of the sewage, followed by separation of treated wastewater from this growth. Aerated lagoons are relatively shallow lagoons in which wastewater is added at a single point either at the edge or middle of the lagoon and the effluent is removed from another point.

These wastewater treatment systems are upgraded to enhance nutrient removal process as per the recommendation from the Virginia Department of Environmental Quality (VDEQ). The point source upgrades will result in annual average effluent concentrations of 3.0 mg/L for total N and 0.30 mg/L for total P. These upgrades will lower both N and P load. The annual costs were broken down to 1/3 debt service of the capital cost, 1/3 salary, and 1/3 power and chemicals (Personal Communication, Bob Canova, March 2010). The best estimated average life for wastewater treatment plant upgrades was 30 years. Based on this information, annual costs for each individual treatment were annualized at 3 percent for 30 years to obtain annual capital costs. Annual salary and power and chemical costs were each assumed equal to annual capital costs. The sum of capital, salary, and power and chemical costs were used to calculate cost per pound for both N and P for treatment plant upgrade. These upgrades are determined to be the most reliable and cost effective means for complying with the nutrient removal objectives for the facility. Further detail on cost and nutrient reduction estimates is provided in Tables 3.5, 3.6, and Appendix A.

Although, there are eight treatment plants in North Fork watershed regions, only five of them are upgraded. The three treatment plants that were not upgraded are: North Fork Regional WWTP was advised by DEQ that no upgrades are required; New Market is not planning to upgrade its treatment facility but will pump to Broadway WWTP; and Stoney Creek Sanitary District is not considering a potential upgrade but it is willing to participate in trading. The nutrient loading from these treatment plants are included in baseline loading (Appendix A). The remaining five treatment plants upgrade costs and plans are summarized below and in Tables 3.5 and 3.6.

- **Woodstock STP:** The existing Woodstock wastewater facility uses oxidation pond or ditch which had daily flow capacity of 0.45 million gallons. With a planned upgrade to the Membrane Bioreactor, daily flow capacity will expand to 2.0 million gallon. The estimated cost for upgrade is $26.5 million. With upgrade, the N load will be reduced from 21,671 to

4,112 lbs/year and similarly P load will be reduced from 4,582 to 411 lbs/year. The annual cost for upgrade would be $224.27 per pound for N and $944.16 per pound for P.

- **Mt Jackson STP:** The Mt Jackson STP serves the Town of Mt Jackson before discharging to the North Fork of the Shenandoah River. The existing oxidation pond or ditch will be upgraded to Sequencing Batch Reactor (SBR) which will expand daily flow from 0.15 to 0.7 million gallons. The estimated cost for upgrade is $8.4 million. With upgrade, the N load will be reduced from 7,705 to 1,828 lbs/year and similarly P load will be reduced from 267 to 137 lbs/year. The cost for upgrade would be $212.38 per pound for N and $9,606.76 per pound for P for the year.

- **George's Chicken:** George's Chicken is a poultry slaughtering and processing company located in Harrisonburg. The treatment plan is currently using Modified Bardenpho process which will be upgraded to include fine bubble aeration and sand filter. The estimated cost for the upgrade is $2 million. The upgrade will reduce P load from 2,392 to 1,270 lbs/year. N load will not be affected. This upgrade will cost $264.92 per pound for P for the year.

- **Strasburg STP:** The Strasburg STP serves Town of Strasburg. The current Oxidation Pond or Ditch will be upgraded to Membrane Bioreactor and Autothermal thermophilic aerobic digestion. This upgrade will expand daily flow from 0.84 to 2.0 million gallon. The estimated cost for upgrade is $21 million. With upgrade, the N load will be reduced from 46,189 to 7,676 lbs/year and similarly P load will be reduced from 6,143 to 768 lbs/year. This upgrade would cost $81.03 per pound for N and $580.53 per pound for P for the year.

- **Broadway WWTP:** The existing treatment plant serves the Towns of Broadway and Timberville, along with Pilgrims Pride and Cargill Foods. The current 3-stage aerated pond treatment system will be upgraded to an enhanced nutrient removal process. The estimated cost for upgrade is $12 million which will expand daily flow from 1.74 to 2.93 million gallon. With upgrade, the N load will be reduced to 7,676 from 79,004 lbs/year and similarly P load will be reduced to 1,590 from 14,746 lbs/year. This upgrade would cost $28.26 per pound for N and $135.44 per pound for P for the year.

Table 3.5 Five Treatment Plants Flows and Upgrade based on 2008 Baseline

		2008 Flows		Upgrade		% Reduced	
	Treatment Plants	Nitrogen (lbs/yr)	Phosphorus (lbs/yr)	Nitrogen (lbs/yr)	Phosphorus (lbs/yr)	Nitrogen	Phosphorus
1	Woodstock STP	21,671	4,582	4,112	411	81%	91%
2	Mt Jackson STP	7,705	267	1,828	137	76%	49%
3	Georges Chicken	16,498	2,392	16,498	1,270	0%	47%
4	Strasburg STP	46,189	6,143	7,676	768	83%	88%
5	Broadway	79,004	14,756	15,900	1,590	80%	89%

Table 3.6 Five Treatment Plants Upgrade Costs based on 2008 Baseline

	Treatment Plant	Annual Cost	Nitrogen loading		Phosphorus loading	
			Reduction w/ Upgrade (lbs/yr)	Cost per pound	Reduction w/ Upgrade (lbs/yr)	Cost per pound
1	Woodstock STP	3,937,894	17,559	224.27	4,171	944.16
2	Mt Jackson STP	1,248,238	5,877	212.38	130	9,606.76
3	George's chicken	297,200	0	NA	1,122	264.92
4	Strasburg STP	3,120,595	38,513	81.03	5,375	580.53
5	Broadway	1,783,197	63,104	28.26	13,166	135.44

3.5. Best Management Practices Efficiency

Although BMPs are the preferred method of reducing NPS pollution, there have been few efforts made to assess the combined effectiveness of long term monitoring and modeling of NPS pollution before and after BMP implementation (Easton, et al., 2008). The cost required to measure and monitor sites before and after BMP implementation makes it difficult to get accurate estimates of their nutrient reducing efficiencies. A more economical approach is to rely primarily on modeling nutrient losses (Carpentier, et al., 1998). Nutrient modeling includes spatial information to analyze nutrient transport and impact on streams. For this study, the most reliable source of BMP nutrient reduction for both N and P is the current Chesapeake Bay Program's efficiency estimates (Table 3.7) for different regions within the Chesapeake Bay watershed (Chesapeake Bay Program, 2010f). These efficiencies are used to determine the nutrient loading reduction for each BMP.

Table 3.7 BMPs Efficiency in Reducing Non-Point Source Pollution

Best Management Practices	Nitrogen	Phosphorus
Agriculture		
Buffers 35 foot wide on cropland (acre)	60%	60%
Fences + 35 foot wide Buffer on pasture (acre)	60%	60%
Buffers 35 foot wide on hayland (acre)	60%	60%
Urban		
Bioretention filters (5 acres drainage capacity) Sandy soils	80%	85%
Bioretention filters (5 acres drainage capacity) Clay soils	85%	85%
Buffers 35 foot wide on urban (acre)	60%	60%

3.6. Nutrient Loading

Nutrient loading is the total amount of N or P entering the water during a given time, such as "pounds of N per year." The reduction in nutrient loading was calculated for each BMP.

It was used to determine the total nutrient loading for the watershed with BMP implementation. Table 3.8 shows the nutrient loading reduction for all the agricultural and urban BMPs.

For example, nutrient loading reduction for pasture buffer was calculated using the total amount of nutrient passing through the pasture (pounds) calculated using the GLEAMS model and nutrient routing algorithm times pasture buffer efficiency to reduce the nutrient divided by total acres of pasture buffer (acres). The resulting unit for reduction in nutrient loading is pounds per acre.

$$\text{Pasture Buffer Reduction In Nutrient Loading} = \frac{\text{Qty of N passing through pasture} * \text{Pasture buffer efficiency}}{\text{Acres of pasture buffer}}$$

In case of no till corn silage, the efficiency was not readily available so the average gross N and P loading was estimated for no-till using GLEAMS and compared with conventional till corn silage to compute the loading reduction. For bioretention filters, the maximum number of filters that can be implemented at 5 acres drainage capacity per filter was generated using the nutrient algorithm. This number was multiplied by 5 to generate the total acres of bioretention area for both sandy soil and clay soil. This resulted in reduction for filters as per acre of bioretention area.

Table 3.8 Reduction in Nutrient Loading for both Agricultural and Urban BMPs

Best Management Practices	Nitrogen (lbs/acre)	Phosphorus (lbs/acre)
Agriculture		
No-till corn silage	0.341	0.251
Buffers 35 foot wide on cropland (acre)	9.094	5.734
Fences + 35 foot wide buffer on pasture (acre)	0.589	0.092
Buffers 35 foot wide on hayland (acre)	1.552	2.074
Urban		
Bioretention filters (5 acres drainage capacity) Sandy soils	7.237	1.232
Bioretention filters (5 acres drainage capacity) Clay soils	55.483	8.892
Buffers 35 foot wide on urban (acre)	6.632	1.063

3.7. Summary

This chapter provides an overview of the data used in the study which includes baseline loading for the watershed, BMP effectiveness at reducing the nutrients and annual cost data for implementing those BMPs. It also provides detailed description of BMPs used in agricultural, urban and point source sectors. The compliance cost calculation methods associated with these BMPs were discussed. The next chapter will describe the equations, variables and parameters within the model.

CHAPTER 4: MODEL STRUCTURE

4.1. Introduction

This chapter discusses the linear programming models that were used to create uniform allocation and sector targeting for both N and P. With the scope and complexity of this problem, the best analytical tool is linear programming (LP). Linear programming models can consistently derive a globally optimal solution, and they allow sensitivity analysis (Hillier and Lieberman, 2010). The model is intended to be a tool for evaluating the potential costs of meeting the nutrient reduction goals under various conditions. It is designed to minimize costs, while achieving the nutrient target, subject to series of constraints such as nutrient loading, land availability, and available BMPs. The economic dimension to the problem is introduced through the cost minimization process. The nutrient loading constraint is directly related to achieving nutrient reduction goals along with the sources and control practices. The land constraints and available BMPs ensure that the reduction goals are based upon conditions found within the North Fork watershed.

4.2. Model Structure

LP models are comprised of four basic parts: decision making variables, constraint equations, parameters and an objective function (Hillier and Lieberman, 2010). The decision making variables in a linear program are a set of quantities that need to be determined in order to solve the problem; i.e., in our case the problem is solved when the cost-minimizing combination of BMPs has been identified. The constraint equations are restrictions on the amount and combination of decision-making variables. The model has three constraints: a nutrient loading constraint which sets the desired amount of nutrient reduction for the watershed, a landuse constraint which limits the acreage that can be devoted to a particular land use, and BMP constraint which places restrictions on a number of particular nutrient control measures that can be implemented. The parameters used in this model are nutrient loading for each land use activity, agricultural and urban BMPs, annual cost of each BMP and per unit cost for upgrades at the treatment plants, landuse acreage and implementable BMPs. These parameter values cannot be controlled by the decision maker and don't change when the solution is implemented.

The main objective of this study is to determine potential cost savings in meeting nutrient reduction goals at the North Fork Watershed using sector targeting. In the model, the nutrient reduction goal is represented by a source of nutrients represented by land use variables, nutrient reduction practices represented by the implementation of efficient best management practices, and load constraints for both N and P. The potential cost saving is determined by the combination of cost-effective BMPs obtained under sector targeting relative to those obtained with uniform allocation of reductions among sectors.

4.2.1. Nutrient Load Constraint

The nutrient load constraint is set up to limit the total annual estimated N and P load for the entire North Fork watershed. This is achieved by including the baseline loading minus the load reductions that result from the implementation of the BMPs. The baseline loading is based on all the potential landuse activities such as cropland, pasture, hayland and urban regions and point source loads. The implemented BMPs are selected based on their effectiveness in reduction of nutrient loading. The reduction in nutrient loading for each BMP is determined by the performance efficiency as described in the previous chapter. In case of point source, per unit costs for reducing nutrient are calculated using the cost of upgrading the wastewater treatment plants and reduction in the discharge of total pound of nutrients. The maximum units of N and P that can be reduced are based on the flow of the respective treatment plants.

4.2.2. Landuse

The model structure is based on the sources of nutrient runoff - agricultural, urban and point source. The agricultural sector is classified further into cropland, pasture and hayland based on landuse activities. The urban sector is divided into low, medium and high intensity regions based on the percentage of impervious surfaces within the region. However BMP implementation is independent of this classification. The model depicts all the landuse activities within the agricultural sector that cause nutrient runoff. For every type of landuse considered in the model, there is at least one BMP for nutrient control that is taken into account.

With the exception of point source flow constraints, all the constraints of the model are either directly or indirectly based upon the available land acreage. Each landuse variable is directly limited by available land through a series of land constraints.

4.2.3. Best Management Practices

The decision making variable is comprised of the combination of BMPs. In the objective function, there is a variable for each BMP and a corresponding cost coefficient. This cost coefficient is the estimated annual cost per acre for installing and maintaining the BMP. Every time a BMP is used the model will reduce nutrient load from that landuse and increase cost in the objective function. There are limits to the extent to which a BMP can be used. This limitation is based on the efficiency of reducing nutrient loading and the number of particular BMPs that can be used on the site.

4.3. Linear Programming Model

GAMS was used to create the linear programming model. It is a mathematical programming system. A traditional tableau format was used in this study to set up the model. In order to measure the cost-effectiveness of sector targeting, costs of achieving a reduction in loadings are compared with uniform allocation in each sector. The tableaus for both N and P using uniform allocation and sector targeting are discussed in detail below.

4.3.1. Uniform Allocation

With uniform allocation, there is a constraint requiring an equal percentage in reductions per each sector. Therefore, the model is set to reduce N loading by 24 percent and P loading by 25 percent for each sector for the North Fork watershed. Tables 4.1, 4.2 and 4.3 represent uniform allocation for agricultural, urban and point sources respectively.

In Table 4.1, the objective function row contains the cost coefficients for the respective agricultural BMPs. These are the decision making variables. The remaining rows are the constraints to the objective function. The nutrient loading constraint is set up to reduce N or P loading by 24 percent from the baseline agriculture runoff. The reduction is achieved by calculating the baseline loading using the nutrient loading from each landuse activity minus load reductions that result from the implementation of the BMP. The positive numbers are the nutrient loading discharge to the watershed outlet and the negative numbers are the reduction in loading with the implementation of the respective BMPs. The next three constraints: cropland acres, pasture acres and hayland acres, sets limit to available land acreage for each landuse activities. The remaining constraints, max no till –corn silage, max cropland buffer, max pasture buffer and max hayland buffer, are the total unit of respective BMPs that can be implemented in the watershed.

Table 4.1 Nitrogen Uniform Allocation Tableau for Agricultural Sector

	Cropland	Pasture	Hayland	No till Corn Silage	Cropland Buffer	Pasture Buffer	Hayland Buffer		
Objective Function	0	0	0	$32.00	$181.11	$746.45	$135.08		
Constraints									
Total Nutrient Loading	0.40	0.03	0.10	-0.341	-9.094	-0.589	-1.552	≤	12,409.07
Cropland Acres	1							=	14,601.56
Pasture Acres		1						=	110,091.45
Hayland Acres			1					=	76,730.45
Max no till - corn silage				1				≤	14,601.56
Max Cropland buffer					1			≤	384.90
Max Pasture buffer						1		≤	2,961.95
Max Hayland buffer							1	≤	2,932.83

Similarly, Table 4.2 represents the uniform allocation for N in the urban sector. The set up for the urban sector is simple because low, medium and high intensity regions are classified based on impervious surface and are lumped into one developed region. The objective function row contains the cost coefficient for the respective urban BMPs. The remaining rows are the constraints to the objective function. The nutrient loading constraint is set up to reduce N by 24 percent from the baseline urban runoff. To achieve the reduction, the baseline loading from urban region is calculated and the load reductions that result from the implementation of the BMP are subtracted. The urban BMPs have their respective nutrient loading reduction. The next three constraints, max sandy soil bioretention, max clay soil retention and max urban buffer are the total units of respective BMPs that can be implemented in the watershed.

Table 4.2 Nitrogen Uniform Allocation Tableau for Urban Sector

	Developed Urban Regions	Bioretention filters Sandy Soil	Bioretention filters Clay Soil	Urban Buffer		
Objective Function	0	$1,514.0	$8,508.0	$3,550.0		
Constraints						
Total Nutrient Loading	0.3897	-7.237	-55.483	-6.632	≤	12,650.06
Urban Acres	1				=	42,710.04
Max Sandy Soil		1			≤	368.00
Max Clay Soil			1		≤	51.00
Max Urban buffer				1	≤	1,505.76

Table 4.3 represents uniform allocation for N for point source. The objective function row contains annual per unit cost of upgrading each of the five treatment plants. The nutrient loading constraint is set up to reduce N by 24 percent from the baseline point source runoff. The reduction is achieved by subtracting from the baseline loading from each treatment plant the reduction in loading after the upgrade. The baseline loading includes loading from all eight treatment plants whereas reduction comes from only five upgraded treatment plant. The positive sign is loading from the treatment plants and negative sign is the reduction after upgrade. The next eight constraints are baseline loading from each treatment plants. The remaining five constraints are the maximum amount of N reduced from the five treatment plant after upgrade.

Table 4.3 Nitrogen Uniform Allocation Tableau for Point Source

	Woodstock Baseline	Mt Jackson Baseline	Georges Baseline	Strasburg Baseline	Broadway Baseline	New Market Baseline	North Fork Regional Baseline	Stoney Creek Baseline	Woodstock Upgrade	Mt Jackson Upgrade	Georges Baseline	Strasburg Upgrade	Broadway Upgrade		
Objective Function	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	$224.27	$212.38	$0.00	$81.03	$28.26		
Constraints															
Total Load after upgrade	1	1	1	1	1	1	1	1	-1	-1	-1	-1	-1	≤	143,724.4
Woodstock load w/o upgrade	1													=	21,671.0
Mt Jackson load w/o upgrade		1												=	7,705.0
Georges load w/o upgrade			1											=	16,498.0
Strasburg load w/o upgrade				1										=	46,189.0
Broadway load w/o upgrade					1									=	79,004.0
New Market w/o upgrade						1								=	9,639.0
North Fork Regional w/o upgrade							1							=	624.0
Stoney Creek w/o upgrade								1						=	7,781.0
Max Woodstock Upgrade									1					≤	17,559.0
Max Mt Jackson Upgrade										1				≤	5,877.4
Max Georges Upgrade											1			≤	0.0
Max Strasburg Upgrade												1		≤	38,513.3
Max Broadway Upgrade													1	≤	63,104.3

Table 4.4, 4.5, and 4.6 represents uniform allocation for P in the agriculture, urban and point source sectors respectively. These tableaus are similar to N mentioned above. The nutrient loading constraints for each sector are set up at 25 percent reduction from the baseline runoff. In the case of agricultural and urban sector, the cost-coefficients and constraints are similar but the nutrient loading and reduction are different. For the point source sector, along with baseline nutrient loading for each the treatment plants, per unit cost for upgrade and maximum reduction in loading for each treatment plants are different.

Table 4.4 Phosphorus Uniform Allocation Tableau for Agricultural Sector

	Cropland	Pasture	Hayland	No till Corn Silage	Cropland Buffer	Pasture Buffer	Hayland Buffer		
Objective Function	0	0	0	$32.00	$181.11	$746.45	$135.08		
Constraints									
Total Nutrient Loading	0.25	0.0041	0.132	-0.251	-5.734	-0.092	-2.074	≤	10,702.91
Cropland Acres	1							=	14,601.56
Pasture Acres		1						=	110,091.45
Hayland Acres			1					=	76,730.45
Max no till - corn silage				1				≤	14,601.56
Max Cropland buffer					1			≤	384.90
Max Pasture buffer						1		≤	2,961.95
Max Hayland buffer							1	≤	2,932.83

Table 4.5 Phosphorus Uniform Allocation Tableau for Urban Sector

	Developed Urban Regions	Bioretention filters Sandy Soil	Bioretention filters Clay Soil	Urban Buffer		
Objective Function	0	$1,514	$8,508	$3,550		
Constraints						
Total Nutrient Loading	0.0625	-1.232	-8.892	-1.063	≤	2,000.59
Urban Acres	1				=	42,710.04
Max Sandy Soil		1			≤	368.00
Max Clay Soil			1		≤	51.00
Max Urban buffer				1	≤	1,505.76

Table 4.6 Phosphorus Uniform Allocation Tableau for Point Source

	Woodstock Baseline	Mt Jackson Baseline	Georges Baseline	Strasburg Baseline	Broadway Baseline	New Market Baseline	North Fork Regional Baseline	Stoney Creek Baseline	Woodstock Upgrade	Mt Jackson Upgrade	Georges Baseline	Strasburg Upgrade	Broadway Upgrade		
Objective Function	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	$944.16	$9,606.76	$264.92	$580.53	$135.44		
Constraints															
Total Load after upgrade	1	1	1	1	1	1	1	1	-1	-1	-1	-1	-1	≤	23,787.0
Woodstock load w/o upgrade	1													=	4,582.0
Mt Jackson load w/o upgrade		1												=	267.0
Georges load w/o upgrade			1											=	2,392.0
Strasburg load w/o upgrade				1										=	6,143.0
Broadway load w/o upgrade					1									=	14,756.0
New Market w/o upgrade						1								=	2,073.0
North Fork Regional w/o upgrade							1							=	68.0
Stoney Creek w/o upgrade								1						=	1,435.0
Max Woodstock Upgrade									1					≤	4,171.0
Max Mt Jackson Upgrade										1				≤	130.0
Max Georges Upgrade											1			≤	1,122.0
Max Strasburg Upgrade												1		≤	5,375.0
Max Broadway Upgrade													1	≤	13,166.0

4.3.2. Sector Targeting

With sector targeting, sectors with lower costs per unit of pollution reduction are targeted for higher reductions. Table 4.7 and 4.8 represents the tableau format for sector targeting N and P respectively. The tableau is a combination of all the three sectors described above but the load reduction is targeted across the sector.

Table 4.7 Tableau for Sector Targeting Nitrogen

	Cropland	Pasture	Hayland	Developed Urban Regions	Woodstock Baseline	Mt Jackson Baseline	Georges Baseline	Strasburg Baseline	Broadway Baseline	New Market Baseline	North Fork Regional Baseline	Stoney Creek Baseline	No till Corn Silage	Cropland Buffer	Pasture Buffer	Hayland Buffer	Bioretention Filters Sandy Soil	Bioretention Filters Clay Soil	Urban Buffer	Woodstock Upgrade	Mt Jackson Upgrade	Georges Baseline	Strasburg Upgrade	Broadway Upgrade		
Objective Function	0	0	0	0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	$32.0	$181.1	$746.5	$135.1	$1,514.0	$8,508.0	$3,550.0	$224.3	$212.4	$0.0	$81.0	$28.3		
Constraints																										
Total Nutrient Loading	0.40	0.03	0.10	0.39	1	1	1	1	1	1	1	1	-0.34	-9.09	-0.59	-1.55	-7.24	-55.48	-6.63	-1	-1	-1	-1	-1	≤	168,783.5
Cropland Acres	1																								=	14,601.6
Pasture Acres		1																							=	110,091.5
Hayland Acres			1																						=	76,730.4
Urban Acres				1																					=	42,710.0
Woodstock load w/o upgrade					1																				=	21,671.0
Mt Jackson load w/o upgrade						1																			=	7,705.0
Georges load w/o upgrade							1																		=	16,498.0
Strasburg load w/o upgrade								1																	=	46,189.0
Broadway load w/o upgrade									1																=	79,004.0
New Market load w/o upgrade										1															=	9,639.0
North Fork Regional w/o upgrade											1														=	624.0
Stoney Creek load w/o upgrade												1													=	7,781.0
Max no till - corn silage													1												≤	14,601.6
Max Cropland buffer														1											≤	384.9
Max Pasture buffer															1										≤	2,962.0
Max Hayland buffer																1									≤	2,932.8
Max Sandy Soil																	1								≤	368.0
Max Clay Soil																		1							≤	51.0
Max Urban buffer																			1						≤	1,505.8
Max Woodstock Upgrade																				1					≤	17,559.0
Max Mt Jackson Upgrade																					1				≤	5,877.4
Max Georges Upgrade																						1			≤	0.0
Max Strasburg Upgrade																							1		≤	38,513.3
Max Broadway Upgrade																								1	≤	63,104.3

Table 4.8 Tableau for Sector Targeting Phosphorus

	Cropland	Pasture	Hayland	Developed Urban Regions	Woodstock Baseline	Mt Jackson Baseline	Georges Baseline	Strasburg Baseline	Broadway Baseline	New Market Baseline	North Fork Regional Baseline	Stoney Creek Baseline	No till Corn Silage	Cropland Buffer	Pasture Buffer	Hayland Buffer	Bioretention Filters Sandy Soil	Bioretention Filters Clay Soil	Urban Buffer	Woodstock Upgrade	Mt Jackson Upgrade	Georges Baseline	Strasburg Upgrade	Broadway Upgrade		
Objective Function	0	0	0	0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	$32.0	$181.1	$746.5	$135.1	$1,514.0	$8,508.0	$3,550.0	$224.3	$212.4	$0.0	$81.0	$28.3		
Constraints																										
Total Nutrient Loading	0.25	0.004	0.13	0.06	1	1	1	1	1	1	1	1	-0.25	-5.73	-0.09	-2.07	-1.23	-8.89	-1.06	-1	-1	-1	-1	-1	≤	36,490.5
Cropland Acres	1																								=	14,601.6
Pasture Acres		1																							=	110,091.5
Hayland Acres			1																						=	76,730.4
Urban Acres				1																					=	42,710.0
Woodstock load w/o upgrade					1																				=	4,582.0
Mt Jackson load w/o upgrade						1																			=	267.0
Georges load w/o upgrade							1																		=	2,392.0
Strasburg load w/o upgrade								1																	=	6,143.0
Broadway load w/o upgrade									1																=	14,756.0
New Market load w/o upgrade										1															=	2,073.0
North Fork Regional w/o upgrade											1														=	68.0
Stoney Creek load w/o upgrade												1													=	1,435.0
Max no till - corn silage													1												≤	14,601.6
Max Cropland buffer														1											≤	384.9
Max Pasture buffer															1										≤	2,962.0
Max Hayland buffer																1									≤	2,932.8
Max Sandy Soil																	1								≤	368.0
Max Clay Soil																		1							≤	51.0
Max Urban buffer																			1						≤	1,505.8
Max Woodstock Upgrade																				1					≤	4,171.0
Max Mt Jackson Upgrade																					1				≤	130.0
Max Georges Upgrade																						1			≤	1,122.0
Max Strasburg Upgrade																							1		≤	5,375.0
Max Broadway Upgrade																								1	≤	13,166.0

4.3.3. Reducing Nitrogen and Phosphorus Simultaneously

The set up for reducing N and P simultaneously from agricultural sector using uniform allocation is similar to Table 4.1 as shown in Table 4.9. The main difference is the nutrient loading constraint. There are two constraints set up to reduce N by 24 percent and P by 25 percent from the baseline agriculture runoff. The objective function row contains the cost coefficients for the respective agricultural BMPs which are similar for both N and P.

Table 4.9 Nitrogen and Phosphorus Uniform Allocation Tableau for Agricultural Sector

	Cropland	Pasture	Hayland	No till Corn Silage	Cropland Buffer	Pasture Buffer	Hayland Buffer		
Objective Function	0	0	0	$32.00	$181.11	$746.45	$135.08		
Constraints									
Total N Nutrient Loading	0.40	0.03	0.10	-0.341	-9.094	-0.589	-1.552	≤	12,409.1
Total P Nutrient Loading	0.25	0.00	0.13	-0.251	-5.734	-0.092	-2.074	≤	10,702.9
Cropland Acres	1							=	14,601.6
Pasture Acres		1						=	110,091.5
Hayland Acres			1					=	76,730.4
Max no till - corn silage				1				≤	14,601.6
Max Cropland buffer					1			≤	384.9
Max Pasture buffer						1		≤	2,962.0
Max Hayland buffer							1	≤	2,932.8

Similarly, Table 4.10 represents uniform allocation for reducing N and P in the urban sector. The set up is similar to one presented on Table 4.2 with the only a difference being in the nutrient loading constraint. There are two separate constraints each for N and P to reduce the loading from the baseline urban runoff.

Table 4.10 Nitrogen and Phosphorus Uniform Allocation Tableau for Urban Sector

	Developed Urban Regions	Bioretention filters Sandy Soil	Bioretention filters Clay Soil	Urban Buffer		
Objective Function	0	$1,514.0	$8,508.0	$3,550.0		
Constraints						
Total N Loading	0.3897	-7.237	-55.483	-6.632	≤	12,650.1
Total P Loading	0.0625	-1.232	-8.892	-1.063	≤	2,000.6
Urban Acres	1				=	42,710.0
Max Sandy Soil		1			≤	368.0
Max Clay Soil			1		≤	51.0
Max Urban buffer				1	≤	1,505.8

Table 4.11 represents uniform allocation for both N and P for point source. The unit cost of reducing N and P load is different so the objective function row contains total cost of upgrading each of the five treatment plants. The nutrient loading constraint is set up to reduce both N and P separately from its baseline runoff. The reduction is achieved by subtracting from the baseline loading from each treatment plant the reduction in N and P loading after the upgrade. The positive sign is loading from the treatment plants and negative sign is the reduction after upgrade. The next sixteen constraints are baseline loading for N and P from each treatment plants. The remaining five constraints are the maximum amount of N and P reduced from five treatment plant after upgrade.

Table 4.12 represents the tableau format for sector targeting for simultaneously reducing N and P loading. The tableau is a combination of all the three sectors described above for combined N and P reduction but the load reduction is targeted across the sector. With sector targeting, sectors with lower costs per unit of pollution reduction are targeted for higher reductions.

Table 4.11 Nitrogen and Phosphorus Uniform Allocation Tableau for Point Source

	Woodstock Baseline	Mt Jackson Baseline	Georges Baseline	Strasburg Baseline	Broadway Baseline	New Market Baseline	North Fork Regional Baseline	Stoney Creek Baseline	Woodstock Upgrade	Mt Jackson Upgrade	Georges Baseline	Strasburg Upgrade	Broadway Upgrade		
Objective Function	$0	$0	$0	$0	$0	$0	$0	$0	$3,937,894	$1,248,238	$297,200	$3,120,595	$1,783,197		
Constraints															
Total N Load after upgrade	1	1	1	1	1	1	1	1	-17559	-5877	0	-38513	-63104	≤	143,724.4
Total P Load after upgrade	1	1	1	1	1	1	1	1	-4171	-130	-1122	-5375	-13166	≤	23,787.0
Woodstock N load w/o upgrade	1													=	21,671.0
Woodstock P load w/o upgrade	1													=	4,582.0
Mt Jackson N load w/o upgrade		1												=	7,705.0
Mt Jackson P load w/o upgrade		1												=	267.0
Georges N load w/o upgrade			1											=	16,498.0
Georges P load w/o upgrade			1											=	2,392.0
Strasburg N load w/o upgrade				1										=	46,189.0
Strasburg P load w/o upgrade				1										=	6,143.0
Broadway N load w/o upgrade					1									=	79,004.0
Broadway P load w/o upgrade					1									=	14,756.0
New Market N load w/o upgrade						1								=	9,639.0
New Market Pload w/o upgrade						1								=	2073
North Fork Regional N load w/o upgrade							1							=	624.0
North Fork Regional P load w/o upgrade							1							=	68.0
Stoney Creek N load w/o upgrade								1						=	7,781.0
Stoney Creek P load w/o upgrade								1						=	1,435.0
Max Woodstock Upgrade									1					≤	1
Max Mt Jackson Upgrade										1				≤	1
Max Georges Upgrade											1			≤	1
Max Strasburg Upgrade												1		≤	1
Max Broadway Upgrade													1	≤	1

Table 4.12 Nitrogen & Phosphorus Sector Targeting Tableau

	Cropland	Pasture	Hayland	Developed Urban Regions	No till Corn Silage	Cropland Buffer	Pasture Buffer	Hayland Buffer	Bioretention filters Sandy Soil	Bioretention filters Clay Soil	Urban Buffer	Woodstock Baseline	Mt Jackson Baseline	Georges Baseline	Strasburg Baseline	Broadway Baseline	New Market Baseline	North Fork Regional Baseline	Stoney Creek Baseline	Woodstock Upgrade	Mt Jackson Upgrade	Georges Baseline	Strasburg Upgrade	Broadway Upgrade		
Objective Function	0	0	0	0	$32.0	$181.1	$746.5	$135.1	$1,514.0	$8,508.0	$3,550.0	0	0	0	0	0	0	0	0	$3,937,894	$1,248,238	$297,200	$3,120,595	$1,783,197		
Constraints																										
Total N Load after upgrade	0.40	0.03	0.10	0.39	-0.34	-9.09	-0.59	-1.55	-7.24	-55.48	-6.63	1	1	1	1	1	1	1	1	-17559	-5877	0	-38513	-63104	≤	168,783.5
Total P Load after upgrade	0.25	0.00	0.13	0.06	-0.25	-5.73	-0.09	-2.07	-1.23	-8.89	-1.06	1	1	1	1	1	1	1	1	-4171	-130	-1122	-5375	-13166	≤	36,490.5
Cropland Acres	1																								=	14,601.6
Pasture Acres		1																							=	110,091.5
Hayland Acres			1																						=	76,730.4
Urban Acres				1																					=	42,710.0
Max no till - corn silage					1																				≤	14,601.6
Max Cropland buffer						1																			≤	384.9
Max Pasture buffer							1																		≤	2,962.0
Max Hayland buffer								1																	≤	2,932.8
Max Sandy Soil									1																≤	368.0
Max Clay Soil										1															≤	51.0
Max Urban buffer											1														≤	1,505.8
Woodstock N load w/o upgrade												1													=	21,671.0
Woodstock P load w/o upgrade																									=	4,582.0
Mt Jackson N load w/o upgrade													1												=	7,705.0
Mt Jackson P load w/o upgrade													1												=	267.0
Georges N load w/o upgrade														1											=	16,498.0
Georges P load w/o upgrade														1											=	2,392.0
Strasburg N load w/o upgrade															1										=	46,189.0
Strasburg P load w/o upgrade															1										=	6,143.0
Broadway N load w/o upgrade																1									=	79,004.0
Broadway P load w/o upgrade																1									=	14,756.0
New Market N load w/o upgrade																	1								=	9,639.0
New Market Pload w/o upgrade																	1								=	2,073.0
North Fork Regional N load w/o upgrade																		1							=	624.0
North Fork Regional P load w/o upgrade																		1	1						=	68.0
Stoney Creek N load w/o upgrade																			1						=	7,781.0
Stoney Creek P load w/o upgrade																									=	1,435.0
Max Woodstock Upgrade																				1					≤	1
Max Mt Jackson Upgrade																					1				≤	1
Max Georges Upgrade																						1			≤	1
Max Strasburg Upgrade																							1		≤	1
Max Broadway Upgrade																								1	≤	1

4.4. Summary

This chapter gives the general overview of the structure of the model. The model is a linear programming optimization model. The tableau format for both N and P using uniform allocation and sector targeting were discussed in detail. The objective function is the mathematical representation of the cost minimizing objective. It is subject to three constraints nutrient loading, acreage of landuse and number of particular nutrient control measures that can be implemented. The following chapter discusses the results from this model.

CHAPTER 5: RESULTS AND ANALYSIS

5.1. Introduction

This chapter discusses the optimal solutions from GAMS for each sector using uniform allocation and sector targeting across the sector for both N and P separately and N and P simultaneously. The outcome is used to meet the research objective to achieve nutrient reduction at lower cost. For uniform allocation, the least cost combination of BMPs was determined for each sector: agricultural, urban, and upgrades for treatment plants. With sector targeting, the least cost combination of BMPs was determined across the sectors to achieve the nutrient reduction. The optimal solution for each sector using uniform allocation and sector targeting was compared for both N and P. Sensitivity analyses were carried out to see the variation in the optimal solution.

5.2. Nitrogen

The model is set to reduce nitrogen loading by 24 percent from the baseline runoff for the North Fork watershed. Two different approaches were used to achieve this reduction: uniform allocation and sector targeting.

5.2.1. Uniform Allocation

With uniform allocation there is a constant reduction required for each sector. From the agricultural sector, the total N baseline loading at the outlet of the North Fork watershed is 16,328 pounds. Total loading with the 24 percent reduction is 12,409 pounds. Agricultural BMPs used for this study are no-till corn silage, cropland buffer, pasture buffer and hayland buffer. Table 5.1 contains the annual per unit cost of each BMP and the numbers of BMPs to achieve the reduction in N loading as obtained from GAMS. The optimal solution was achieved at $129,856 with a 24 percent reduction in N loading. This reduction was achieved with 445 acres of hayland buffer and 385 acres of cropland buffer. Hayland is the main contributor of N loading with 46 percent. The cropland only contributes 36 percent of N loading. The cropland buffer offers the highest reductions in N loading per acre as a result all the cropland buffers were implemented.

Table 5.1 Optimal Solution for Nitrogen Reduction in the Agricultural Sector

	No till Corn Silage	Cropland Buffer	Pasture Buffer	Hayland Buffer	Optimal Solution
Objective Function Coefficients	$32.0	$181.1	$746.5	$135.1	$129,856.6
Objective Function Variable	-	384.9	-	445.3	

The total baseline N loading from the urban sector is 16,645 pounds. Urban BMPs used for this study are bioretention filters using sandy soil and clay soil and urban buffer. The optimal solution was achieved at $671,251 with a 24 percent reduction in N loading from urban sector to 12,650 pounds. This reduction was achieved with 157 bioretention filters using sandy soil and 51 bioretention filters using clay soil at 5 acres drainage capacity. Bioretention filters using sandy soil were the cheapest alternative. Bioretention filters using clay soil offers the highest reductions in N loading per acre. Table 5.2 represents the annual per unit cost of each BMP and the combination of urban BMPs used to achieve the N loading reduction from GAMS.

Table 5.2 Optimal Solution for Nitrogen Reduction in the Urban Sector

	Bioretention filters Sandy Soil	Bioretention filters Clay Soil	Urban Buffer	Optimal Solution
Objective Function Coefficients	$1,514.0	$8,508.0	$3,550.0	$671,251.1
Objective Function Variable	156.8	51.0	-	

The total N loading from the point source at the outlet of the watershed is 189,111 pounds for the baseline. The five treatment plants that are required to upgrade as advised by VDEQ are Woodstock, Mt. Jackson, George's Chicken, Strasburg and Broadway. Broadway represents 42 percent of the total N loading from point source. Table 5.3 contains the cost of upgrade for per unit of N at five treatment plants and levels of reduction per plant obtained from GAMS. The optimal solution was achieved at $1,282,625 with a 24 percent reduction in N loading for point source. This reduction came from Broadway only with 45,387 pounds of N as the cost of upgrade was lowest.

Table 5.3 Optimal Solution for Nitrogen Reduction from Point Source

	Woodstock Upgrade	Mt Jackson Upgrade	Georges Baseline	Strasburg Upgrade	Broadway Upgrade	Optimal Solution
Objective Function Coefficients	$224.3	$212.4	$0.0	$81.0	$28.3	$1,282,625.3
Objective Function Variable	-	-	-	-	45,386.6	

5.2.2. Sector Targeting

With sector targeting, sectors with lower costs per unit of pollution reduction are targeted for higher reductions. The total baseline loading for N at the outlet of the watershed is 204,040 pounds. Table 5.4 shows the annual per unit cost of each BMP and per unit cost of upgrade at five treatment plants and levels of reductions per each point or non-point source obtained from GAMS. The optimal solution was achieved at $1,483,892 with a 24 percent reduction in N loading. This reduction was achieved with 385 acres of cropland buffer and 50,042 pounds of N reduction from the Broadway treatment plant. The point source contributes 85 percent of N loading reduction with Broadway representing 42 percent of the loading from point source. The cost of upgrading is lowest at Broadway as compared to other the four treatment plants which explains why most of the reduction is seen here. Cropland buffers are effective in reducing N loading per acre as a result all the cropland buffers were implemented. This led to total reduction of 3,258 pounds of N with cropland buffers.

Table 5.4 Optimal Solution for Nitrogen Using Sector Targeting

	No till Corn Silage	Cropland Buffer	Pasture Buffer	Hayland Buffer	Bioretention Filters Sandy Soil	Bioretention Filters Clay Soil	Urban Buffer	Woodstock Upgrade	Mt Jackson Upgrade	Georges Baseline	Strasburg Upgrade	Broadway Upgrade	Optimal Solution
Objective Function Coefficients	$32	$181	$746	$135	$1,514	$8,508	$3,550	$224	$212	$0	$81	$28	$1,483,892
Objective Function Variable	-	385	-	-	-	-	-	-	-	-	-	50,042	

5.2.3. Uniform Allocation vs. Sector Targeting

The comparison between the costs of achieving a reduction in N loadings with uniform allocation helps to quantify the cost-effectiveness of sector targeting (Table 5.5). The 24 percent reduction in N loading was achieved at total cost of $2,083,733 for uniform allocation compared to $1,483,883 from sector targeting. This highlights sector targeting as the cost effective approach which resulted in 29 percent reduction in cost compared to uniform allocation. Most of the reduction for both approaches came from point source as it is the main contributor of N loading and has lowest costs per unit of N reduction. For uniform allocation, the dollar per pound for point source was lowest whereas in the urban sector it was highest. Urban BMPs are expensive compared to other sectors. For sector targeting, most of the reduction also came from point source but there was no reduction from the urban sector. The overall average dollar per pound cost for uniform allocation is $39 compared to $28 for sector targeting.

Table 5.5 Uniform Allocation vs. Sector Targeting for Nitrogen

Sectors	Uniform Allocation			Sector Targeting		
	Reduction (lb)	Cost ($)	$/lbs	Reduction (lb)	Cost ($)	$/lbs
Agricultural	3,918.7	129,856.6	33.1	3,258.2	69,802.9	21.4
Urban	3,994.8	671,251.1	168.0	-	-	-
Point	45,386.6	1,282,625.3	28.3	50,041.9	1,414,080.1	28.3
Total	53,300.0	2,083,733.0	39.1	53,300.0	1,483,883.0	27.8

5.3. Phosphorus

The model is set to reduce P loading by 25 percent from the baseline runoff. The total P loading at the outlet of the North Fork watershed for the baseline is 45,078 pounds. The optimal solutions from GAMS for both uniform allocation and sector targeting are discussed below:

5.3.1. Uniform Allocation

With uniform allocation there is a constant constraint of equal percentage reductions per each sector. The baseline total P loading from the agricultural sector at the outlet of the North Fork watershed is 14,271 pounds. Table 5.6 represents the annual per unit cost of each agricultural BMP and selected number of BMPs to achieve the nutrient reduction from GAMS. The optimal solution was achieved at $146,905 with a 25 percent reduction in P loading. This reduction was achieved with 572 acres of hayland buffer and 385 acres of cropland buffer. Hayland contributes almost 71 percent of the P loading from agricultural activities and as a result most of the reduction came from there. The cropland buffer offers the highest reductions in P loading per acre from all agricultural buffers and, as a result, all the cropland buffers were implemented.

Table 5.6 Optimal Solution for Phosphorus Reduction in the Agricultural Sector

	No till Corn Silage	Cropland Buffer	Pasture Buffer	Hayland Buffer	Optimal Solution
Objective Function Coefficients	$32.0	$181.1	$746.5	$135.1	$146,905.3
Objective Function Variable	-	384.9	-	571.5	

Table 5.7 represents the annual per unit cost of each BMP and combination of BMPs to achieve levels of nutrient reduction obtained from GAMS. The total P loading from the urban sector is 2,667 pounds. The optimal solution was achieved at $698,484 with a 25 percent reduction in P loading from urban sector. This reduction was achieved with 175 bioretention filters using sandy soil and 51 bioretention filters using clay soil at 5 acres drainage capacity. Bioretention filters using sandy soil are the cheapest alternative. Bioretention filters using clay soil offer the highest reductions in P loading and, as a result, all the filters using clay soil were implemented.

The total cost of reducing N loading from the urban sector is only $671,251 compared to cost of P loading at $698,484. This difference in cost is significant given that the total amount of N loading reduced from urban sector to achieve 24 percent reduction is 3,994 pounds compared to a reduction in P loading of 640 pounds. This result indicates that the urban BMPs are not cost-effective in reducing P loading.

Table 5.7 Optimal Solution for Phosphorus Reduction in the Urban Sector

	Bioretention filters Sandy Soil	Bioretention filters Clay Soil	Urban Buffer	Optimal Solution
Objective Function Coefficients	$1,514.0	$8,508.0	$3,550.0	$698,483.8
Objective Function Variable	174.8	51.0	-	

The total P loading from the point source at the outlet of the watershed is 31,716 pounds. The unit costs of upgrades at five treatment plants are considerably higher for P compared to N. Broadway represents 47 percent of the total P loading from point source. Table 5.8 contains the cost of upgrade per unit of P at five treatment plants and levels of reduction per plant obtained from GAMS. The optimal solution was achieved at $1,073,904 with a 25 percent reduction in P loading for point source. This reduction came from only Broadway with 7,929 pounds of P as the cost of upgrade was lowest there.

Table 5.8 Optimal Solution for Phosphorus Reduction in Point Source

	Woodstock Upgrade	Mt Jackson Upgrade	Georges Baseline	Strasburg Upgrade	Broadway Upgrade	Optimal Solution
Objective Function Coefficients	$944.2	$9,606.8	$264.9	$580.5	$135.4	$1,073,903.8
Objective Function Variable	-	-	-	-	7,929.0	

5.3.2. Sector Targeting

Sector targeting minimizes the total cost by targeting the sectors with lower costs per unit of pollution reduction to get higher reductions. The total P loading at the outlet of the watershed is 48,654 pounds. The optimal solution was achieved at $937,915 with a 25 percent reduction in P loading. This reduction was achieved with 14,602 acres of no-till corn silage, 385 acres of cropland buffer, 2,933 acres of hayland buffer and 35 pounds of reduction came from

Broadway. Although the point source contributes 65 percent of P loading, most of the reductions came only from the agricultural sector. Implementing agricultural BMPs is the cost effective way to achieve the desired reduction in P loading. Table 5.9 shows the annual cost of each BMP and per unit cost of upgrade at each treatment plant and decision making variables obtained using sector targeting from GAMS.

Table 5.9 Optimal Solution for Phosphorus Using Sector Targeting

	No till Corn Silage	Cropland Buffer	Pasture Buffer	Hayland Buffer	Bioretention Filters Sandy Soil	Bioretention Filters Clay Soil	Urban Buffer	Woodstock Upgrade	Mt Jackson Upgrade	Georges Baseline	Strasburg Upgrade	Broadway Upgrade	Optimal Solution
Objective Function Coefficients	$32.0	$181.1	$746.5	$135.1	$1,514.0	$8,508.0	$3,550.0	$944.2	$9,606.8	$264.9	$580.5	$135.4	$937,914.7
Objective Function Variable	14,601.6	384.9	-	2,932.8	-	-	-	-	-	-	-	35.4	

5.3.3. Uniform Allocation vs. Sector Targeting

Comparing the costs of achieving reduction in P loadings with uniform allocation shows sector targeting is the more cost-effective approach (Table 5.10). The 25 percent reduction in P loading was achieved at total cost of $937,915 compared to $1,919,293 using uniform allocation. The sector targeting resulted in 51 percent reduction in cost compared to uniform allocation.

Most of the reduction for uniform allocation came from point source as it is the main contributor of P loading. For uniform allocation, the dollar per pound for the agricultural sector was lowest and urban sector was the highest. The cost of reducing P loading from urban sectors is expensive compared to other sectors. For sector targeting, the reduction only came from the agricultural sector. The overall average dollar per pound for uniform allocation is $160 compared to $78 for sector targeting.

Table 5.10 Uniform Allocation vs. Sector Targeting for Phosphorus

Sectors	Uniform Allocation			Sector Targeting		
	Reduction (lb)	Cost ($)	$/lbs	Reduction (lb)	Cost ($)	$/lbs
Agricultural	3,424.9	146,905.0	42.9	11,958.8	933,125.8	78.0
Urban	640.2	698,483.8	1,091.1	-	-	-
Point	7,929.0	1,073,903.8	135.4	35.4	4,788.9	-
Total	11,994.1	1,919,292.6	160.0	11,994.1	937,914.7	78.0

5.4. Nitrogen and Phosphorus Combined

The model is set to reduce N and P loading by 24 and 25 percent simultaneously from the baseline loading. This solution shows both stakeholders and policymakers how an implementation of control measure reduces both N and P loading. The optimal solutions from GAMS for both uniform allocation and sector targeting are discussed below:

5.4.1. Uniform Allocation

Table 5.11 represents the annual per unit cost of each agricultural BMP and combination of BMPs to achieve the nutrient reduction using GAMS. The optimal solution was achieved at $146,905 with a 24 percent reduction in N and 25 percent reduction in P loading. This reduction was achieved with 385 acres of cropland buffer and 572 acres of hayland buffer. The achieved optimal solution is similar to uniform allocation for P in Table 5.6. The shadow price of N loading constraint was zero which means by the time 25 percent reduction in P loading was achieved the N loading was already attained.

Hayland is the main contributor of both N and P loading at 46 and 71 percent respectively and, as a result, most of the reduction came from there. Compared to all types of agricultural buffers, the cropland buffer offers the highest reductions in both N and P loading per acre and, as a result, all the cropland buffers were implemented.

Table 5.11 Optimal Solution for Phosphorus and Nitrogen in the Agricultural Sector

	No till Corn Silage	Cropland Buffer	Pasture Buffer	Hayland Buffer	Optimal Solution
Objective Function Coefficients	$32.0	$181.1	$746.5	$135.1	$146,905.3
Objective Function Variable	-	384.9	-	571.5	

Table 5.12 represents the annual per unit cost of each urban BMP and selected BMPs to achieve levels of nutrient reduction using GAMS. The optimal solution was achieved at $698,484 with a 25 percent reduction in P loading and 24 percent reduction in N loading from urban sector. This reduction was achieved with 175 bioretention filters using sandy soil and 51 bioretention filters using clay soil at 5 acres drainage capacity. As discussed before, urban BMPs are least cost-effective in reducing P loading. The achieved optimal solution is similar to uniform allocation for P in Table 5.7. As in the previous case, the shadow price of N loading constraint was zero which means by the time 25 percent reduction in P loading was achieved the N loading was already attained.

Table 5.12 Optimal Solution for Phosphorus and Nitrogen in the Urban Sector

	Bioretention filters Sandy Soil	Bioretention filters Clay Soil	Urban Buffer	Optimal Solution
Objective Function Coefficients	$1,514.0	$8,508.0	$3,550.0	$698,483.8
Objective Function Variable	174.8	51.0	-	

The total N and P loadings from the point source at the outlet of the watershed are 189,111 and 31,716 pounds, respectively. Since the unit cost of upgrade at five treatment plants are different for both N and P, total cost of upgrade for each plant was used. Table 5.13 contains the overall upgrade cost for each treatment plant and decimal fraction of upgrade per plant in the final solution. The optimal solution was achieved at $1,282,531 with a 24 and 25 percent reduction in N and P loading respectively. This reduction can be achieved with 72 percent of the upgrade cost from Broadway. This reduces 45,387 pounds of N and 7,929 pounds of P from Broadway.

Table 5.13 Optimal Solution for Phosphorus & Nitrogen in the Point Source Sector

	Woodstock Upgrade	Mt Jackson Upgrade	Georges Baseline	Strasburg Upgrade	Broadway Upgrade	Optimal Solution
Objective Function Coefficients	$3,937,894.3	$1,248,238.2	$297,199.6	$3,120,595.5	$1,783,197.4	$1,282,531.4
Objective Function Variable	-	-	-	-	0.72	

5.4.2. Sector Targeting

The total baseline loadings for N and P are 222,084 pounds and 48,654 pounds, respectively. The optimal solution was achieved at $1,483,788 with a 24 percent and 25 percent reduction in N and P loading, respectively. This reduction was achieved with 385 acres of cropland buffer and with 79 percent of the upgrade cost from Broadway. The cost of upgrading is lowest at Broadway as compared to the other four treatment plants. Cropland buffer offers the highest reductions in N and P loading. Table 5.14 shows the annual per unit cost of each BMP and overall cost of upgrade at each treatment plant, and selected BMPs and percentage upgrades obtained using sector targeting from GAMS. The achieved optimal solution is similar to sector targeting for N in Table 5.4. The shadow price of P loading constraint was zero so by the time 24 percent reduction in N loading was achieved the P loading was already attained.

Table 5.14 Optimal Solution for Phosphorus & Nitrogen Using Sector Targeting

	No till Corn Silage	Cropland Buffer	Pasture Buffer	Hayland Buffer	Bioretention Filters Sandy Soil	Bioretention Filters Clay Soil	Urban Buffer	Woodstock Upgrade	Mt Jackson Upgrade	Georges Baseline	Strasburg Upgrade	Broadway Upgrade	Optimal Solution
Objective Function Coefficients	$32	$181	$746	$135	$1,514	$8,508	$3,550	$3,937,894	$1,248,238	$297,200	$3,120,595	$1,783,197	$1,483,788
Objective Function Variable	-	385	-	-	-	-	-	-	-	-	-	0.793	

5.4.3. Uniform Allocation vs. Sector Targeting

The total nutrient reduction of 65,295 pounds was achieved at total cost of $2,127,921 for uniform allocation compared to $1,483,788 from sector targeting (Table 5.15). Sector targeting is the cost effective approach resulting in a 30 percent reduction in cost compared to uniform allocation. Most of the reduction for both approaches came from point source as it is the main contributor of both N and P loading. The overall average dollar per pound cost for uniform allocation is $33 compared to $23 for sector targeting. For uniform allocation, the dollar per pound for agricultural sector was lowest whereas in the urban sector it was highest. For sector targeting, most of the reduction also came from point source but there was no reduction from the urban sector. The reduction in costs is similar to sector targeting for N as represented in Table 5.4. The shadow price for the loading constraint of P was zero, which meant that at the level where a 24 percent reduction in N was achieved, the P loading was already attained.

Table 5.15 Uniform Allocation vs. Sector Targeting for both Nitrogen and Phosphorus[1]

Sectors	Uniform Allocation			Sector Targeting		
	Reduction (lb)	Cost ($)	$/lbs	Reduction (lb)	Cost ($)	$/lbs
Agricultural	7,343.6	146,905.3	20.0	5,707.4	69,708.7	12.2
Urban	4,634.9	698,483.8	150.7	-	-	-
Point	53,316.0	1,282,531.4	24.1	59,587.1	1,414,079.4	23.7
Total	65,294.5	2,127,920.5	32.6	65,294.5	1,483,788.1	22.7

5.5. Sensitivity Analysis

Sensitivity analysis provides flexibility to the model. It helps to determine how "sensitive" the optimal solution is with different scenarios. This provides policy makers with "what if" options. For this study sewage treatment plant baseline flow in 2008 was replaced with discharge based on design capacity flow. This sensitivity analysis asks the question "What if the baseline scenario involved the communities expanding their sewage emissions to the levels indicated by the design flow, but without any upgrade in nutrient removal capacity?" Then the upgrade would involve reducing nutrients relative to this baseline. This shows the difference in the cost of upgrading treatment plants and amount of wastewater that could be discharged based on the design flow in comparison to 2008 baseline flow.

5.5.1. Discharge Based on Design Capacity Flows

Design flow is the amount of wastewater that could be discharged from a treatment plant as opposed to what was pumped in 2008. Table 5.16 shows the new baseline loading based on design flow along with reduction in loading with upgrade for the five treatment plants. The new

[1] Both P and N are added together when calculating the nutrient reduction

baseline loading does not include loading based on design flow from three treatment plants: North Fork Regional WWTP, New and Stoney Creek Sanitary District. The design flow for these treatment plants cannot be calculated due to limited information. Table 5.17 shows the upgrade cost per pound of N and P. Compared to the scenario where the baseline flow was based on 2008, design capacity flow has a higher nutrient loading prior to the upgrade and consequently a larger reduction from the upgrade. Consequently the upgrade cost per pound at each treatment plant is lower. A detailed breakdown of discharge based on design capacity flow and costs is provided in Appendix A.

Table 5.16 Treatment Plant Loadings with Design Cap Flows and with Treatment Upgrade

Treatment Plants	Design cap flows		Upgrade		% Reduced	
	Nitrogen (lbs/yr)	Phosphorus (lbs/yr)	Nitrogen (lbs/yr)	Phosphorus (lbs/yr)	Nitrogen	Phosphorus
1 Woodstock STP	96,316	20,364	18,276	1,828	81%	91%
2 Mt Jackson STP	35,957	1,246	8,529	640	76%	49%
3 George's chicken	20,177	2,925	20,177	1,553	0%	47%
4 Strasburg STP	109,974	14,626	18,276	1,828	83%	88%
5 Broadway	133,035	24,848	26,774	2,677	80%	89%
Total Nutrient Loading	395,459	64,010	92,031	8,526	77%	87%

Table 5.17 Treatment Plants Upgrade Cost Based on Design Capacity Flows

Treatment Plant	Annual Cost	Nitrogen loading		Phosphorus loading	
		Reduction w/ Upgrade (lbs/yr)	Cost per pound	Reduction w/ Upgrade (lbs/yr)	Cost per pound
1 Woodstock STP	3,937,894	78,040	50.46	18,537	212.44
2 Mt Jackson STP	1,248,238	27,428	45.51	606	2,058.59
3 George's chicken	297,200	0	NA	1,372	216.61
4 Strasburg STP	3,120,595	91,698	34.03	12,799	243.82
5 Broadway	1,783,197	106,262	16.78	22,170	80.43

Table 5.18 shows the total loading at the outlet of the North Fork watershed for N and P with design capacity flow. The N loading from five treatment plants increases by 131 percent from 171,067 pounds to 395,459 pounds with design cap flow. Similarly, P loading from five treatment plants increases by 127 percent to 64,010 pounds from 28,140 pounds. The N loading based on design capacity from point source represents 92% of the total loading. Similarly, P loading from point source represents 79% of the total P loading.

Table 5.18 Nutrient Loading at the Outlet with Design Capacity Flows

Landuse	Area (acre)	Nitrogen (lbs)	Phosphorus (lbs)
Agriculture			
Crops	14,602	5,834	3,678
Pasture	110,091	2,907	452
Hayland	76,730	7,586	10,140
	201,423	16,328	14,271
Urban			
Developed, Low Intensity	40,193	15,611	2,484
Developed, Medium Intensity	1,899	762	138
Developed, High Intensity	618	272	46
	42,710	16,645	2,667
Point sources	-	395,459	64,010
Total	**244,133**	**428,431**	**80,948**

Tables 5.19 and 5.20 represent the tableau format used to set up uniform allocation for N and P for point source based on design capacity flow. The objective function row contains per unit cost of upgrading each of the five treatment plants. The nutrient loading constraint is set up to reduce N by 24 percent and P by 25 percent from the baseline runoff. The reduction in nutrient loading is achieved by subtracting the baseline loading from each treatment plant, with the reduction in loading, after the upgrade. The positive sign indicates loading from the treatment plants and negative signs are the possible reductions after upgrade. The next five constraints are

the baseline loadings from each treatment plant. The remaining five constraints are the maximum amount of N and P reduced from each treatment plant after the upgrade. The tableau format remains same as the one used for the 2008 baseline flow but per unit cost of upgrade (objective function coefficients) is cheaper, initial loading (see plant loads without upgrade in Table 5.19 and 5.20) and potential loading reductions are higher (see plant load upgrades in Table 5.19 and 5.20) resulting in higher reduction compared to the 2008 baseline for both N and P.

Table 5.19 Nitrogen Uniform Allocation Tableau Based on Design Capacity Flows

	Woodstock Baseline	Mt Jackson Baseline	Georges Baseline	Strasburg Baseline	Broadway Baseline	Woodstock Upgrade	Mt Jackson Upgrade	Georges Baseline	Strasburg Upgrade	Broadway Upgrade		
Objective Function	$0.00	$0.00	$0.00	$0.00	$0.00	$50.46	$45.51	$0.00	$34.03	$16.78		
Constraints												
Total Load after upgrade	1	1	1	1	1	-1	-1	-1	-1	-1	≤	300,549
Woodstock load w/o upgrade	1										=	96,316
Mt Jackson load w/o upgrade		1									=	35,957
Georges load w/o upgrade			1								=	20,177
Strasburg load w/o upgrade				1							=	109,974
Broadway load w/o upgrade					1						=	133,035
Max Woodstock upgrade						1					≤	78,040
Max Mt Jackson upgrade							1				≤	27,428
Max Georges upgrade								1			≤	0
Max Strasburg upgrade									1		≤	91,698
Max Broadway upgrade										1	≤	106,261

Table 5.20 Phosphorus Uniform Allocation Tableau Based on Design Capacity Flows

	Woodstock Baseline	Mt Jackson Baseline	Georges Baseline	Strasburg Baseline	Broadway Baseline	Woodstock Upgrade	Mt Jackson Upgrade	Georges Baseline	Strasburg Upgrade	Broadway Upgrade		
Objective Function	$0.00	$0.00	$0.00	$0.00	$0.00	$212.44	$2,058.59	$216.61	$243.82	$80.43		
Constraints												
Total Load after upgrade	1	1	1	1	1	-1	-1	-1	-1	-1	≤	48,007
Woodstock load w/o upgrade	1										=	20,364
Mt Jackson load w/o upgrade		1									=	1,246
Georges load w/o upgrade			1								=	2,925
Strasburg load w/o upgrade				1							=	14,626
Broadway load w/o upgrade					1						=	24,848
Max Woodstock upgrade						1					≤	18,536
Max Mt Jackson upgrade							1				≤	606
Max Georges upgrade								1			≤	1,372
Max Strasburg upgrade									1		≤	12,798
Max Broadway upgrade										1	≤	22,171

Table 5.21 represents the tableau format for sector targeting for simultaneously reducing N and P loading with point source loading based on design capacity flows. This tableau is similar to table 4.12 with combination of all the three sectors. The only difference is the 2008 baseline loading for N and P from treatment plants are replaced with loading based on design capacity flows.

Table 5.21 Nitrogen & Phosphorus Sector Targeting Based on Design Capacity Flows

	Cropland	Pasture	Hayland	Developed Urban Regions	No till Corn Silage	Cropland Buffer	Pasture Buffer	Hayland Buffer	Bioretention filters Sandy Soil	Bioretention filters Clay Soil	Urban Buffer	Woodstock Baseline	Mt Jackson Baseline	Georges Baseline	Strasburg Baseline	Broadway Baseline	Woodstock Upgrade	Mt Jackson Upgrade	Georges Upgrade	Strasburg Upgrade	Broadway Upgrade		
Objective Function	0	0	0	0	$32.0	$181.1	$746.5	$135.1	$1,514.0	$8,508.0	$3,550.0	0	0	0	0	0	$3,937,894	$1,248,238	$297,200	$3,120,595	$1,783,197		
Constraints																							
Total N Load after upgrade	0.40	0.03	0.10	0.39	-0.34	-9.09	-0.59	-1.55	-7.24	-55.48	-6.63	1	1	1	1	1	-17559	-5877	0	-38513	-63104	≤	155,070.0
Total P Load after upgrade	0.25	0.00	0.13	0.06	-0.25	-5.73	-0.09	-2.07	-1.23	-8.89	-1.06	1	1	1	1	1	-4171	-130	-1122	-5375	-13166	≤	34,259.3
Cropland Acres	1																					=	14,601.6
Pasture Acres		1																				=	110,091.5
Hayland Acres			1																			=	76,730.4
Urban Acres				1																		=	42,710.0
Max no till - corn silage					1																	≤	14,601.6
Max Cropland buffer						1																≤	384.9
Max Pasture buffer							1															≤	2,962.0
Max Hayland buffer								1														≤	2,932.8
Max Sandy Soil									1													≤	368.0
Max Clay Soil										1												≤	51.0
Max Urban buffer											1											≤	1,505.8
Woodstock N load w/o upgrade												1										=	21,671.0
Woodstock P load w/o upgrade												1											4,582.0
Mt Jackson N load w/o upgrade													1									=	4,582.0
Mt Jackson P load w/o upgrade													1									=	7,705.0
Georges N load w/o upgrade														1								=	267.0
Georges P load w/o upgrade														1								=	16,498.0
Strasburg N load w/o upgrade															1							=	2,392.0
Strasburg P load w/o upgrade															1							=	46,189.0
Broadway N load w/o upgrade																1						=	6,143.0
Broadway P load w/o upgrade																1						=	79,004.0
Max Woodstock Upgrade																	1					≤	1
Max Mt Jackson Upgrade																		1				≤	1
Max Georges Upgrade																			1			≤	1
Max Strasburg Upgrade																				1		≤	1
Max Broadway Upgrade																					1	≤	1

Table 5.22 contains the cost of upgrade for per unit of N at five treatment plant based on design capacity flow and decision making variables using uniform allocation approach from GAMS. The optimal solution using a uniform allocation was $1,592,593 with a 24 percent reduction in N loading for point source. There was reduction of 94,910 of N pounds from Broadway because the cost of upgrade was lowest. Table 5.23 shows the cost of upgrade per unit of N at five treatment plant based on the 2008 baseline flow and GAMS output using uniform allocation. The optimal solution based in design flow costs an additional $432,348 compared to the scenario where 2008 loadings were used as the baseline. Although per unit cost of upgrade is cheaper compared to the 2008 baseline, the amount of N reduced is higher. The reduction of 94,910 pounds of N using design capacity flow compared to 41,056 pounds reduction using 2008 baseline flow.

Table 5.22 Optimal Solution for N based on Design Capacity Flow using Uniform Allocation

	Woodstock Upgrade	Mt Jackson Upgrade	Georges Baseline	Strasburg Upgrade	Broadway Upgrade	Optimal Solution
Objective Function Coefficients	$50.5	$45.5	$0.0	$34.0	$16.8	$1,592,593.2
Objective Function Variable	-	-	-	-	94,910.2	

Table 5.23 Optimal Solution for N based on 2008 Baseline Flow using Uniform Allocation

	Woodstock Upgrade	Mt Jackson Upgrade	Georges Baseline	Strasburg Upgrade	Broadway Upgrade	Optimal Solution
Objective Function Coefficients	$224.3	$212.4	$0.0	$81.0	$28.3	$1,160,245.4
Objective Function Variable	-	-	-	-	41,056.1	

Table 5.24 shows the GAMS output for N based on design capacity flow using sector targeting. The optimal solution was found at $1,729,443 with 24 percent reduction in N loading. This reduction was achieved with 103,070 pounds of N reduction from Broadway. Table 5.25 shows the GAMS output for N based on 2008 baseline flow using sector targeting. The optimal solution was found at $1,361,510 with 24 percent reduction in N loading. The N loading reduction came from both agricultural and point source sectors. The optimal solution based in design flow costs an additional $367,933 compared to 2008 baseline flow because the amount of N reduced is higher with design capacity flow. The reduction of 48,970 pounds of N using 2008 baseline flow compared to 103,070 pounds reduction using design capacity flow.

Table 5.24 Optimal Solution for N based on Design Capacity Flow using Sector Targeting

	No till Corn Silage	Cropland Buffer	Pasture Buffer	Hayland Buffer	Bioretention Filters Sandy Soil	Bioretention Filters Clay Soil	Urban Buffer	Woodstock Upgrade	Mt Jackson Upgrade	Georges Baseline	Strasburg Upgrade	Broadway Upgrade	Optimal Solution
Objective Function Coefficients	$32.0	$181.1	$746.5	$135.1	$1,514.0	$8,508.0	$3,550.0	$50.5	$45.5	$0.0	$34.0	$16.8	$1,729,442.7
Objective Function Variable	-	-	-	-	-	-	-	-	-	-	-	103,070.0	

Table 5.25 Optimal Solution for N based on 2008 Baseline Flow using Sector Targeting

	No till Corn Silage	Cropland Buffer	Pasture Buffer	Hayland Buffer	Bioretention Filters Sandy Soil	Bioretention Filters Clay Soil	Urban Buffer	Woodstock Upgrade	Mt Jackson Upgrade	Georges Baseline	Strasburg Upgrade	Broadway Upgrade	Optimal Solution
Objective Function Coefficients	$32	$181	$746	$135	$1,514	$8,508	$3,550	$224	$212	$0	$81	$28	$1,361,510
Objective Function Variable	-	385	-	-	-	-	-	-	-	-	-	45711	

Table 5.26 shows the optimal solution for P using uniform allocation from GAMS along with the cost of upgrade per unit of P at five upgradeable treatment plants based on design capacity flow. The optimal solution using uniform allocation was $1,287,001 with a 25 percent reduction in P loading from point source. The reduction came from Broadway with 16,002 pounds of P as the cost of upgrade was lowest there. Table 5.27 shows the GAMS output for P

based on 2008 baseline flow using uniform allocation. The optimal solution with design capacity flow has an additional cost of $334,180 compared to the 2008 baseline loading. Per unit cost of the upgrade is cheaper compared to the 2008 baseline, but the amount the P reduced is higher. The total reduction of 16,001 pounds of P was achieved using design capacity flow compared to 7,035 pounds reduction using 2008 baseline flow.

Table 5.26 Optimal Solution for P based on Design Cap Flow using Uniform Allocation

	Woodstock Upgrade	Mt Jackson Upgrade	Georges Baseline	Strasburg Upgrade	Broadway Upgrade	Optimal Solution
Objective Function Coefficients	$212.4	$2,058.6	$216.6	$243.8	$80.4	$1,287,000.6
Objective Function Variable	-	-	-	-	16,001.5	

Table 5.27 Optimal Solution for P based on 2008 Baseline Flow using Uniform Allocation

	Woodstock Upgrade	Mt Jackson Upgrade	Georges Baseline	Strasburg Upgrade	Broadway Upgrade	Optimal Solution
Objective Function Coefficients	$944.2	$9,606.8	$264.9	$580.5	$135.4	$952,820.4
Objective Function Variable	-	-	-	-	7,035.0	

Table 5.28 shows the optimal solution for P based on design capacity flow using sector targeting. The optimal solution was found at $1,412,826 with 25 percent reduction in P loading. This reduction was achieved with 385 acres of cropland buffer, 2,933 acres of hayland buffer and 11,774 pounds of P reduction from Broadway. Table 5.29 shows the optimal solution for P based on 2008 baseline flow using sector targeting. The optimal solution was achieved at $766,187.6 with a 25 percent reduction in P loading. The optimal solution was $646,639 less, almost 46 percent, compared to sector targeting using design capacity flow. With 2008 baseline flow,

reductions came only from the agricultural sector because per unit upgrade cost for P is very high. The P reduction came from both agricultural and point source sector using 2008 baseline flow.

Table 5.28 Optimal Solution for P based on Design Cap Flow using Sector Targeting

	No till Corn Silage	Cropland Buffer	Pasture Buffer	Hayland Buffer	Bioretention Filters Sandy Soil	Bioretention Filters Clay Soil	Urban Buffer	Woodstock Upgrade	Mt Jackson Upgrade	Georges Baseline	Strasburg Upgrade	Broadway Upgrade	Optimal Solution
Objective Function Coefficients	$32.0	$181.1	$746.5	$135.1	$1,514.0	$8,508.0	$3,550.0	$224.3	$212.4	$0.0	$81.0	$28.3	$1,412,826.2
Objective Function Variable		384.9		2932.8								11773.6	

Table 5.29 Optimal Solution for P based on 2008 Baseline Flow using Sector Targeting

	No till Corn Silage	Cropland Buffer	Pasture Buffer	Hayland Buffer	Bioretention Filters Sandy Soil	Bioretention Filters Clay Soil	Urban Buffer	Woodstock Upgrade	Mt Jackson Upgrade	Georges Baseline	Strasburg Upgrade	Broadway Upgrade	Optimal Solution
Objective Function Coefficients	$32.0	$181.1	$746.5	$135.1	$1,514.0	$8,508.0	$3,550.0	$224.3	$212.4	$0.0	$81.0	$28.3	$766,187.6
Objective Function Variable	9,384.7	384.9	0.0	2,932.8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	

Table 5.30 shows the optimal solution for N and P using sector targeting along with the annual per unit cost of each BMP and upgrade cost for each treatment plant based on design capacity flow. The optimal solution was achieved at $ $1,729,576 with a 24 percent and 25 percent reduction in N and P loading, respectively. The reduction was achieved with 97 percent of the upgrade cost from Broadway. The upgrade cost for Broadway is lowest compared to the other four treatment plants. Table 5.30 shows the annual per unit cost of each BMP and overall cost of upgrade at each treatment plant, and selected BMPs and percentage upgrades obtained using sector targeting from GAMS. The resulting optimal solution compared to sector targeting for N and P based on design capacity flow is $368,160 less costly. The reduction for optimal solution based on design capacity flow only came from point source sector whereas one based on 2008 baseline flow it came from both agricultural and point source sector.

Table 5.30 Optimal Solution for Joint N and P using Sector Targeting on Design Cap Flow

	No till Corn Silage	Cropland Buffer	Pasture Buffer	Hayland Buffer	Bioretention Filters Sandy Soil	Bioretention Filters Clay Soil	Urban Buffer	Woodstock Upgrade	Mt Jackson Upgrade	Georges Baseline	Strasburg Upgrade	Broadway Upgrade	Optimal Solution
Objective Function Coefficients	$32	$181	$746	$135	$1,514	$8,508	$3,550	$3,937,894	$1,248,238	$297,200	$3,120,595	$1,783,197	$1,729,576
Objective Function Variable	-	-	-	-	-	-	-	-	-	-	-	0.970	

Table 5.31 Optimal Solution for Joint N and P using Sector Targeting on 2008 Baseline Flow

	No till Corn Silage	Cropland Buffer	Pasture Buffer	Hayland Buffer	Bioretention Filters Sandy Soil	Bioretention Filters Clay Soil	Urban Buffer	Woodstock Upgrade	Mt Jackson Upgrade	Georges Baseline	Strasburg Upgrade	Broadway Upgrade	Optimal Solution
Objective Function Coefficients	$32	$181	$746	$135	$1,514	$8,508	$3,550	$3,937,894	$1,248,238	$297,200	$3,120,595	$1,783,197	$1,361,416
Objective Function Variable	-	385	-	-	-	-	-	-	-	-	-	0.724	

The sensitivity analysis using design capacity flow shows policymakers and stakeholders how the cost and amount of nutrient reduction changes compared to 2008 baseline flow. With the design cap flow, both N and P loading increased considerably without the upgrade (compared to 2008 flows) and the reduction in N and P loadings as a result of the upgrade is larger. As a result, the upgrade cost per pound at each treatment plant is lower. The optimal solution using uniform allocation for N and P separately were higher since the amount of nutrients reduced is higher. Similarly, the optimal solution using sector targeting was higher in cost. The optimal solution for N and P jointly with design capacity flow is also higher in cost compared to 2008 baseline flow. This analysis show 2008 baseline flows is cost-effective for reducing both N and P loading compared to design capacity flow.

CHAPTER 6: SUMMARY & CONCLUSION

6.1. Introduction

Excess nutrient loads from tributary streams and rivers have adversely impacted the water quality and aquatic health of the Chesapeake Bay. This continues to be a point of concern for scientists, policy makers, and stakeholders and has led to a push for TMDLs. The TMDL program increases the scope of water quality management to address both point and nonpoint source pollution on a watershed basis. The process of developing the TMDL is data centric and requires complex mathematical modeling to characterize nutrient loadings. However, there is less emphasis given to the economic cost of reducing loadings. With targeting, areas with high concentration of nutrient loading and lower cost per unit of reduction in nutrients can be identified and treated accordingly. In this study, sector targeting is used to minimize the total cost by targeting sectors with lower costs per unit of pollution reduction to get higher reductions. This study focuses on the North Fork of the Shenandoah River Watershed of Virginia. The objective of this research project is to determine potential cost savings in meeting N or P reduction goals by sector targeting in the North Fork Watershed.

The study focused upon the sources of N and P, the BMPs used for reducing these loadings, their efficiency in reducing nutrient loading and the economic costs associated with these BMPs. This study focused on three main sectors of pollution sources: point sources, agricultural sources, and urban sources. Best management practices are implemented to reduce nutrient loading from all these sectors. The BMPs used for the agricultural sector are no-till, cropland buffers, pasture buffers and hayland buffers. Urban BMPs include; bioretention filters using sandy soils and clay soils and urban buffers. Five treatment plants are included for potential point source upgrades. The cost saving from targeting is realized by reducing the compliance cost by implementing cost effective BMPs.

The set of data used in the study are nutrient loading from each sectors and BMP efficiency in reducing nutrients and cost associated with implementing BMPs. Daily mass loading and inflows from agricultural sector to North Folk Watershed were calculated using GLEAMS. The nutrient loading from urban sectors was calculated using GWLF. Point source nutrient loading was obtained directly from the respective treatment plants. BMP efficiency and implementation cost were estimated using numbers found in the literature.

6.2. Summary of Procedures and Results

Linear programming models were created to determine an optimal solution that minimized total cost to implement BMPs subject to targeted loading reductions in N and P into the watershed. BMPs are selected based on their performance to reduce nutrient loadings and the annual cost per unit of P and N load reductions. The least cost combination of BMPs was determined for each sector using uniform allocation and sector targeting for both N and P. The optimal solutions for each sector using uniform allocation and sector targeting were compared for both N and P and N and P simultaneously.

6.2.1. Sector Targeting is a Cost-Effective Approach

The cost of achieving reduction from uniform allocation was compared to sector targeting cost to quantify the cost-effectiveness of sector targeting. The total cost of reducing N loadings using uniform allocation at each sector was $2,083,733 compared to $1,483,883 from sector targeting. Sector targeting achieved 24 percent reduction in N with 29 percent reduction in cost compared to uniform allocation. The overall average dollar per pound cost for uniform allocation is $40 compared to $28 for sector targeting. Similarly, 25 percent reduction in P loading with uniform allocation was achieved at total cost of $1,919,293 compared to $937,915 from sector targeting. This resulted in a 51 percent reduction in cost compared to uniform allocation. The overall average dollar per pound cost for uniform allocation is $166 compared to $71 for sector targeting. When N and P were reduced simultaneously, sector targeting was found to be cost effective approach which resulted in 30 percent reduction in cost compared to uniform allocation. The reduction in N and P together has almost the same cost reduction as sector targeting for N. This implies the N constraint tends to be more binding than the P constraint.

Sector targeting is more cost-effective than uniform allocation. Sector targeting achieves load reduction by targeting sectors with low costs per unit of pollution reduction. In case of N, the reduction came from agricultural sector and point source because costs of achieving reduction were lowest there. With uniform allocation, there is a constant reduction from each sector without considering the cost. The sensitivity analysis using design capacity flow also showed sector targeting is cost effective approach although the optimal solution was costly compared to one using 2008 baseline flows.

6.2.2. Urban BMPS are least Cost-Effective

The average cost of removing one pound of N and P for urban BMPs is expensive compared to agricultural and point source BMPs. The average cost of removing one pound of N is $168 per pound and $1,091 per pound of P at the North Fork watershed. The optimal solutions for N and P separately and N and P simultaneously using sector targeting involved no contribution from the urban sector. Urban BMPs are not efficient in term of nutrient reduction and cost.

6.2.3. Hypothesis Testing

The two hypotheses that were tested during the study were urban BMPS are least cost-effective and with sector targeting, proportionately more reduction will come from agriculture sector. The first hypothesis was not rejected as the average cost of removing one pound of N and P for urban BMPs is expensive compared to other BMPs. There was also no contribution from urban sector on optimal solution achieved from sector targeting. The second hypothesis was rejected as the most of reduction came from point source sector. There is less contribution to N and P loadings from agriculture activities around North Fork watershed. The nutrient loading from point source represents 84 percent and 62 percent of the total N and P loading respectively.

6.3. Implications

The study develops a cost-effective watershed-scale model for reducing nutrient loading. The general framework for evaluating pollution reductions and costs by sector for the North Fork watershed could be possibly applied to other watersheds. The model structure can be used to assess other potential pollutants such as sediments, or heavy metals.

Stakeholders have incentives to minimize costs of reducing pollution loads, therefore, economic feasibility and efficiency are important factors in determining suitable BMPs. Sector targeting helps in determining the combination of pollution control measures that will achieve nutrient reduction goals at lower cost. As a result, both stakeholders and policymakers potentially could benefit by lowering compliance costs for reducing point or nonpoint source of pollution. Actual benefits by stakeholder group depend on how costs are imposed on stakeholders with sector targeting. .

This study demonstrates the benefits of sector targeting which gives policymakers incentives to pursue such strategies for meeting TMDL reduction. The ultimate goal is to improve water quality. Sector targeting can also be used to resolve one of the primary issues that arise in TMDL development and implementation: lack of economic consideration. Incorporating economic considerations in the TMDL planning process can help in developing a cost-effective implementation plan. The policymakers could utilize these results to target cost-share dollars towards implementing the recommended cost-effective BMPs, thereby ensuring the most efficient use of available resources. For example, if the total N loading needs to be reduced significantly within the watershed, then the cost-share programs for N-based BMP should get more emphasis. Similarly, if the agricultural activities are the main contribution of nutrient loading then associated agricultural BMPs should be more incentivized.

This study can provide insightful information on how to develop a cost-effective water management plan which in turn can be used to develop and implement TMDL allocations and provide a guide for cost-share programs.

6.4. Limitation and Future Research

There have been numerous studies on understanding the benefits of BMPs. These benefits are specific to the physical and economic characteristics of the study areas. There needs to be additional research on long term effectiveness of BMPs, and all costs regarding installation and long term operation of BMPs.

This study only focuses on reducing the compliance cost associated with implementing BMPs. Transaction costs such as information and enforcement costs will be equally important in the formation of costs assessments for using the BMP. Due to difficulties associated with estimating these costs, transaction costs are not included in this study. Including transaction cost along with compliance cost would be a useful extension of this study.

Further research is needed on political constraints to targeting. Stakeholders may be concerned about the fairness of TMDL reductions or reductions under other policies. Due to such concerns and associated political constraints, sectors with highest cost reduction might get equal or higher allocation. Understanding stakeholder concerns for fairness and the effects on allocations among stakeholders can be useful extension to this study.

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APPENDIX A

A.1 Sub-Watersheds

The North Fork watershed has 30 sub-watersheds. Table A-1 below lists the sub-watershed with respective areas.

Table A-1: Sub-watersheds within North Fork of the Shenandoah River

	Sub-Watershed	Area (acre)
1	Molly Booth Run-North Fork Shenandoah River	11,835.85
2	Mountain Run-Smith Creek	13,649.48
3	Dry Fork	12,632.92
4	Linville Creek	29,298.30
5	Turley Creek-North Fork Shenandoah River	14,874.88
6	Runion Creek-North Fork Shenandoah River	20,371.59
7	Shoemaker River	23,310.09
8	Capon Run-North Fork Shenandoah River	30,253.93
9	Little Dry River	21,126.18
10	German River	19,860.75
11	Crab Run	18,305.32
12	War Branch-Smith Creek	14,180.12
13	Long Meadow-North Fork Shenandoah River	33,949.91
14	Holmans Creek-North Fork Shenandoah River	16,176.78
15	Gap Creek-Smith Creek	25,161.31
16	Crooked Run-Mill Creek	29,672.14
17	Riles Run-Stony Creek	33,209.33
18	Yellow Spring Run-Stony Creek	11,046.57
19	Narrow Passage Creek-North Fork Shenandoah River	39,431.94
20	Toms Brook-North Fork Shenandoah River	16,372.93
21	Tumbling Run-North Fork Shenandoah River	23,069.68
22	Meadow Brook-Cedar Creek	30,638.00
23	Lower Passage Creek	23,744.87
24	Froman Run-Cedar Creek	14,288.87
25	Duck Run-Cedar Creek	18,438.98
26	Fall Run	11,208.70
27	Upper Passage Creek	32,370.01
28	Paddy Run-Cedar Creek	26,294.63
29	Painter Run-Stony Creek	27,844.50
30	Mt Jackson-North Fork Shenandoah River	17,491.58

A.2 Annual Cost of Agricultural BMPs

The agricultural BMPs considered for this study are continuous no-till corn silage, buffers for hayland and cropland, and fencing that was placed along with buffer for pastureland. Table A-2 shows the calculation involved in obtaining annual costs for agricultural BMPs. The unit of each agricultural BMP is acres except for fencing which is measured in feet. The lifespan for each BMP is used to annualize the capital cost. All costs are expressed in 2009 dollars using the National Agricultural Statistics Services (US department of Agriculture) Index of Prices Paid for Commodities and Services, Interest, Taxes and Wages rates. The land area removed with implementation of each BMP is used in calculation of land opportunity costs.

No-till costs or corn grain were estimated by comparing corn enterprise budgets on Productivity Group 2 soils for minimum tillage and conventional tillage (Virginia Cooperative Extension, 2007). The corn silage cost, $31.56, is the difference in silage net receipts on Productivity Group 2 soils for conventional vs. minimum-till corn silage.

In the North Fork watershed, 35-foot wide buffers were applied to cropland, hayland and pasture. In the case of pasture buffer, capital costs include buffer establishment plus fencing (NRCS, 2009). The four strand barbed wire fencing capital costs are $3.06/foot (NRCS, 2009). The annualized capital costs include annual interest and depreciation. Capital costs were amortized based on a 10-year life for the buffer, a 20-year life for fence, and a 7 percent interest rate (NRCS, 2009).The opportunity costs for cropland, hayland, and pasture buffer are based on foregone net returns from corn grain, alfalfa hay, and pasture grazing, respectively (Virginia Cooperative Extension, 2007). The annual operating and maintenance costs include maintaining fences and buffers (NRCS, 2009).

The total annual cost is the sum of annualized capital costs, opportunity costs, and annual operating and maintenance costs. The cost of implementing cropland and hayland buffers were $181.11 and $135.08 per acre respectively. The difference in the costs was attributed due to the higher land opportunity cost for cropland. Pasture has the highest cost of agricultural buffers due to the high construction and maintenance costs of fence.

Table A-2: Annual Cost of Agricultural BMPs[2]

Best Management Practices	Unit of BMP	Lifespan (yrs)	Inflation Factor (2009 $)	Land Area Removed (acre)	Annualized Capital Cost (2009 $)	Land Opportunity Costs (2009 $)	Operating & Maintenance Costs (2009 $)	Total Annual Cost (2009 $)
Continuous no-till--corn silage	Acre	1	1.14	0.00	0.00	31.56	0.00	31.56
Cropland buffers	Acre	10	1.00	1.00	40.98	131.50	8.63	181.11
Hayland buffers	Acre	10	1.00	1.00	40.98	85.47	8.63	135.08
Buffers (pasture + fence)	Acre	10	1.00	1.00				746.45
Buffers (pasture-no fence)	Acre	10	1.00	1.00	40.98	32.87	8.63	82.49
Fencing (4 strand barbed wire)	Foot	20	1.00	N/A	0.29	0.00	0.24	0.53

2 Inflation factor provides for future increase in the cost resulting from inflation. It was multiplied to the original price/cost item to convert it to 2009 dollars.

A.3 Annual Cost of Urban BMPs

The Urban BMPs selected for this study are bioretention filters using sandy soils and clay soils, and urban buffers. Table A-3 shows the calculation involved in obtaining annual cost for urban BMPs. The unit of each urban BMP is acres. The lifespan for bioretention filters is 20 years (Wossink and Hunt, 2003) and for urban buffers is 10 years (NRCS, 2009). All costs are expressed in 2009 dollars.

The bioretention filters were placed in a drainage capacity of 5 acres and a 35-foot wide buffer was applied to urban areas. Estimated construction cost (2003 dollars) in clay soil = $\$10{,}162X^{1.088}$ and sandy soil = $\$2{,}861X^{0.438}$ where X is size of the area draining into the bio-filter in acres (Wossink and Hunt, 2003). The annualized capital costs were amortized over their respective lifespans with a 7 percent interest rate (NRCS, 2009). The opportunity costs were estimated assuming that 2.5 percent of the watershed drainage area is occupied by bioretention areas (Wossink and Hunt, 2003). Urban opportunity costs are foregone income from developing buffer land (Wossink and Hunt, 2003). The annual operating and maintenance costs include maintaining filters and buffer. The cumulative (20-year) maintenance and operating costs for both sand and clay soils are estimated by $3{,}437X^{0.152}$.

The total annual cost is the sum of annualized capital costs, opportunity costs, and annual operating and maintenance costs. The annual cost of implementing bioretention filters with sandy soils and clay soils are $1,514 and $8,508 per unit of 5-acre drainage capacity. Bioretention in clay soils is much more expensive than in sandy soils due to the need to replace existing clay with sand and other organic matter. The estimated cost for urban buffers is $287.81/acre (Wossink and Hunt, 2003; NRCS, 2009).

Table A-3: Annual Cost of Urban BMPs[3]

Best Management Practices	Capital cost	Unit of BMP	Lifespan (Yrs)	Inflation Factor (2009 $)	Land Area Removed (acre)	Annualized Capital Cost (2009 $)	Land Opportunity cost (2009 $)	Operating & Maintenance Costs (2009 $)	Total annual cost (2009 $)
Bioretention in clay soils	Construction:C=10,162X$^{1.088}$ (acre) Maintenance: C=3,437X$^{0.152}$ (Acre)	5 acres	20	1.40	0.13	7,762	438	308	8,508
Bioretention in sandy soil	Construction: C=2,861X$^{0.438}$ (acre) Maintenace: C=3,437X$^{0.152}$ (acre)	5 acres	20	1.40	0.13	768	438	308	1,514
Urban buffer	$287.81/acre (warm season grass)	acre	10	1.00	1.00	41	3,500	9	3,550

[3] Inflation factor provides for future increase in the cost resulting from inflation. It was multiplied to the original price/cost item to convert it to 2009 dollars.

A.4 Annual Cost of Upgrading Treatment Plants Based on 2008 Baseline Flow

There are eight treatment plants in North Fork watershed regions but only five of them are upgraded. The three treatment plants that were not upgraded are included in baseline loading. The five upgradeable treatment plants are mainly using biological nutrient removal processes: Oxidation Pond, Activated Sludge and Aerated Lagoons. These wastewater treatment systems were upgraded to enhance the nutrient removal process as per the recommendation from VDEQ. The 2008 design flows for each WWTP were obtained from the local authorities at each plant.

The 2008 annual average effluent concentration (mg/L), daily flow which was used to calculate yearly flow (million gallons) and nutrient loading for both N and P (lbs) were provided by the local plan authorities. These treatment plants were upgraded to achieve annual average effluent concentrations of 3.0 mg/L for total N and 0.30 mg/L for total P. These upgrades will also expand the daily flow capacity while lowering both N and P load. There was no upgrade done at George's Chicken to lower N loading. With the upgrade both daily flow and yearly flow were expanded at the respective treatment plants. With the expansion both N and P loading was reduced at each treatment plants as shown in Table A-4.

Table A-5 shows the cost of upgrade for each treatment plant. The capital cost for each individual treatment plant was annualized at 3 percent based on best estimated average life for wastewater treatment plant, 30 years. The annual costs were broken down to 1/3 debt service of the capital cost, 1/3 salary, and 1/3 power and chemicals (personal communication- Bob Canova). This cost was used to calculate cost per pound for both N and P for treatment plant upgrade.

Table A-4: Nutrient Loading at the Upgraded Treatment Plants Based on 2008 Baseline Flow

Treatment Plant	2008 Baseline						Treatment Upgrade						Reduced Amount		Reduction %	
	Avg TN (mg/L)	Avg TP (mg/L)	Daily Flow (mill gal)	Yearly Flow (mill gal)	N (lbs)	P (lbs)	N (mg/L)	P (mg/L)	Daily Design Flow (mill gal)	Yearly Design Flow (mill gal)	N (lbs)	P (lbs)	N (lbs)	P (lbs)	N %	P %
1 Woodstock STP	16.97	3.48	0.45	164.25	21,671	4,582	3.0	0.3	2	730.0	4,112	411	17,559	4,171	81%	91%
2 Mt Jackson STP	16.08	0.75	0.15	54.75	7,705	267	4.0	0.3	0.7	255.5	1,828	137	5,877	130	76%	49%
3 George's chicken	6.35	1.22	1.39	507.35	16,498	2,392	6.4	0.3	1.7	620.5	16,498	1,270	0	1,122	0%	47%
4 Strasburg STP	18.25	2.48	0.84	306.60	46,189	6,143	3.0	0.3	2	730.0	7,676	768	38,513	5,375	83%	88%
5 Broadway	22.58	3.6	1.74	635.10	79,004	14,756	3.0	0.3	2.93	1,069.5	15,900	1,590	63,104	13,166	80%	89%
6 New Market STP	7.22	1.52	0.55	201.00	9,639	2,073										
7 North Fork Regional WWTP	17.96	2.26	0.04	15.00	624	68										
8 Stoney Creek Sanitary District STP	4.78	0.83	0.56	204.00	7,781	1,435										

Table A-5: Cost of Upgrading Treatment Plants and Cost per Pound of N and P Reduction[4]

Treatment Plant	Capital Cost	Annualized Capital Cost	Annual Cost	Nitrogen loading		Phosphorus loading	
				Reduction w/ Upgrade (lbs/yr)	Cost per pound	Reduction w/ Upgrade (lbs/yr)	Cost per pound
1 Woodstock STP	26,500,000	1,312,631	3,937,894	17,559	224.27	4,171	944.16
2 Mt Jackson STP	8,400,000	416,079	1,248,238	5,877	212.38	130	9,606.76
3 George's chicken	2,000,000	99,067	297,200	0	NA	1,122	264.92
4 Strasburg STP	21,000,000	1,040,198	3,120,595	38,513	81.03	5,375	580.53
5 Broadway	12,000,000	594,399	1,783,197	63,104	28.26	13,166	135.44

[4] The annual cost includes annualized capital cost, salary, and power and chemicals with the latter two being equal to annualized capital cost.

A.5 Annual Cost of Upgrading Treatment Plants Based on Design Capacity Flow

Design flow is the amount of sewage flow that could be discharged based on a given capacity of the treatment plant. Table A-6 shows the nutrient loading based on design capacity flow for each treatment plants. The 2008 baseline nutrient loading for both N and P (lbs) and yearly flow (millions gallons) were provided by the local authorities. These treatment plants were upgraded to achieve annual average effluent concentrations of 3.0 mg/L for total N and 0.30 mg/L for total P. The daily flow was used to calculate yearly flow (million gallons).

Based on design flow, the reductions in total N and P were calculated as follows. First, the emission with the upgrade was calculated multiplying the concentration times design flow. Then emissions without the upgrade but the plant running at the expanded capacity were calculated multiplying the emissions estimated without the upgrade for 2008 times the ratio of design flow to 2008 flow. Then reduction was calculated by subtracting emissions without the upgrade from the emission with the upgrade.

Table A-7 shows the cost of upgrade for each treatment plant which is similar to the cost calculation for 2008 baseline as shown in Table 5.

Table A-6: Nutrient Loading at the Treatment Plants Based on Design Capacity Flow

Treatment Plants	2008 Baseline Flow			Treatment Upgrade				Design Cap Flow: W/O Upgrade		Design Cap Flow: With Upgrade		Reduced Amount		Reduction %	
	Yearly Flow (mill gal)	Nitrogen (lbs)	Phosphorus (lbs)	Planned N (mg/L)	Planned P (mg/L)	Daily Design Flow (mill gal)	Yearly Design Flow (mill gal)	Nitrogen (lbs)	Phosphorus (lbs)	Nitrogen (lbs)	Phosphorus (lbs)	Nitrogen (lbs)	Phosphorus (lbs)	N %	P %
1 Woodstock STP	164.25	21,671	4,582	3	0.3	2	730.0	96,316	20,364	18,276	1,828	78,040	18,537	81%	91%
2 Mt Jackson STP	54.75	7,705	267	4	0.3	0.7	255.5	35,957	1,246	8,529	640	27,428	606	76%	49%
3 George's chicken	507.35	16,498	2,392	6.35	0.3	1.7	620.5	20,177	2,925	20,177	1,553	0	1,372	0%	47%
4 Strasburg STP	306.60	46,189	6,143	3	0.3	2	730.0	109,974	14,626	18,276	1,828	91,698	12,799	83%	88%
5 Broadway	635.10	79,004	14,756	3	0.3	2.93	1,069.5	133,035	24,848	26,774	2,677	106,262	22,170	80%	89%

Table A-7: Cost of Upgrading Treatment Plants Based on Design Capacity Flow

Treatment Plant	Capital Cost	Annualized Capital Cost	Annual Cost	Nitrogen load lbs/year: Reduction w/ Upgrade (lbs/yr)	Nitrogen load lbs/year: Cost per pound	Phosphorus load lbs/year: Reduction w/ Upgrade (lbs/yr)	Phosphorus load lbs/year: Cost per pound
1 Woodstock STP	26,500,000	1,312,631	3,937,894	78,040	50.46	18,537	212.44
2 Mt Jackson STP	8,400,000	416,079	1,248,238	27,428	45.51	606	2,058.59
3 George's chicken	2,000,000	99,067	297,200	0	NA	1,372	216.61
4 Strasburg STP	21,000,000	1,040,198	3,120,595	91,698	34.03	12,799	243.82
5 Broadway	12,000,000	594,399	1,783,197	106,262	16.78	22,170	80.43