ABSTRACT

Title of Document: EVALUATION OF NITROGEN NONPOINT-SOURCE LOADINGS USING HIGH RESOLUTION LAND USE DATA IN A GIS: A MULTIPLE WATERSHED STUDY FOR THE STATE OF MARYLAND.

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The performance of three monitoring perspectives, for the detection of watershed compliance with water quality standards, was evaluated. In order to compare performances 35 watershed nonpoint-source nitrogen loading cases were calculated within a GIS. Calculations showed that the probability of loads exceeding a criterion at the watershed outlet is more representative of upstream conditions than a nominal mean load comparison at the watershed outlet. Combined outlet compliance interpretations were found to isolate loading conditions that on average did not exceed the criterion; however, variations within loading distributions were large such that compliant conditions were threatened. The whole watershed perspective mapped the relationship between stream network structure, land cover/land use, and loadings. Comparisons between the perspectives suggested that both outlet perspectives usually are consistent with whole watershed conditions. Semivariograms were demonstrated to characterize spatial variability in loadings and predict the accuracy with which monitoring sites represent loads at upstream locations.

EVALUATION OF NITROGEN NONPOINT-SOURCE LOADINGS USING HIGH RESOLUTION LAND USE DATA IN A GIS: A MULTIPLE WATERSHED STUDY FOR THE STATE OF MARYLAND.

By

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To my grandpa
Owen Schneider.

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Chapter 1: Introduction

1.1 Problem Statement

1.1.1 Nonpoint-source Pollution

Maryland's 305(b) water quality reports and current Section 303(d) impaired waters list continue to confirm nonpoint-source (NPS) pollution as the main outstanding unregulated pollution source statewide. NPS pollution can be defined as pollution that is not associated with a specific location, pipe effluent discharge, or point. The diffuse nature of NPS pollution makes both the control and the identification of the pollution source difficult. Because of easier identification and control of point-source pollution, NPS pollution now accounts for a large share of all water pollution (Carpenter *et al.* 1998). Of particular concern are nitrogen, phosphorus, and sediment and their cumulative impact on streams and rivers. Under natural conditions nutrients and sediment result in gradual eutrophication and sedimentation in surface waters, but the process has been accelerated by upstream land use activities. In extreme cases NPS pollution has impaired aquatic resources, resulting in closed recreational areas or threatened public health.

1.1.2 Current Monitoring Programs

In compliance with the Clean Water Act (CWA), Maryland has instituted a five-year watershed cycling strategy to detect and monitor impaired watersheds (MDE 2004). The State has divided approximately 16,000 kilometers (km) of first to fourth order streams and rivers into 18 major basins and 138 eight-digit watersheds grouped into 84 primary sampling units. The State distributes fixed monitoring sites and probability-based monitoring sites among these units with the intention of establishing monitoring programs that cover 20 percent of Maryland's non-tidal streams and rivers each year.

These monitoring programs, however, are resource intensive and are generally done on a short-term basis in limited geographic areas. In fact, only one to three fixed sites in only 39 of the 138 watersheds are sampled each month (MDE 2004). The fixed sites (54 stations total) are predominately located in central Maryland watersheds; streams and rivers on the Eastern Shore and in Southern Maryland are not currently being sampled. Additionally, only 15.75 km of streams, in 75 meter (m) segments, are randomly selected each year. The remaining fixed monitoring sites are selected for special purposes (*e.g.*, for monitoring high quality natural stream conditions) and do not directly identify NPS impaired streams. As a result, the current monitoring methods leave a large percentage of streams and rivers unmonitored each year. None of these monitoring methods utilize readily available land use data in selecting sample sites for watershed monitoring programs.

1.1.3 Land Use Characteristics

Meanwhile, environmentally-concerned agencies, departments, and partnerships such as the Metropolitan Washington Council of Governments (MWCOG), the U.S. Environmental Protection Agency (USEPA), the Maryland Department of the Environment (MDE), and the Chesapeake Bay Program Office (CBPO) recognize that the impact of NPS pollution on a watershed can strongly depend on land use. These groups have reported pollutant loading rates specific to land use categories which have supported the following observations: Different land uses can produce the same kinds of pollution. For example, urban, forest, and agricultural land use can all discharge nitrogen, phosphorus and sediment loads. Some land uses, however, cause more severe problems. In particular urban areas, which cover about 18.3 percent of the land base in the State (Hopkins *et al.* 2000), are generally under the highest environmental stress. Urban areas can alter the transport of nutrients and other pollutants to surface water bodies (Interlandi and Crockett 2003). Often, urban areas attenuate nutrients less efficiently than agricultural areas since the proportion of impervious surface in urban areas is high, and, in many cases, water flow in urban areas is efficiently channeled to surface waters through storm sewers (Soranno *et al.* 1996). On the other hand, agricultural areas, which cover about 21 percent of the land base in the State (Hopkins *et al.* 2000), can produce soil erosion and lead to increased nutrient and sediment loads to surface waters (Osborne and Wiley 1988; Cooper 1993; Lenat and Crawford 1994; Johnson *et al.* 1997; Carpenter *et al.* 1998). The amount of nutrients coming off the land can be moderated by the percentage of local forest (Castillo *et al.* 2000). Forest areas cause minor environmental impact and cover about 31 percent of the land base in the State (Hopkins *et al.* 2000). The non-homogenous spatial distribution of land use categories suggests high internal variability of pollutant loads within a watershed. Changed land use distributions upstream of a monitoring site could, therefore, have greater influences on local stream conditions than on conditions observed downstream at a sampling site (Peterjohn and Correll 1984). Readily available land use data could identify monitoring sites that are not representative of upstream conditions.

1.1.4 Loading as a Function of Land Use

Many models estimating the impact of land use data on pollutant loads to surface waters have been based on pollutant loading rates in equations such as

$$L = \sum_{i=1}^{n} c_i A_i \tag{1-1}$$

where *L* is the total load from the land (in units of mass per year); *n* is the number of land use types; *c* is the loading rate for land use *i* (in units of mass per area per time); and *A* is the area of land use *i* (in units of area). It is reasonable to estimate mean annual nutrient and sediment NPS loads using the USEPA CBPO loading rates (MDE 2006). The MDE reports that these mean values are not site-specific; the MDE, however, still supports the assertion that "they provide reasonable, defensible loading rates for which improvements may be proposed in the future." When used as a planning tool, the estimation of nutrient and sediment loads as long-term trends is acceptable (DeVantier and Feldman 1993; MDE 2006). In addition, the MDE recommends the use of USEPA CBPO loading rates so that there is consistency with the Tributary Strategies under the Chesapeake Bay Agreement 2000 (C2K).

Because of their simplification, loading rates do not account for the loading patterns within a watershed. Typically loading rates are applied to land use areas that have been lumped into a single contributing area; a lumped area does not take advantage of the spatial distribution of land use within a watershed. Decision-makers need to know if a watershed has the potential to have high internal variability in loads so that appropriate measures toward pollution management can be taken at the watershed monitoring sites or outlet. Ideally, decision-makers would know if the estimated pollution from one loading rate scenario causes more or less internal variation in loads than the impacts from an alternative scenario. Additionally, the current application of Equation 1-1 does not provide a way to estimate the probability that pollutant loads at a monitoring site exceed a given threshold level of pollution. This model simplification overlooks the seasonal and inter-annual variations in climate and discharge rates, which are major drivers of NPS pollution (Interlandi and Crockett 2003). Assuming that loading rates have probabilities associated with a random loading event, an understanding of the loading distribution at a single monitoring site could help decision-makers identify those watersheds that are on the verge of becoming impaired.

The loading rate application is simple. Some alternative models include complex hydrologic models and distributed parameter models (Beven 1989; DeVantier and Feldman 1993; Grayson *et al.* 1992). These complex models are typically perceived to better represent and predict the reality of watershed hydrology as compared to the ability of models such as the simple loading rate Equation 1-1. In actuality, the complex model predictions tend to be in error despite or even because of the so-called "physical basis" of the model (Beven 1989). The "physical basis" of these models tries to account for the complexity in fundamental components that appear detectable at certain spatial resolutions, but the complexity is rarely supported by available monitoring data. As parameters are added to account for all hydrological processes within a watershed, over parameterization may occur (Beven 1989). The interdependence of parameters, therefore, causes complex models to produce large prediction errors (Beven 1989; Grayson *et al.* 1992). A simplified model could minimize prediction errors for locations where monitoring data is scarce.

1.2 Research Need Statement

There is a need to identify those surface waters at greatest risk to high levels of NPS pollution so that action can be taken to reduce the risk. Although there have been attempts to monitor and model NPS loading to streams and rivers, no comprehensive approach exists to evaluate potential loadings to streams based on land cover/land use (LCLU) spatial distributions at watershed scales for all of Maryland. This thesis, therefore, evaluates the use of LCLU to explain the spatial distribution of NPS pollution, specifically nitrogen. I developed a simple method that integrates nitrogen loading rates and Geographical Information Systems (GIS) to assess NPS pollution. Moreover, my method of predicting NPS pollution addresses the spatial distribution of the loading rates and is used to evaluate the performance of three monitoring perspectives.

1.3 Goals and Objectives

The goal of this thesis is to develop tools within a GIS to identify stream locations with a maximum potential for improving water quality, which could be considered in an improved monitoring network for watersheds of all sizes and locations within Maryland. The following objectives shall be met to achieve this goal:

1. Develop a model that utilizes the spatial variation in the USEPA CBPO loading rates and the variation in LCLU remotely sensed data obtained from an existing

database to estimate a distribution of total mean annual nitrogen loads at high spatial resolution within a GIS environment.

2. Assess the probability of detecting points within a stream network as being in or out of compliance based on USEPA accepted total maximum daily load (TMDL) criteria.
3. Contrast Current condition loads with Tributary Strategy condition loads to identify the areas in the watershed that fit into the following categories: always noncompliant; noncompliant for Current conditions, but compliant for Tributary Strategy conditions; and always compliant.
4. Use the compliance status and the load spatial variation of the watershed to recommend the most effective use of monitoring resources to measure conditions in the watershed.

Because the output from the model may be particularly useful in assessing state water quality, this thesis explores the potential of LCLU data to identify subareas within the watershed that display the greatest susceptibility to changes in land use activities as displayed by the loading rates. Because the areas on the borderline of compliance to MDE/USEPA standards are the most vulnerable to water quality problems, monitoring sites within these areas can provide a warning system for potential watershed scale water quality problems. Ideally, decision-makers will be able to assess estimated impacts of the Current conditions and the likelihood of their exceeding watershed criterion.

1.4 Potential Implications of the Research

The proposed GIS integrated LCLU approach to water-pollution management will facilitate the rapid selection of sample sites for identifying the location of NPS pollution and assessing the water quality of streams. The method will help managers identify not only the location of environmental problems but also highlight immediate restoration opportunities that exist within a drainage network. The method can assist in the identification of healthy stream lengths that may be in need of environmental protection. The method can help provide an initial overview of environmental conditions in any number of Maryland watersheds and in prioritizing future restoration efforts. Finally, although the method was developed for nitrogen impairments, it could be similarly applied to analyze phosphorus and sediment impairments as well.

Chapter 2: Background/Literature Review

2.1 Introduction

This chapter discusses important aspects of the relationship between LCLU and NPS pollution. Some of the more recent integrated GIS/NPS modeling efforts are investigated, and Maryland's approach to addressing water quality via USEPA CBPO loading rates and TMDL criteria is discussed.

2.2 Land Use Approaches to Nonpoint-source Pollution Assessment

Studies have shown that the distribution of different LCLU categories within a watershed can account for some of the spatial variability in NPS pollution (*e.g.*, Griffith *et al.* (2002), Griffith (2002), and Jones *et al.* (2001) gave a thorough account of significant relationships between LCLU data and NPS pollution of various types). For example, some studies created nutrient budgets that found significant relationships between LCLU and phosphorus and nitrogen (*e.g.*, Lowrance *et al.* 1985; Peterjohn and Correll 1984). Other studies developed significant empirical relationships between LCLU and nutrient and sediment data using multivariate and regression analyses (*e.g.*, Basnyat *et al.* 1999; Keeney and DeLuca 1993; Osborne and Wiley 1988; Swank and Bolstad 1997; Weller *et al.* 2003; Yates and Sheridan 1983). In particular Jones *et al.* (2001) demonstrated that the percent of various LCLU in a watershed could explain a large fraction of the variation in yields of total nitrogen, dissolved phosphorus, and suspended sediments for 78 watersheds in the five-state Mid-Atlantic region. Earlier, Johnson *et al.* (1997) found that the strength of relationship between riparian scale land-cover patterns versus stream-water chemistry and watershed scale varied by season and with the amount of dissolved chemical constituents in Michigan streams. As such, land use is a good predictor of the spatial patterns of stream nutrient levels. More recently, Carle *et al.* (2005) characterized the effects of urbanization on watershed scale hydraulic response and water quality.

As observed by Sidle and Hornbeck (1991), recent studies have been progressing towards whole watershed analysis in their efforts to address NPS pollution discharge from land use activities. Allan (2004) says that earlier studies had the limited perspective of a few hundred meters of stream reaches and ignored the importance of the larger watershed. Other studies found that a comprehensive analysis of stream condition must take account of both small and large spatial scales (Johnson and Gage 1997; Johnson *et al.* 1997). This is exemplified by the CBPO movement towards analyzing average drainage areas of 1,900 square kilometers (km^2), where the average reach length is 170 km (Linker *et al.* 2002).

Geographic Information Systems (GIS) and remotely sensed data have become a fundamental part of studying NPS pollution in relation to the spatial distribution of LCLU (Johnson and Gage 1997; Johnson *et al.* 1997). GIS and remotely sensed data have allowed recent research to quantify LCLU patterns to better understand their spatial heterogeneity from a watershed perspective (Turner and Carpenter 1998). Allan *et al.* (1997) used a complex distributed parameter model linked to a GIS to demonstrate that an increase in forested land cover results in dramatic declines in runoff and sediment and nutrient loads. There have also been several attempts to take advantage of the spatial data analysis tools within GIS and intuitively simple empirical equations like the aforementioned loading rate Equation 1-1. For example, Basnyat *et al.* (1999) and Swank and Bolstad (1997) both used regression techniques to relate LCLU with the pollution levels in the stream using spatially distributed LCLU data inferred from remotely sensed data and other data entered in a GIS. Other work showed that coarser resolution data could be used to detect water quality problems at a large spatial scale, while finer-resolution data must be used to detect critical NPS pollution conditions at a small spatial scale (Hunsaker and Levine, 1995). Similarly, GIS and remotely sensed data are essential tools used in the watershed scale methodology presented in this thesis.

2.2.1 Other Simple Nonpoint-source Models in a GIS

The following section evaluates two simple loading rate methodologies: PLOAD, and Sorrano *et al.* (1996). The evaluation is done in the context that these two methodologies are similar to the methods applied in this thesis. PLOAD is a good example of an established GIS based NPS application which follows a simplified empirical loading rate approach (USEPA 2001). Methods used within PLOAD are endorsed by water quality managers such as the USEPA (USEPA 1992, 2001) and have been integrated into several GIS environments (*e.g.*, BASINS and GISHydro). The GIS-based model calculates pollutant NPS loads on a mean annual basis for any user-specified pollutant within the watershed of interest.

The loads may be calculated by using either the loading rate or the Simple Method. The loading rate approach calculates loads for each specified pollutant type by watershed using the exact form of Equation 1-1. The loading rates are derived from tables, while the land use areas are interpreted from the land use and watershed GIS data. The Simple Method was developed by Schueler (1987) such that Equation 1-1 is modified by replacing the loading rate parameter (c_i) with four new parameters

$$L_p = \sum_U (P * P_J * R_{UV} * C_U * A_U * 2.72 / 12) \quad (2\text{-}1)$$

$$R_{UV} = 0.05 + (0.009 * I_U) \quad (2\text{-}2)$$

where P is the precipitation in inches per year (in/yr); P_J is the fraction of annual rainfall events that produce runoff; R_{VU} is the runoff coefficient for land use type U and is determined from Equation 2-2; I_U is the percent imperviousness; C_U is the event mean concentration for land use type U in milligrams per liter (mg/l); and A_U is the area of land use type U in acres (ac).

One advantage of the Simple Method over the loading rate method is that the total pollutant concentrations from all land use types can be estimated by dividing by the rainfall event discharge data. These concentrations can be used to estimate the probability that pollutant concentrations exceed a given threshold level through a direct understanding of the event runoff data. These exceedance frequencies refer to the percent of runoff events in which a given concentration level is equaled or exceeded (Schueler 1987). Another advantage is that the calculated concentrations can be compared to existing water quality standards and water quality criteria developed by the USEPA.

The disadvantages, however, are that the Simple Method only estimates pollutant loads during rainfall events and does not represent the total load from the site (Schueler 1987). It does not consider baseflow generated runoff and associated pollutant loads. Additionally, load calculations are limited by the availability of reliable event mean concentrations and are limited to one square mile (Schueler 1987; USEPA 2001). The PLOAD methods, therefore, are not universally applicable to a large region.

More recent work done by Soranno *et al.* (1996) has modified Equation 1-1, the same equation used by the loading rate method in PLOAD. Unlike PLOAD, the Soranno *et al.* (1996) study only applied to NPS phosphorus loading. The modifications were made with the objective to account for the amount of phosphorus that is attenuated between pixels in a GIS. Soranno *et al.* (1996) used spatially referenced databases of watershed land use, topography, and hydrography at a GIS resolution of 100 m pixels. The equation follows:

$$L = \sum_{i=1}^{m} \sum_{p=1}^{n} f_i A_{p,i} T_i^p \tag{2-3}$$

where L is total phosphorus loading from the land in kilograms per year (kg/yr); m is the total number of land-use types, which equaled 6 land use types for the watershed of interest; n is the total number of pixels in the contributing area; p is the distance of each land use to the receiving water in the path of surface overland flow; f is the phosphorus loading rate for land in kilograms per hectare per year (kg/ha/yr); A is the area of land use i at distance p from open water in hectares (ha); and T is the transmission coefficient, which represents the proportion of phosphorus that is transported to the next pixel in the path of surface overland flow. Soranno *et al.* (1996) used the least squares method to fit T for all non-urban land uses and f_i for agricultural and urban lands to data obtained by stream sampling. The fitted equation was then used to look at extreme land use conversion conditions. Soranno *et al.* (1996) found that (1) complete urbanization could double phosphorus loading, and (2) changes in phosphorus loading were strongest with conversions of undisturbed lands, especially forest areas, to urban or agricultural lands.

An innovative part of the Sorranno *et al.* (1996) study was the examination of effective land area, defined as the area that actually contributes to runoff. The transmission coefficient, *T*, of Equation 2-3 is linearly related to the effective land area. As *T* decreases, the effective land area decreases. Soranno *et al.* (1996) found that in low-runoff years, only 30 percent of the contributing area transported phosphorus to surface waters, but, during a particular high-runoff year, 87 percent of the contributing area provided a source of phosphorus. This finding is important to land use-based NPS estimation models, since land use within the effective land area may be quite different from land use within the entire watershed. In the future, it would be valuable to incorporate a contributing area coefficient into the model described in my thesis.

The major drawback of the Soranno *et al.* (1996) study was that Equation 2-3 only applied to phosphorus transport in overland flow. The Sorrano *et al.* (1996) method was not recommended for nitrogen because it ignored the transport in groundwater. According to Peterjohn and Correll (1984), transport through groundwater is very important to the nitrogen loading process. Additionally, Sorrano *et al.* (1996) reports that inputs such as atmospheric deposition were not included in the model. Lastly, testing of the Sorrano *et al.* (1996) results was limited to the Lake Mendota watershed in Wisconsin.

My thesis documents the development of a method to estimate nitrogen, phosphorus, and sediment NPS loads for the entire state of Maryland. While the methodology was developed from the same loading rate method used in Equation 1-1, the determination of the loading rates and the end analyses are fundamentally different from both the PLOAD (USEPA 2001) and Soranno *et al.* (1996) works. Unlike these other works, my thesis explores the possibility of estimating probability distributions from the loading rate method based on the known spatial distribution of CBPO nitrogen loading rates. This may be an advantage over the Simple Method, given that the dependency on precipitation data is not a limiting factor in its use. Another difference is that the Soranno *et al.* (1996) study used pre-settlement, current, and projected future land use scenarios. My thesis assumes constant land use. This being said, the objective of my thesis was to understand watershed stream conditions and their compliance interpretations to better guide monitoring decisions. The loading rates, therefore, are adjusted to account for changes in best management practices rather than land use. These loading rates do not directly address load attenuation or groundwater; however, their effects are accounted for in the original data from which the model loading rates were derived (Linker *et al.* 2002). Furthermore, my thesis combines MDE and USEPA approved approaches to determine stream conditions within the watershed. The remaining literature review discusses referenced resources concerning the development of the three watershed compliance perspectives examined in my thesis. Additionally, the issue of spatial load variation is presented in the context of monitoring programs.

2.3 Chesapeake Bay Program Office Loading Rates

The loading rates used in my thesis were developed for estimating mean annual NPS loads within the Chesapeake Bay Watershed (MDE 2006). Historically, loading rates have been estimated by monitoring NPS runoff from watersheds and dividing the amount of estimated constituent delivery by the entire watershed drainage area (Soranno *et al.* 1996). My thesis presents, by contrast, land-use specific loading rates that were developed using the results of application Phase 4.3 of the Chesapeake Bay Watershed Model (WSM) (Linker *et al.* 2002). The total NPS load can be calculated by summing all of the individual land use areas and multiplying by the corresponding land use loading rates as shown in Equation 1-1.

2.3.1 Chesapeake Bay Watershed Model Details and Assumptions

The WSM is a GIS based LCLU model based on the Hydrologic Simulation Program – Fortran (HSPF) Version 11 (Bicknell *et al.* 1996). The WSM is an example of a complex model which attempts to represent physical processes such as infiltration and evaporation, among others. The WSM model is not directly used in this study as its complexity warranted unrealistic amounts of data, time and skill to operate (Tim and Crumpton 2003).

The advantage of the WSM is that the model can estimate loads for nutrients and sediment from all areas within the Chesapeake Bay watershed (Linker *et al.* 2002). HSPF is an example of a lumped-parameter model; a single land use is assumed for each relatively homogenous hydrologic unit, or modeled segment, for ease of model calculation (Hopkins *et al.* 2000). Model segment size is dictated by land and soil properties, location of model calibration stations, model computation time, and availability of pertinent model input data. A single spatial segment typically contains multiple land uses. All land uses are assumed to be in direct hydrologic connection. The main forcing function is hourly precipitation, averaged for each model segment. Loads are calculated for a period of 10 years (1985 to 1995) at an hourly time step. The model results are aggregated into 10 year average loads. The use of this mean annual load allows for a typical mix of wet, dry, and average hydrologic years throughout the basin (USEPA 2008). Version 4.0 of the WSM was calibrated for the 1984 to 1992 period and validated for the 1993 to 1995 period, for which no significant difference in model accuracy was found (Linker *et al.* 2002).

The WSM simulation for nutrient loads accounts for fate and transport of NPSs from conventional-tilled cropland, conservation-tilled cropland, hay, pasture, pervious urban land, impervious urban land, forest, animal waste areas, and atmospheric deposition directly to water surfaces (Linker *et al.* 2001). Nitrogen fates include volatization into the atmosphere and denitrification. Nutrients are exported from pervious land in one of two ways, the first being mechanistic nutrient cycling and export, using storages of nutrients in soil and plant mass and parameters to govern movement between the storages (AGCHEM). The second method of nutrient exportation utilizes an empirically-based approach, with potency factors for surface runoff and monthly specified concentrations in the subsurface (PQUAL). Nitrogen was exported from pervious areas including forest, crops, pasture and pervious urban land using AGCHEM. Animal waste contributions assume nitrogen concentrations that are multiplied by runoff. Impervious urban areas related the storage of nitrogen from atmospheric deposition to the rainfall intensity.

2.3.2 Inherited Loading Rate Assumptions

The loading rates derived from WSM inherit six major assumptions. The first assumption is that there is a linear relationship between each land use area and the NPS load. This is in contrast to Soranno *et al.* (1996) in which delivery ratios decrease with watershed area. Although the WSM model accounts for complex relationships within each model segment, the relationships are averaged in the loading rates. These loading rates are then applied to different watershed scales within the modeled segment; this application may or may not adequately represent the true loading of small areas. The second assumption is that the order of land use through which discharge passes does not affect the final loading at the watershed outlet. Additionally, the WSM loads are not estimates of the NPS loads generated in a given year. Instead, the loads are estimates of the long-term mean annual load, accounting for variations in annual rainfall over 10 years and conditions on the ground in a given year. The third and fourth assumptions, therefore, are that rainfall and land use are not varying. The fifth assumption made when using the different available loading rates is that changes in mean annual loads are due to changes in land use activities. The sixth assumption is that the entire watershed area is contributing to the load estimate. The third and sixth assumptions would cause an average daily load to be biased for a given season because a simple division of annual loads by 365 days does not account for the observation made by Soranno *et al.* (1996) that variation in precipitation and, thus, the contributing area occurs throughout the year. This is an important observation when considering daily time steps for total maximum daily loads (TMDL).

2.4 Water Quality Standards

Water quality monitoring programs are required to support State water quality standards for the protection of both human health and aquatic life (Code of Maryland Regulations Title 26, Subtitle 08). Water quality standards categorize watersheds by designated use and assign water quality criteria designed to protect that use. Designated uses include activities such as swimming, drinking water supply, and shellfish propagation and harvest (Table 2-1).

Table 2-1: Designated uses in the State of Maryland (MDE 2007).

Code	Description
Use I	Water Contact Recreation, and Protection of Non-tidal Warm water Aquatic Life
Use I-P	Water Contact Recreation, Protection of Aquatic Life, and Public Water Supply
Use II	Support of Estuarine and Marine Aquatic Life and Shellfish Harvesting
Use II-P	Support of Estuarine and Marine Aquatic Life and Shellfish Harvesting and Public Water Supply
Use III	Non-tidal Cold Water
Use III-P	Non-tidal Cold Water and Public Water Supply
Use IV	Recreational Trout Waters
Use IV-P	Recreational Trout Waters and Public Water Supply

2.4.1 Concentrations as Criteria

Numeric criteria set the minimum water quality to meet designated uses. More specifically, numeric criteria are values assigned to measurable constituents of water quality. Numeric criteria can be more useful than narrative criteria mainly because they provide quantitative interpretations of compliant and noncompliant conditions. Most of the nation's watersheds, however, are not assessed through numeric nutrient criteria (USEPA 2000a, 2000b). The lack of numeric criteria makes it difficult to evaluate the watershed condition and difficult to develop protective water quality standards. Nutrient criteria are needed as standards for management planning and assessment activities to better guide National Pollutant Discharge Elimination System permit limits and TMDL values.

2.4.2 Nitrogen Water Quality Indicators

Nitrogen is a pollutant in the sense that, if it exceeds a specific concentration, it can render a watershed noncompliant with water quality standards and useless in serving its designated function. The MDE, however, does not have a methodology based solely upon nutrient concentrations for listing impaired waters (USEPA 2004). To compensate for this, the MDE uses concentrations of dissolved oxygen and Chlorophyll a as indicators of nutrient impairments for TMDL development (USEPA 2004; Dalmasy, pers. comm., 2007). In some cases MDE has identified impaired watersheds based solely upon land use practices (USEPA 2004). My thesis, therefore, turns to the development of TMDLs to serve as an intermediate step between criteria development and watershed-based management planning.

2.4.3 Total Maximum Daily Loads as Criteria

The U.S. Environmental Protection Agency (USEPA) oversees Maryland's water quality under 303(d) of the 1972 Clean Water Act by requiring the state to establish a total maximum daily load (TMDL) of pollutants for any surface water that violates numeric or narrative water quality standards. The 303(d) list identifies waters that fail to meet standards even after all of the required management measures are in place. The logic of the Clean Water Act is straightforward. If required pollution management measures are in place but remaining pollutants still cause water quality standards to be violated, then it is necessary to conduct a scientific study of the water to determine a pollution budget that will meet water quality standards. This type of study is commonly called a "TMDL analysis" or "TMDL report."

A TMDL is defined as the maximum quantity of a pollutant that can be released to a watershed without exceeding the capacity of the watershed to assimilate pollutant loadings given its designated use. A TMDL, expressed in terms of mass per time, can be described generically by the following equation (USEPA 1999):

$$TMDL = LC = \sum WLA + \sum LA + \sum MOS + \sum F \qquad (2\text{-}4)$$

where *LC* is the loading capacity, or the greatest loading a water body can receive without exceeding water quality standards; *WLA* is the wasteload allocation, or the portion of the *TMDL* allocated to existing point-sources; *LA* is the load allocation of the portion of the TMDL allocated to existing nonpoint-sources and natural background; *MOS* is the margin of safety which is provided implicitly through analytical assumptions or explicitly by reserving a portion of loading capacity; and *F* is the portion of the *TMDL* allocated to future sources, although some reports include future allocations in the *WLA* and *LA* terms.

Although consistency with water quality standards is required under federal law, federal regulations and guidelines do not prescribe all of the specific steps necessary to achieve and maintain standards. In particular the federal government does not prescribe procedures for implementing TMDLs. The USEPA CBPO, therefore, released aforementioned land-use-specific edge-of-stream loading rates for nitrogen, phosphorus, and sediment. MDE is advocating the use of these loading rates to support TMDL development in Maryland.

In the last three years more than 90 TMDLs have been completed for Maryland (MDE 2008). TMDLs determine how much excess pollution is entering a specific water body and how much pollution needs to be reduced to meet water quality standards. TMDLs are a critical, and often first, step in developing a credible, quantitative cleanup for watersheds.

2.4.3.1 Annual Time Step

TMDLs can be expressed at temporal resolutions ranging from daily to annual. The name total maximum "daily" load implies that the loads would be reported on a daily time step. Counter to this expectation, most daily loads are reported on an annual time step. As a result of the recent D.C. Circuit Court of Appeals decision in Friends of the Earth, Inc. v. USEPA, *et al.*, No. 05-5015 (D.C. Cir. 2006), however, the USEPA recommends that all future TMDLs and associated LAs and WLAs be expressed in terms of a daily time step in addition to other temporal resolutions (*e.g.*, annual, seasonal) that may be necessary to manage the applicable water quality standards (USEPA 2007).

For TMDLs in which long (non-daily) term allocations are determined to be informative, the daily load expression can provide a tool for assessing load reduction progress towards meeting long-term TMDL allocations and, therefore, water quality standards. This is particularly useful when dealing with pollutants for which numeric criteria do not exist (Moglen 2007; USEPA 2007). With the use of post-TMDL monitoring data, managers can calculate observed loads to compare against established daily load targets to determine progress in reducing watershed loads to levels required by the TMDL.

The numeric value chosen for the TMDL criterion can affect the criterion's usefulness in evaluating watershed compliance. There is a very wide range of daily load values that make up the total mean annual load. Using a median daily load as the allowable daily maximum criterion assumes that, under compliant conditions, 50 percent of expected loads will exceed the allowable criterion. A median daily load criterion, therefore, is too restrictive to address expected variation in daily load distributions. The USEPA (2007), therefore, recommends that the daily load criterion should be selected so that the criterion value is rarely exceeded by the daily load distribution.

One concern of my thesis is the appropriateness of the annual time step for nutrient TMDL criteria. For many TMDL pollutants, such as nutrients and sediment, the accuracy of pollutant loading estimates increases as the length of the calculation period increases (USEPA 2007). The USEPA CBPO loading rate model selected for this thesis does not produce daily output. The loading rate model mean annual load output, therefore, would have to be disaggregated using a set of discharge ratios. One of the goals of my thesis is to develop tools to inform the selection of monitoring sites within an ungaged watershed. In the interest of data availability and model accuracy, therefore, an annual time step was chosen over a daily time step.

2.5 Variance in Context with Hydrologic Data

Spatial variability is an underlying complication in the regulation of NPS pollution. Large changes in load variation may not be detected using water quality samples. Although concentration monitoring may be the most direct way to identify the effect of BMP implementation on a designated use, sensitivity may be low (Coffey and Smolen 1990). When the probability of detecting a trend in water quality samples is small, load monitoring may be used. The benefit to load monitoring is that it can be used to evaluate changes in magnitude of pollutant sources or to evaluate changes in pollutant load at a fixed monitoring site. Additionally, point estimates, taken before and after BMP implementation, cannot confirm an effect if the natural variability is greater than the change due to the BMP (Coffey and Smolen 1990). Knowledge of the variability and the distributions of the spatial and point variabilities, therefore, are important in identifying compliance with water quality standards. Large variability requires a larger change to imply that the observed change is not due only to random events (Spooner *et al.* 1987). The effects of management activities may not be detectable as a change in a mean value but rather as a change in variability (Coffey and Smolen 1990). Meals (1991) recommends the collection and evaluation of existing data as the first step in a monitoring effort, recognizing that additional background data may be needed to identify noncompliant areas or fill information gaps.

Typically, an understanding of a historical data set can help to identify the magnitude of natural variability and possible sources. Historical data sets, however, are unavailable for ungaged watersheds. My thesis, therefore, turns to remotely sensed

LCLU within a GIS environment along with averaged historical data, as represented by loading rates, to better understand the spatial loading variability within a watershed.

Chapter 3: Methods and Materials

3.1 Introduction

This chapter explains the development of a method for calculating edge-of-stream, nitrogen NPS pollutant loading scenarios for 35 watersheds within the State of Maryland. The GIS load calculation method aided the evaluation of three perspectives used to detect watershed compliance with water quality standards as represented by load allocation (LA) criteria collected from TMDL reports. The LA criteria were used instead of designated use water quality indicators. This information is needed by managers and engineers to make rational NPS pollution decisions at the watershed level. The chapter is organized as follows: The first section describes the basic load calculations. Subsequent sections describe alterations made to the basic load calculations as well as methods developed to interpret the model output for use in monitoring and management applications.

3.2 Basic Load Calculations

The basic load calculations use an empirical loading rate approach. The simplification of mechanistic processes (such as physical, chemical, and biological processes that affect water quality) within watersheds facilitate the analysis of regions where a more detailed mechanistic assessment is not supportable. For instance, one objective of the method is to analyze ungaged watersheds where data is in short supply. A loading rate approach is, therefore, more appropriate because the loading rate approach is assumed to produce less uncertainty compared to a more rigorous mechanistic modeling approach that is not supported given existing data.

The basic load calculations involve a four-step procedure. First, the areas within each land use category are obtained for the region of interest. Second, loading rates are paired with each land use category. Third, the paired data are used to calculate the load for each land use category, which is the product of the land use category area and the corresponding loading rate. Fourth, the loads for each land use category are summed to obtain the total NPS load. Figure 3-1 shows a flow chart outlining the described procedure.

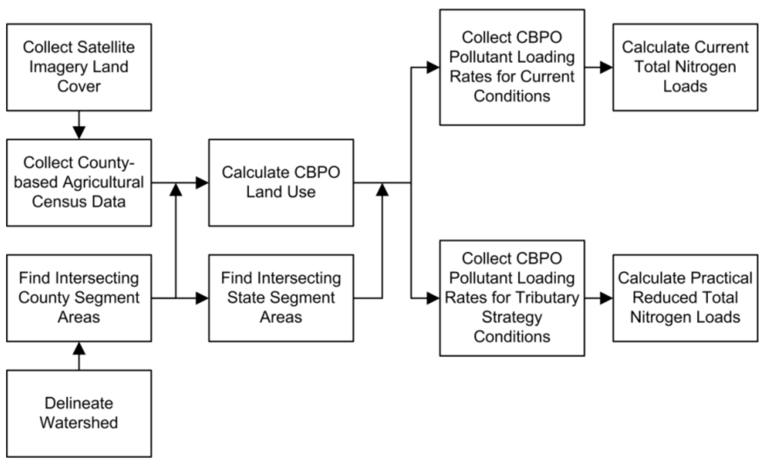


Figure 3-1: Flow chart of basic load calculation procedure.

The basic load calculations do not estimate NPS loads generated in a given year. They estimate long-term mean annual loads, accounting for variations in annual rainfall over 10 years (1985 to 1994), and conditions on the ground in a given year (Linker *et al.* 2000; MDE 2006). This procedure, therefore, allows comparisons between years due solely to changes in land use or BMPs based on the Chesapeake Bay Program Tributary Strategy Plan. Only changes in BMPs were considered in this thesis.

3.2.1 Inferred Land Use from CBPO Phase 4 Land Cover

The land use for each watershed is inferred from CBPO Phase 4 land cover grid data obtained from the CBPO Office Data Hub (Moglen 2007). The land cover grid data corresponds to year 2000 land use. Figure 3-2 shows a map of available CBPO Phase 4 land cover data for the State of Maryland. Table 3-1 lists the nine land cover classifications. The conversions of land cover data to land use data are based on equations developed by the CBPO (Hopkins *et al*. 2000; Moglen 2007).

Table 3-1: CBPO Phase 4 land cover classification numbers (RESAC 2003).

Identification Number	CBPLU Land Cover Classification	Simple Land Use Category
11	High Intensity Urban	Urban
12	Low Intensity Urban	Urban
13	Herbaceous Urban	Urban
14	Woody Urban	Urban
20	Herbaceous	Agricultural
30	Woody	Forest
40	Exposed	Urban
60	Water	Water
70	Herbaceous Wetlands	Forest

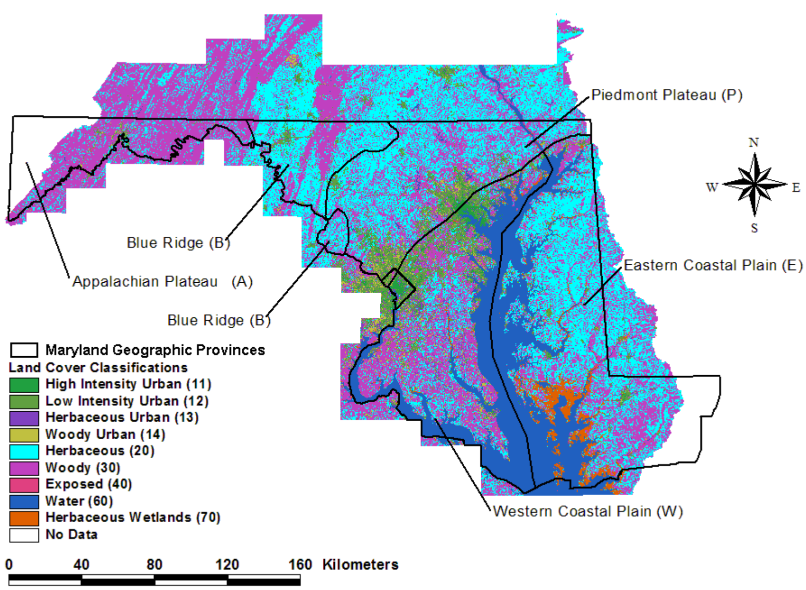


Figure 3-2: Map of 30 meter resolution CBPO Phase 4 land cover.

Land cover Herbaceous (20) is disaggregated into six agricultural land use categories within a GIS: high tilled, low tilled, pasture, hay, manure, and non-agricultural herbaceous. The proportions of Herbaceous (20) assigned to each category are assumed from reported agricultural census data from the table "1990 Phase 4.2 Watershed Model Land Use Sorted by Major Tributary Basin" (Hopkins *et al.* 2000; Moglen 2007). The proportions are CBPO county segment dependent. Within each county segment, it is assumed that all land use, determined from herbaceous land cover, is evenly distributed. The land use of a specific category is determined by

$$LU_j = \sum_{i=1}^{n} (LC_{20})_i (P_j)_i \qquad (3\text{-}1)$$

in which i is the index for county segment, n is the number of county segments that intersect the watershed of interest; LU_j is the area in acres (ac) of land use category j summed across n county segments; LC_{20} is the area of land cover Herbaceous (20) within county segment i (ac); and P is the proportion of land use category j within county segment i (dimensionless). The watershed area, therefore, is divided into subareas based on county segment lines. Figure 3-3 shows a map of county segments that fall within the State of Maryland.

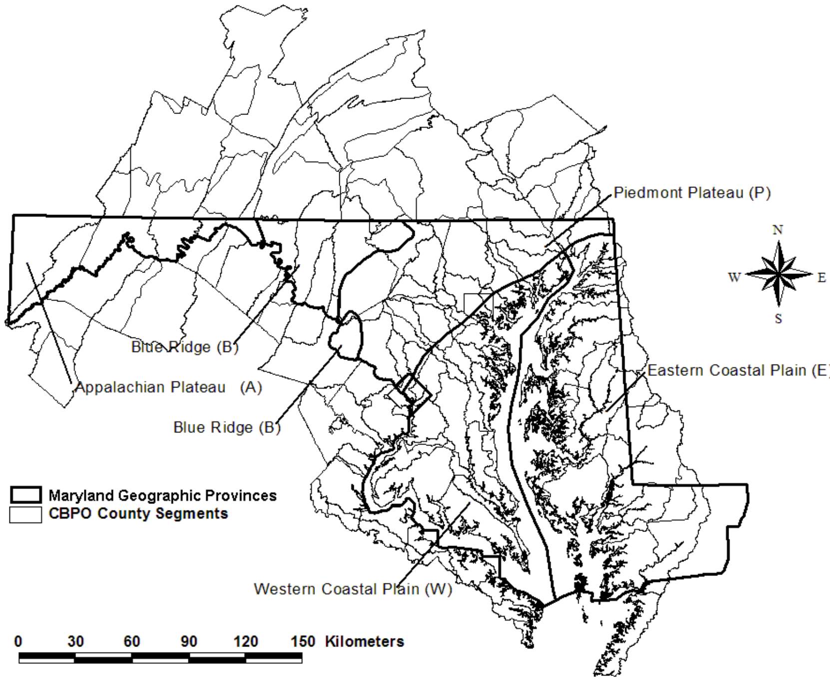


Figure 3-3: Map of Delaware, Maryland, Pennsylvania, Virginia, and Washington, DC county segments used in the disaggregation of land cover Herbaceous (20).

The remaining land cover classifications are used to infer the following four land use categories: forest, impervious urban, pervious urban, and water. These land use categories are determined by

$$LU_{forest} = (LC_{30} + LC_{70}) \tag{3-2}$$

$$LU_{impervious\ urban} = (0.85LC_{11} + 0.4LC_{12} + 0.1LC_{13} + 0.1LC_{14} + 0.4LC_{40}) \tag{3-3}$$

$$LU_{pervious\ urban} = (0.15LC_{11} + 0.6LC_{12} + 0.9LC_{13} + 0.9LC_{14} + 0.6LC_{40}) \tag{3-4}$$

$$LU_{water} = (LC_{60}) \tag{3-5}$$

in which *LU* is the area (ac) of a particular land use category and *LC* is the area (ac) of a particular land cover classification. The weight assumed for each *LC* is assumed by the CBPO (Hopkins *et al.* 2000).The distribution of land use for each land use category is assumed to be uniform within a county segment.

The Lake Linganore watershed, located in Frederick and Carroll Counties, is considered for demonstration purposes. Figure 3-4 shows the location of three county segments that coincide with the watershed. The total watershed area of 52,449.6 ac is divided into subareas of 5,396.2 ac, 46,970.2 ac, and 83.2 ac for county segments 210024021, 210024013, and 760024013, respectively (Figure 3-4).

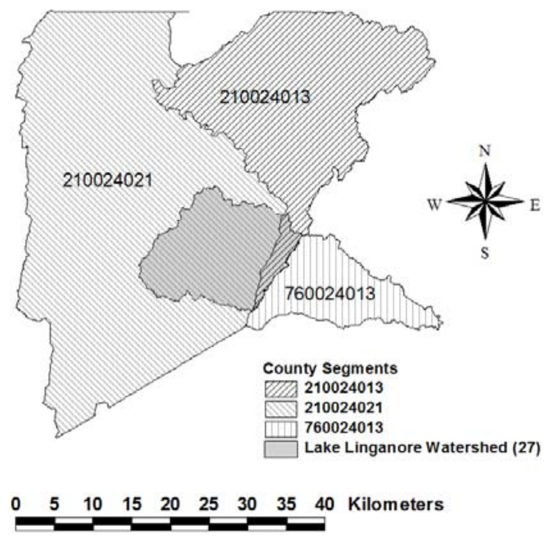


Figure 3-4: Three county segments coincide with the Lake Linganore watershed.

Within each county segment, the area for each land cover classification is determined as shown in Table 3-2. The land cover Herbaceous (20) subarea is disaggregated into appropriate proportions of land use using Equation 3-1 and the proportions provided in Table 3-3. The remaining land cover categories are used in Equation 3-2 through Equation 3-5 to calculate the non-herbaceous land use areas provided in Table 3-4. For example, the forest land use Equation 3-2 requires CBPO land covers Woody (30) and Herbaceous Wetlands (70), which are reported as 2,501.1 ac and 0.7 ac for county segment 210024013 (Table 3-2). The forest land use is calculated as follows:

$$LU_{forest} = (2{,}501.1\ ac + 0.7\ ac) = 2{,}501.8\ ac \quad (3\text{-}6)$$

Table 3-2: Lake Linganore CBPLU land cover.

Land Cover ID	CBPLU Classification	Land Cover Area (ac) by County Segment		
		210024013	210024021	760024013
11	High Intensity Urban	4.9	5.8	2.2
12	Low Intensity Urban	101.9	910.0	38.3
13	Herbaceous Urban	31.1	362.1	5.6
14	Woody Urban	41.4	145.0	0
20	Herbaceous	2,715.2	29,016.5	32.5
30	Woody	2,501.1	16,300.0	4.7
40	Exposed	0	0	0
60	Water	0	223.1	0
70	Herbaceous Wetlands	0.7	7.8	0
Total Area (ac) by County Segment		5396.3	46970.3	83.3

Table 3-3: Lake Linganore land use from herbaceous (20) land cover.

Land Use Classification	Land Use Proportion (Dimensionless) by County Segment			Land Use Area (ac) by County Segment		
	210024013	210024021	760024013	210024013	210024021	760024013
High Tillage	0.2096	0.0226	0.2096	569.1	655.8	6.8
Low Tillage	0.2561	0.3780	0.2560	695.4	10968.2	8.3
Pasture	0.1358	0.1961	0.1358	368.7	5690.1	4.4
Hay	0.1549	0.2301	0.1549	420.6	6676.7	5.0
Manure	0.0006	0.0012	0.0006	1.6	34.8	0.0
Non-Agricultural Herbaceous	0.2430	0.1719	0.2430	659.8	4987.9	7.9
Total Area (ac) by County Segment				2715.2	29016.5	32.5

Table 3-4: Lake Linganore land use from non-herbaceous land cover.

Land Use Categories	Land Use Areas (ac) by County Segment		
	210024013	210024021	760024013
Forest	2501.7	16307.8	4.7
Impervious Urban	52.2	419.6	17.8
Pervious Urban	127.1	1003.3	28.3
Water	0	223.1	0
Total Area by County Segment	2681.0	17953.7	50.7

3.2.2 Loading Rates

Loading rates are identified using a look-up table provided by Gary Shenk, USEPA-CBPO Integrated Analysis Coordinator, (Moglen, pers. comm., 2008). The loading rates are land use category and state segment specific. Figure 3-5, on the following page, shows a map of state segments that fall within the State of Maryland. The term state segment has been adopted by the USEPA and this term is being used within this thesis for consistency. State segments represent the intersection of state and county political boundaries with hydrologic boundaries.

Loading rates are available for the estimation of loads for nitrogen, phosphorus, and sediment. Only nitrogen loading rates are considered in this thesis; however, the methods reported in this thesis are transferable to an analysis of phosphorus and sediment. In addition, loading rates are available for edge-of-stream and bay-delivered conditions. Only the edge-of-stream loading rates, however, were used in calculating loads because the objective is to analyze local stream conditions.

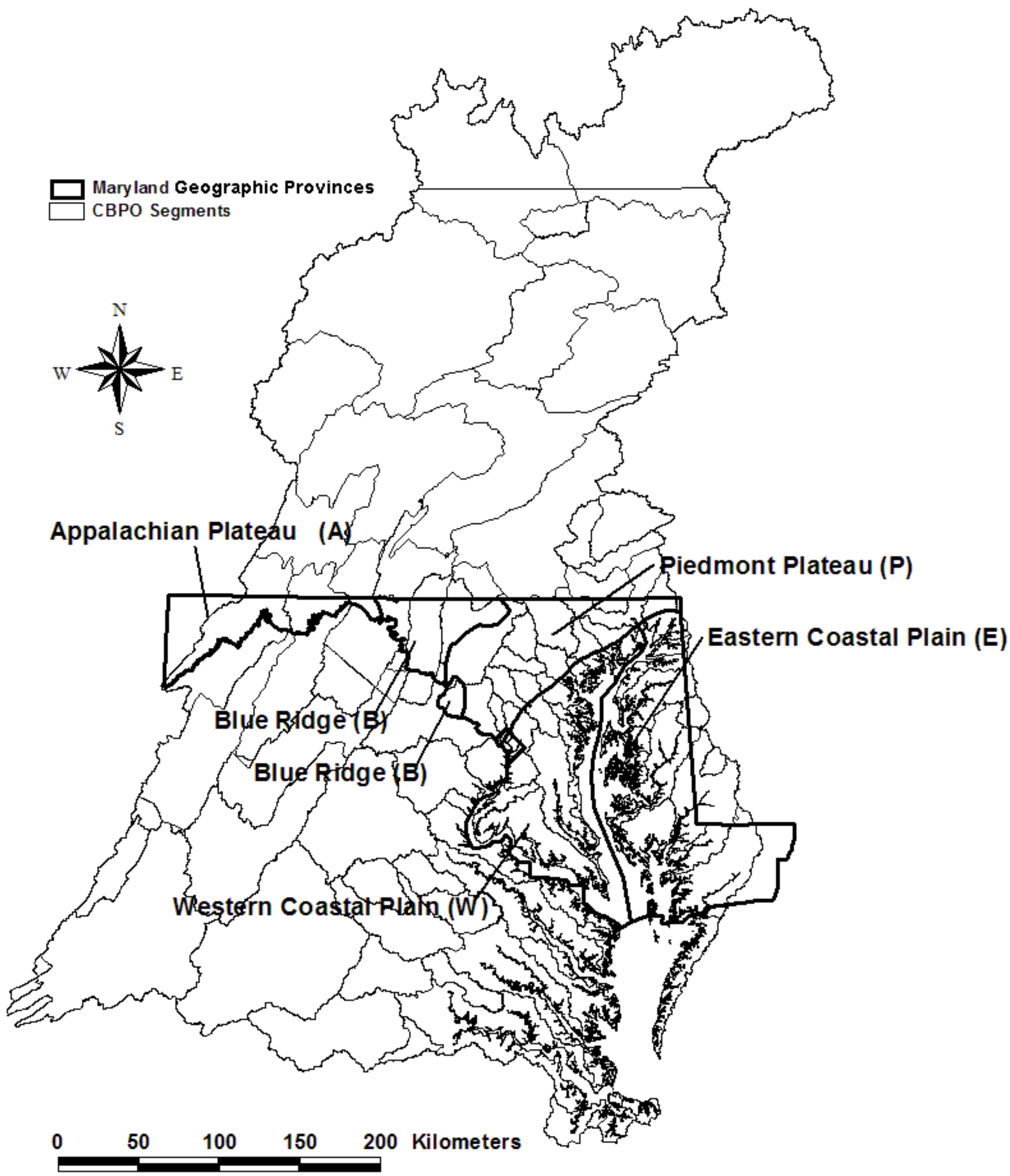


Figure 3-5: Map of Maryland, New York, Pennsylvania, Virginia, and Washington, DC state segments used in the pairing of land use specific loading rates.

3.2.2.1 Loading Rates for Comparison

Two types of loading rates are considered: Current condition, and Tributary Strategy condition. The Current condition loading rates account for the most current NPS nitrogen loading rates by land use category. The Current condition loading rates are used to answer the question, "What is the current mean annual nitrogen load from a particular watershed?" These loading rates represent average affects of BMP implementation for the WSM calibration years 1985 to 1994 (Linker *et al.*, 2002). The Tributary Strategy loading rates account for the Maryland's Tributary Strategy Statewide Implementation Plan, which includes BMPs to reduce nutrient and sediment pollution from every source, including agricultural fields, urban and suburban lands, and wastewater treatment plants (DNR, 2008). The Tributary Strategy Plan requires an eventual reduction by more than 50 percent of 1985 nutrient loads, which is difficult to obtain immediately. Tributary Strategy condition loading rates, however, are intermediate rates that do not meet the Tributary Strategy goals but define realistic, attainable goals in appropriate timeframes (DNR 2008; MDE 2006).

Tributary Strategy condition loading rates are used to calculate the lowest viable NPS load using conventional BMPs. Tributary Strategy condition loading rates are considered in this thesis as practical estimates of lowest nitrogen loading rates. In support of this statement, Tributary Strategy condition loading rates are considered "very ambitious" by the MDE (2006). Tributary Strategy condition loading rates, therefore, are used to assess the feasibility of achieving TMDL goals. Section 3.4 of this thesis discusses the comparison between calculated Tributary Strategy condition

NPS loads, calculated Current condition NPS loads, and collected LA criteria from TMDL reports.

3.2.3 Load Estimates

Loads are calculated following the general form of Equation 1-1. A more specific equation is given as

$$L = \sum_i \sum_j \sum_k (c_{i,j,k})(A_{i,k}) \tag{3-7}$$

in which L is the nitrogen load in pounds per year (lb/yr) summed across all land use categories i, state segments j, and county segments k; $c_{i,j,k}$ is the loading rate (lb/yr/ac) for nitrogen from state segment j in county segment k for land use category i; and $A_{i,k}$ is the area (ac) of county segment k in land use category i. An inventory of areas for each land use category, including open water for cases in which there are large water bodies, and loading rates for each land use category are collected. Loads are calculated for each land use as a product of each land use area and loading rate. Total NPS loads at the watershed outlet are estimated as the summed set of loads for each land use category.

The calculation of Current condition load estimates is exemplified in the continued discussion of the Lake Linganore watershed. Figure 3-6 shows that the watershed coincides with state segments 4210 and 4760. The state segment 4210 coincides with county segments 210024013 and 210024021 as shown by the identical Current condition loading rates in Table 3-5. The state segment 4760 coincides with county segment 760024013.

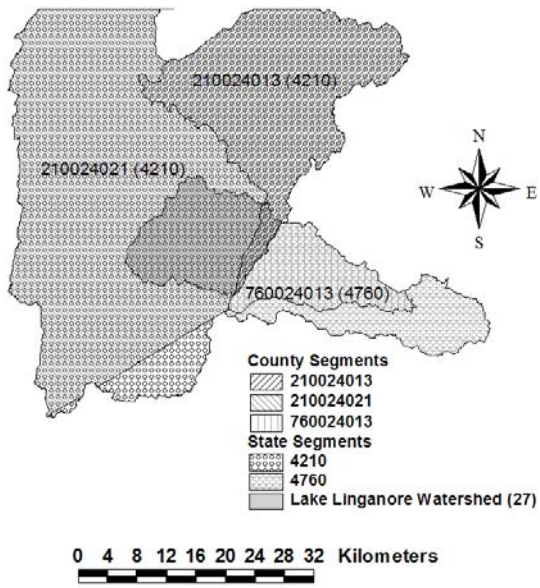


Figure 3-6: Two state segments correspond with the Lake Linganore watershed.

Equation 3-7 is applied to the land use areas in Table 3-3 and Table 3-4 to calculate the Current condition loads reported in Table 3-5. For example, county segment (state segment) combinations 210024013 (4210) and 210024021 (4210) and 760024013 (4760) have Current condition loading rates 2.0 lb/ac, 2.0 lb/ac, and 1.4 lb/ac, respectively. These loading rates are paired with forest land use areas 2,501.7 ac, 16,307.8 ac, and 4.7 ac, respectively. The products of the loading rates and areas follow:

$$L_{210024013} = \left(2.0\frac{lbs}{acre}\right)(2{,}501.7\ acres) = 5{,}003\ lbs \tag{3-8}$$

$$L_{210024021} = \left(2.0\frac{lbs}{acre}\right)(16{,}307.8\ acres) = 32{,}616\ lbs \tag{3-9}$$

$$L_{760024013} = \left(1.4\frac{lbs}{acre}\right)(4.7\ acres) = 7\ lbs \tag{3-10}$$

The Current condition total load from forest land use within the Lake Linganore watershed is calculated by taking the sum of Equations 3-8 through 3-10 as follows:

$$L_{\text{forest}} = 5{,}003\ lbs\ +\ 32{,}616\ lb + 7\ lbs = 37{,}626\ lbs \qquad (3\text{-}11)$$

Table 3-5 continues the calculations shown in Equations 3-8 through 3-11 for the remaining land use categories identified within the Lake Linganore watershed. The total loads by land use category are summed to calculate a mean annual load at the watershed outlet of 592,600 lb/yr. Table 3-6 repeats the procedure using Tributary Strategy condition loading rates to calculate a practical minimum annual average loading of 353,537 lb/yr. The Tributary Strategy condition loading rates reduce the Current condition mean annual load by 60 percent.

Table 3-5: Lake Linganore Current condition load calculations.

Land Use Categories	Current Loading Rate (lb/acre) by County Segment			Current Loads (lb) by County Segment			Mean Annual Loads (lb/yr) by Land Use
	210024013	210024021	760024013	210024013	210024021	760024013	
High Tillage	27.9	27.9	24.3	15,878	18,296	165	34,340
Low Tillage	22.2	22.2	17.5	15,437	243,495	145	259,078
Pasture	11.4	11.4	8.9	4,795	76,114	45	80,954
Hay	7.8	7.8	6.3	2,876	44,383	28	47,287
Manure	1,985.3	1,985.3	1,897.8	3,234	69,128	37	72,399
Non-Agricultural Herbaceous	6.7	6.7	5.4	4,421	33,419	43	37,882
Forest	2.0	2.0	1.4	5,003	32,616	7	37,626
Impervious Urban	9.9	9.9	9.7	516	4,154	172	4,843
Pervious Urban	13.3	13.3	10.8	1,690	13,343	306	15,339
Water	10.4	10.4	10.1	0	2,320	0	2,320
Mean Annual Load (lb/yr) by County Segment				53,851	537,269	947	592,067

Table 3-6: Lake Linganore Tributary Strategy condition load calculations.

Land Use Categories	Tributary Strategy Loading Rate (lb/yr/ac) by County Segment			Tributary Strategy Loads (lb/yr) by County Segment			Mean Annual Loads (lb/yr) by Land Use
	210024013	210024021	760024013	210024013	210024021	760024013	
Hi Till	15.3	15.3	17.1	8,707	10,033	116	18,857
Low Till	12.1	12.1	10.8	8,414	132,716	90	141,219
Pasture	10.0	10.0	5.1	4,206	66,767	26	70,999
Hay	7.8	7.8	6.5	2,876	44,383	29	47,288
Manure	20.2	20.2	19.2	33	703	0	737
Non-Agricultural Herbaceous	4.8	4.8	3.9	3,167	23,942	31	27,140
Forest	1.8	1.8	1.3	4,503	29,354	6	33,863
Impervious Urban	6.1	6.1	6.0	318	2,560	106	2,984
Pervious Urban	7.4	7.4	5.9	941	7,424	167	8,531
Water	8.6	8.6	8.5	0	1,918	0	1,918
Mean Annual Load (lb/yr) by County Segment				33,165	319,801	571	353,537

3.3 Probability Distribution Interpretation

3.3.1 Introduction

The basic load calculations assume that the topography, land use, and loading rates are homogeneously distributed, producing a single mean annual NPS load for the watershed outlet. Comparison between the mean annual NPS load and a LA criterion provided in the watershed TMDL report, therefore, produces a nominal interpretation of the watershed compliance with water quality standards (*i.e.*, yes, the watershed is compliant with MDE/USEPA standards; no, the watershed is noncompliant with MDE/USEPA standards). The nominal compliance interpretation overshadows the fact that within a watershed with a noncompliant outlet, there may be compliant stream lengths; alternatively, within a watershed with a compliant outlet, there may be noncompliant stream lengths. One question that this thesis addresses is how important is the effect of spatial load variability within a watershed on the compliance interpretation.

A probability distribution method is developed to account for spatial variability of land use and loading rates within a watershed. To do this, the basic load calculation is modified in three ways: First, the set of watershed land use areas are calculated at smaller computational elements called pixels. Second, two parameters, local mean and standard deviation, of loading rate distributions by land use category are assumed based on CBPO model information. Third, the relative accumulated areas by land use category and loading rate distribution parameters are used to calculate an area relative load distribution for each pixel within a stream network of a watershed.

3.3.2 GIS for Small Regions of Interest

A GIS is used to determine the composition of LCLU and loading characteristics in Maryland. All datasets are projected in the Maryland state plane coordinate system. The required data includes digital elevation model (DEM) and land cover in 30 meter grid format. County segment and state segment maps are in vector format. Loading rates by county segment are in tabular format.

The GIS environment is used to delineate every incremental watershed down a length of stream so that the basic load calculation can calculate accumulated loads at every stream pixel. The land cover areas are calculated by summing the incremental drainage areas along every pixel in the stream. Each pixel land cover area is converted to land use area using Equation 3-1 through Equation 3-6. A final set of 10 land use areas are divided by the total drainage area at each pixel in the stream so that the mean annual load is area relative.

3.3.2.1 Mean and Standard Deviation of Loading Rates by Adjacent Segments

The basic load calculations assumed an average loading rate per state segment. In reality, an instantaneous change in loading rates does not occur at defined boundaries. A more realistic representation of loading rates is a graduated change in loading rates between adjacent state segments. Figure 3-7 shows the Current condition loading rates, based on atmospheric deposition, for the water land use category. Figure 3-8 on the adjacent page shows Current condition loading rates for eight of the remaining nine land use categories. For the most part, there is an observable transition in loading rates across the maps. At extreme locations on a map there may be differences in the local population distributions.

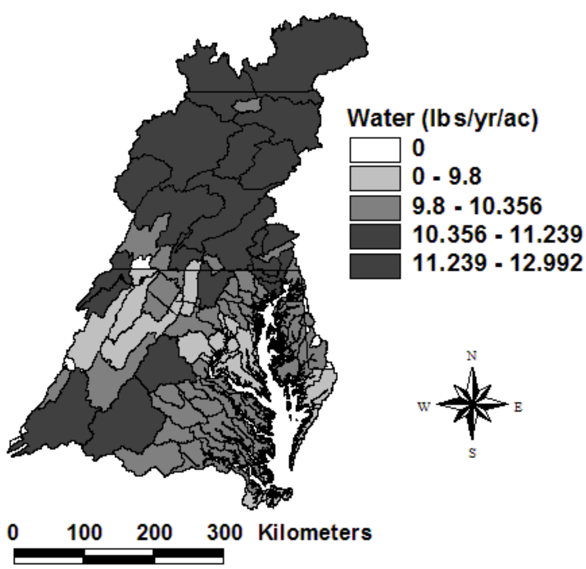


Figure 3-7: Map of Current condition water loading rates based on state segment locations.

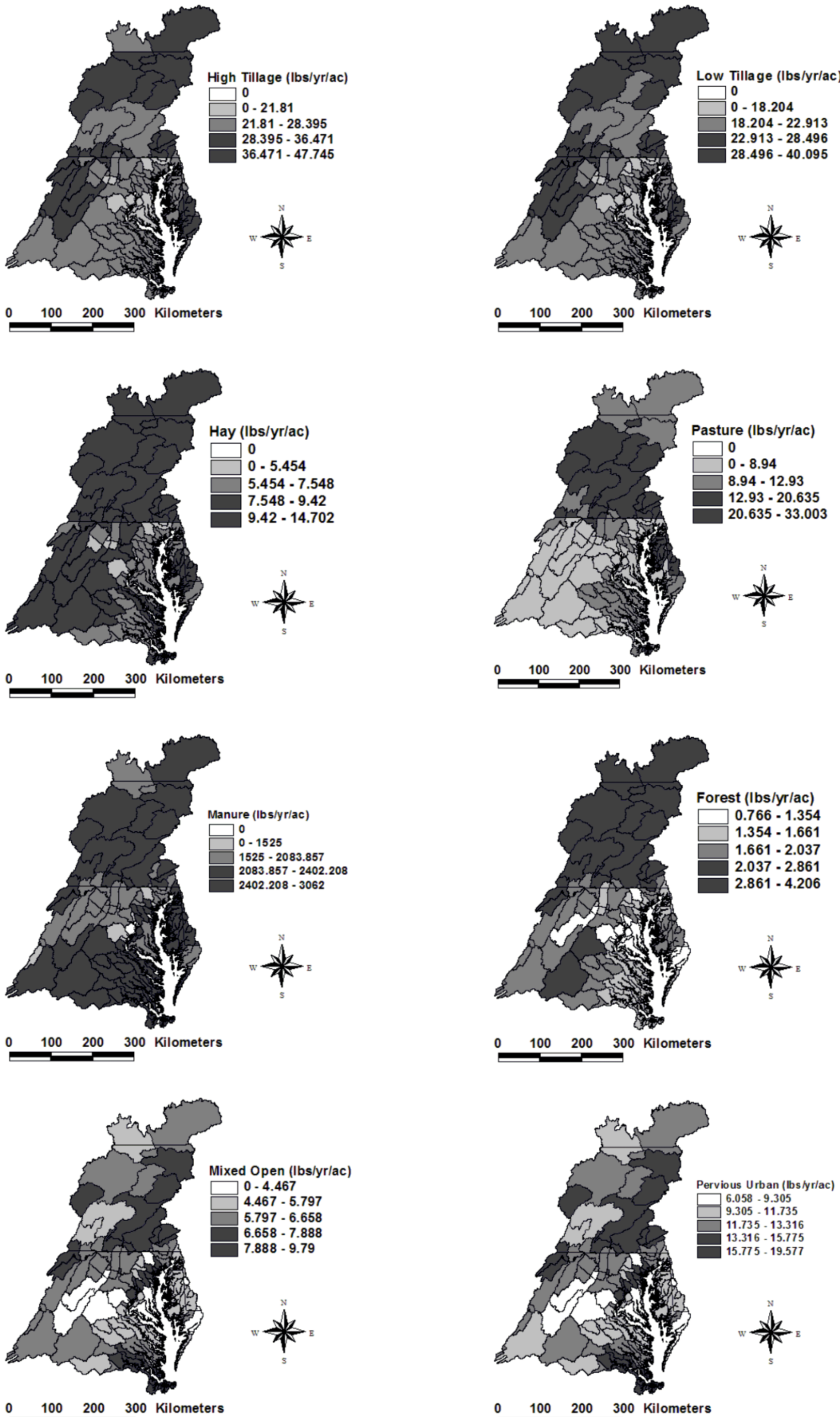


Figure 3-8: Maps of land use specific Current condition loading rates based on state segment locations.

Variability of NPS loading rates within a watershed are estimated using the standard deviation of a nearest neighbor sample. This is an empirical approach developed for this thesis that calculates the standard deviation of all loading rates associated with state segments adjacent to a local state segment. A local segment is defined as a segment coincident with a watershed centroid. Based on that local state segment, a local loading rate is identified. The assumption is that a local loading rate associated with a state segment coincident with a watershed centroid is representative of watershed conditions; a nearest neighbor mean is representative of conditions in the vicinity of a watershed. For purposes of modeling a watershed, a local loading rate is used.

For example, the Lake Linganore watershed centroid is located within state segment 4210. The local state segment Current condition loading rate for the impervious urban land use, therefore, is 9.9 lb/yr/ac (Figure 3-9). Thirteen adjacent Current condition loading rates and the local loading rate for impervious urban land use are identified. These loading rates are as follows: 10.37 lb/yr/ac, 9.30 lb/yr/ac, 9.63 lb/yr/ac, 9.90 lb/yr/ac, 9.79 lb/yr/ac, 9.40 lb/yr/ac, 9.30 lb/yr/ac, 9.69 lb/yr/ac, 5.43 lb/yr/ac, 9.48 lb/yr/ac, 9.69 lb/yr/ac, 9.47 lb/yr/ac, 9.85 lb/yr/ac, and 9.90 lb/yr/ac. The standard deviation of these loading rates for impervious urban land use, therefore, is 1.2 lb/yr/ac. Table 3-7 reports the Current condition loading rate mean for the local state segment and the nearest neighbor standard deviation for each of the 10 land use categories for the Lake Linganore watershed.

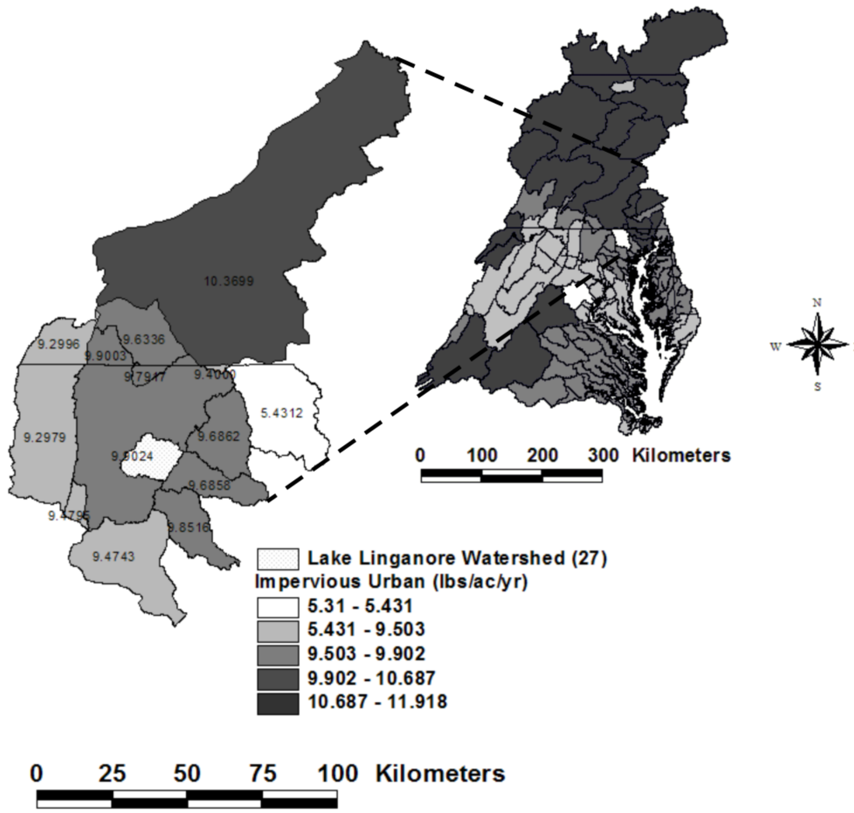


Figure 3-9: Map of Current condition loading rate for the impervious urban land use category. The map highlights adjacent state segments for the Lake Linganore watershed.

Table 3-7: Assumed Current condition loading rate mean and standard deviation for each land use category in the Lake Linganore watershed.

Land Use Category	Mean (lb/yr/ac)	Standard Deviation (lb/yr/ac)
High Till	27.86	4.79
Low Till	22.20	3.99
Hay	7.83	1.44
Pasture	11.39	3.53
Manure	1985.31	329.50
Forest	2.03	0.43
Non-Agricultural Herbaceous	6.66	1.17
Pervious Urban	13.31	2.35
Impervious Urban	9.90	1.17
Water	10.44	2.73

3.3.2.2 Testing for the Cumulative Distribution Function of the Loading Rates

The Kolmogorov-Smirnov one-sample (KS-1) test was used to test the null hypothesis that the sample loading rates (Tables 3-9 and 3-10) are likely to have been sampled from a normal probability distribution function (PDF) against the two tailed alternative. The two-tailed test statistic (k) is the maximum absolute difference between the cumulative distribution function (CDF) of the sample and the CDF of the probability function specified in the null hypothesis. The CDF for the sample was determined by rank-ordering the sample values from the smallest to the largest and dividing the rank by the sample size (n). If the computed value of the test statistic (k) is greater than the critical (c) value, the null hypothesis is rejected at either a five or 10 percent level of significance (Table 3-8). The test was repeated for the log-normal distribution by taking the log of the sample loading rates prior to computing the CDF, sample mean, sample standard deviation, and maximum difference. Both the entire set of non-zero state segment loading rates and a localized set of non-zero loading rates for the Lake Linganore watershed were evaluated.

Table 3-8: Critical values for sample sizes used in Table 3-9 and Table 3-10.

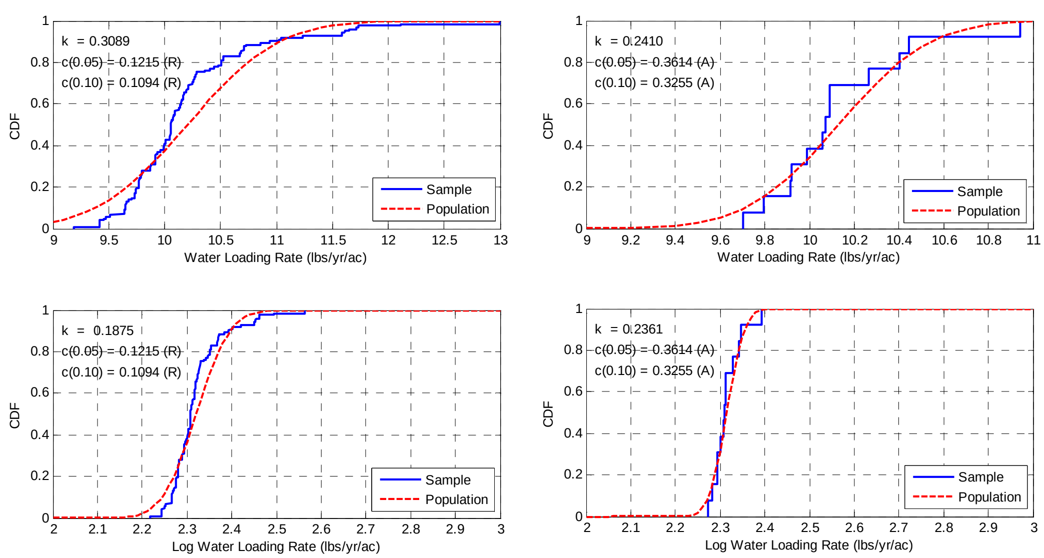
	Sample Size n						
Level of Significance	13	14	118	122	128	132	133
0.05	0.3614	0.3489	0.1235	0.1215	0.1187	0.1169	0.1164
0.10	0.3255	0.3142	0.1112	0.1094	0.1068	0.1052	0.1048

The KS-1 test for all state segments has a study location that crosses state boundaries (*i.e.*, Delaware, Maryland, New York, Pennsylvania, Virginia, and Washington, DC) and has a sample size of approximately 136 Current condition loading rates for each land use category. Both the normal distribution and log-normal distribution sample means and sample standard deviations are shown in Table 3-9.

Comparing the maximum differences for the normal and log-normal distributions in Table 3-9 to the critical values provided in Table 3-8 suggest that, on average, the log-normal distribution fits the sample loading rates slightly better than the normal-distribution. The null hypothesis is accepted for six out of 10 land use categories for the log-normal distribution. The null hypothesis is accepted for four out of 10 land use categories for the normal distribution. The observed KS-1 statistic (k) is approximately equal to the critical value for all land use categories, except for impervious urban and water categories, for both the normal distribution and the log-normal distribution. Fifty percent of the time the observed KS-1 statistic (k) is less for the normal distribution compared to that of the log-normal distribution. The CDF of the normal distribution (Figures 3-10a and 3-11) and the CDF of the log-normal distribution (Figures 3-10a and 3-12) suggest that both distributions are equally acceptable assumed distributions.

When the loading rates are evaluated for the local and adjacent state segments for a specific watershed, the decision to use a normal or log-normal distribution becomes less important. For example, a reduced sample size of Current condition loading rates local to the Lake Linganore watershed (Figure 3-9) show that both the normal and log-normal distribution can be assumed. A sample set of all 14 state segments are used for all land use categories except for water. The water category used 13 of the 14 state segments because one segment does not have a water loading rate. Both the normal and log-normal sample means and sample standard deviations are computed as shown in Table 3-10. The maximum differences for the normal and log-normal distributions in Table 3-10 are compared to the critical values provided in

Table 3-8. The null hypothesis is accepted for both distributions for all land use categories, except for impervious urban. The null hypothesis is rejected in both Table 3-9 and Table 3-10 for the impervious urban land use category. The rejection of the null hypothesis for the impervious urban land use category is due to two state segments having loading rates that are notably different from the other loading rates. This observation is interesting because impervious urban land use may occur in more isolated circumstances and represents the largest human impact of the 10 land use categories. However, testing the normal distribution (Figures 3-10b and 3-13) and log-normal distribution (Figures 3-10b and 3-14) supports that either distribution is consistent with observed loading rates for all land use categories, even though both distributions are not ideal for impervious urban land use.



(a) All Non-zero State Segments.

(b) State segments local to the Lake Linganore watershed.

Figure 3-10: Cumulative distribution functions for the water land use category.
Note: k = observed maximum difference; *c*(0.05) = critical value at the 5 percent level of significance; *c*(0.10) = critical value at the 10 percent level of significance; A = accepted the null; R = rejected null.

Table 3-9: KS-1 test on normal versus log-normal distributions for all state segments

		Normal Distribution			Log Normal Distribution		
Land Use Category	Sample Size (n)	Mean (lb/yr/ac)	Standard Deviation (lb/yr/ac)	Observed Statistic	Mean (lb/yr/ac)	Standard Deviation (lb/yr/ac)	Observed Statistic
Hi Till	128	26.65	5.55	0.13	3.26	0.21	0.09
Lo Till	128	21.81	4.86	0.17	3.06	0.22	0.13
Hay	128	7.82	2.10	0.09	2.02	0.28	0.09
Pasture	128	11.33	5.49	0.16	2.34	0.41	0.10
Manure	118	2141.60	358.04	0.08	7.65	0.19	0.12
Forest	133	1.83	0.60	0.19	0.56	0.29	0.01
Non-Ag. Herbaceous	132	6.14	1.27	0.07	1.79	0.22	0.09
Pervious Urban	133	12.29	2.54	0.07	2.49	0.21	0.09
Impervious Urban	133	9.63	0.83	0.23	2.26	0.10	0.27
Water	122	10.20	0.65	0.31	0.06	0.06	0.19

Table 3-10: KS-1 test on Normal versus log-normal distributions for the Lake Linganore watershed

		Normal Distribution			Log Normal Distribution		
Land Use Category	Sample Size (n)	Mean (lb/yr/ac)	Standard Deviation (lb/yr/ac)	Observed Statistic	Mean (lb/yr/ac)	Standard Deviation (lb/yr/ac)	Observed Statistic
Hi Till	14	26.18	4.79	0.20	3.24	0.23	0.26
Lo Till	14	20.96	3.99	0.18	3.02	0.22	0.22
Hay	14	7.46	1.44	0.14	1.99	0.23	0.19
Pasture	14	10.92	3.53	0.21	2.34	0.34	0.19
Manure	14	1989.50	329.50	0.24	7.58	0.20	0.29
Forest	14	1.78	0.43	0.14	0.55	0.27	0.19
Non-Ag. Herbaceous	14	6.36	1.17	0.16	1.83	0.22	0.18
Pervious Urban	14	12.74	2.35	0.15	2.53	0.22	0.18
Impervious Urban	14	9.37	1.17	0.40	2.23	0.16	0.43
Water	13	10.13	0.32	0.24	2.32	0.03	0.24

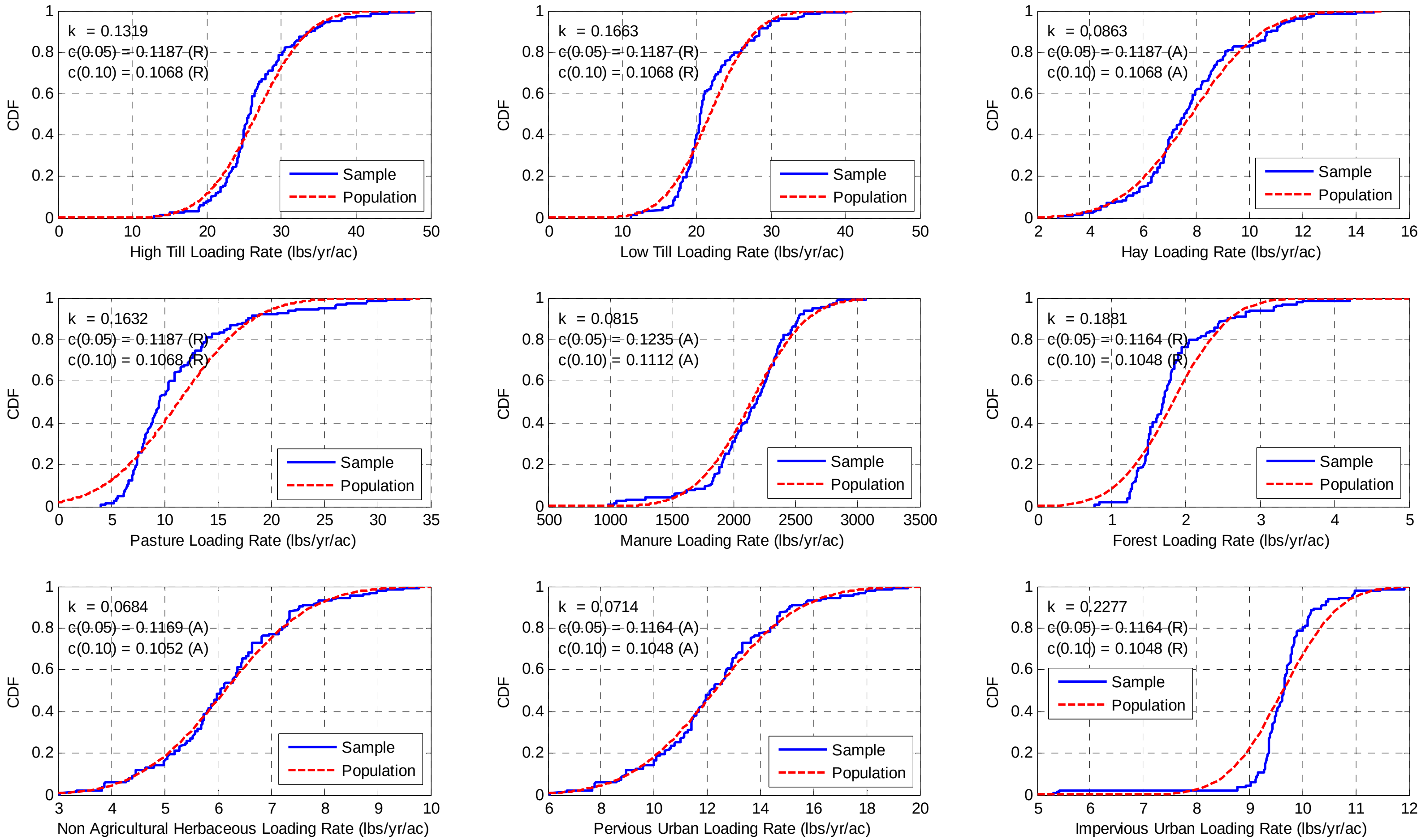


Figure 3-11: Normal cumulative distribution functions for all non-zero state segments.
Note: k = observed maximum difference; *c*(0.05) = critical value at the 5 percent level of significance; *c*(0.10) = critical value at the 10 percent level of significance; A = accepted the null; R = rejected null.

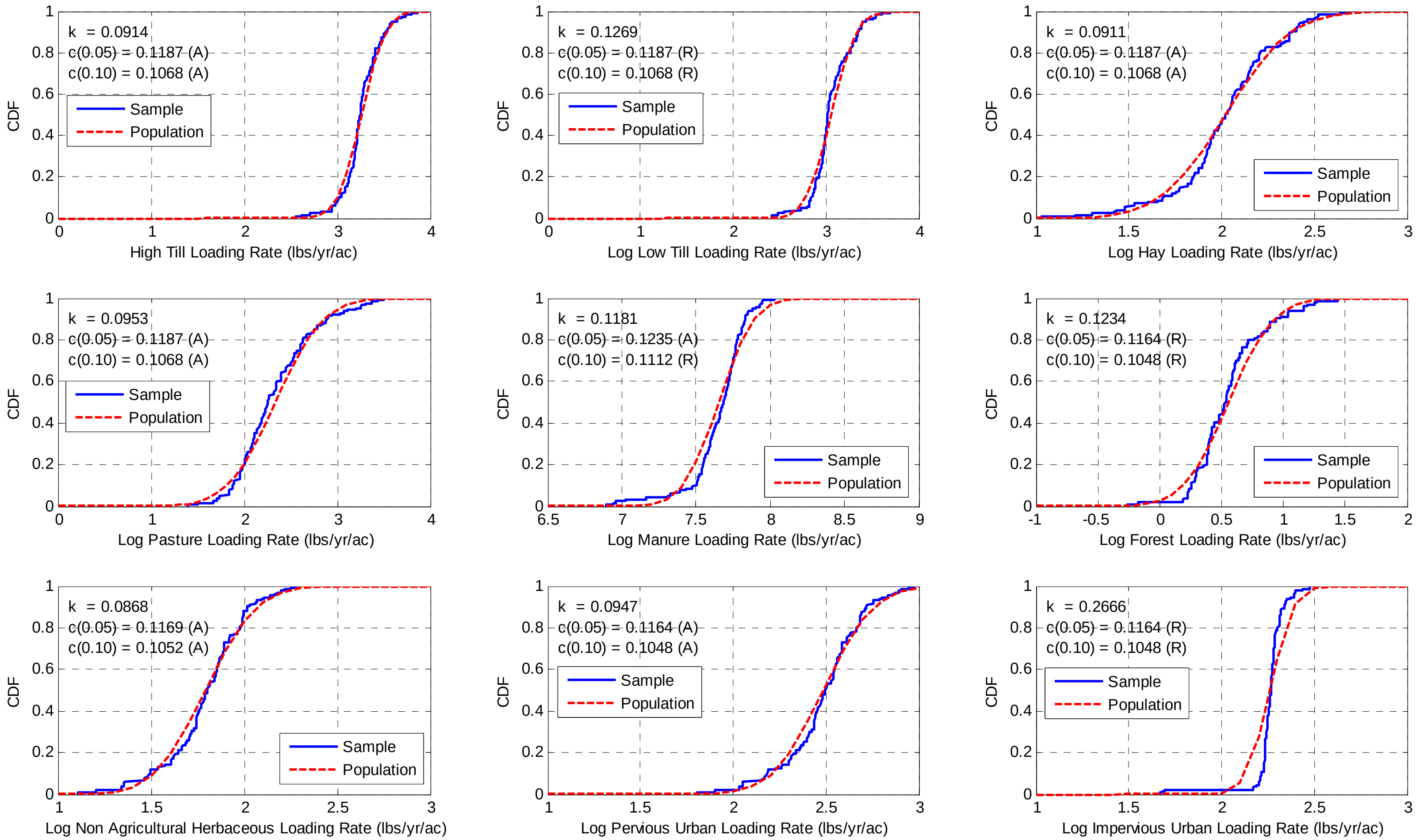


Figure 3-12: Log-normal cumulative distribution functions for all non-zero state segments.
Note: k = observed maximum difference; *c*(0.05) = critical value at the 5 percent level of significance; *c*(0.10) = critical value at the 10 percent level of significance; A = accepted the null; R = rejected null.

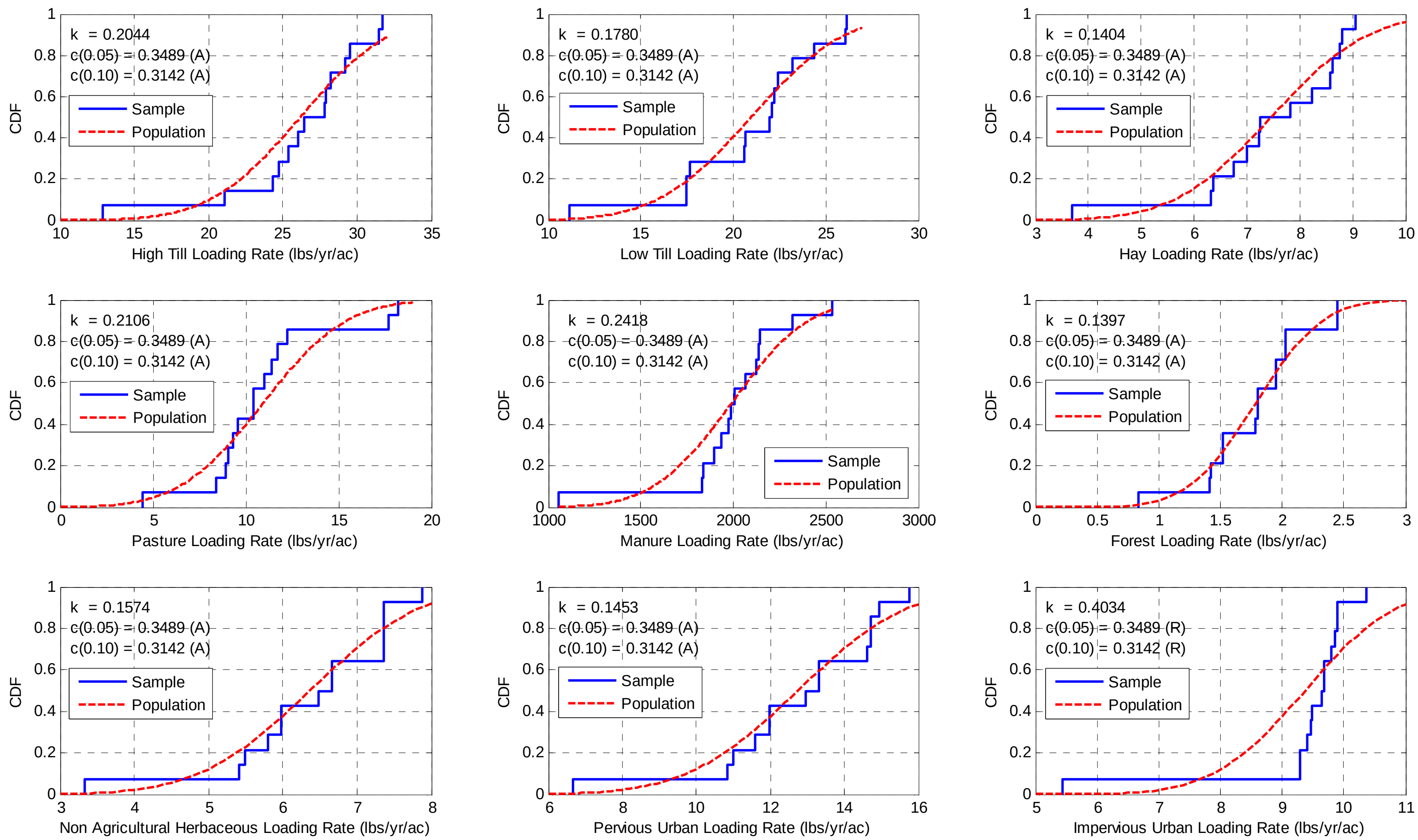


Figure 3-13: Normal cumulative distribution function for the Lake Linganore watershed.

Note: k = observed maximum difference; *c*(0.05) = critical value at the 5 percent level of significance; *c*(0.10) = critical value at the 10 percent level of significance; A = accepted the null; R = rejected null.

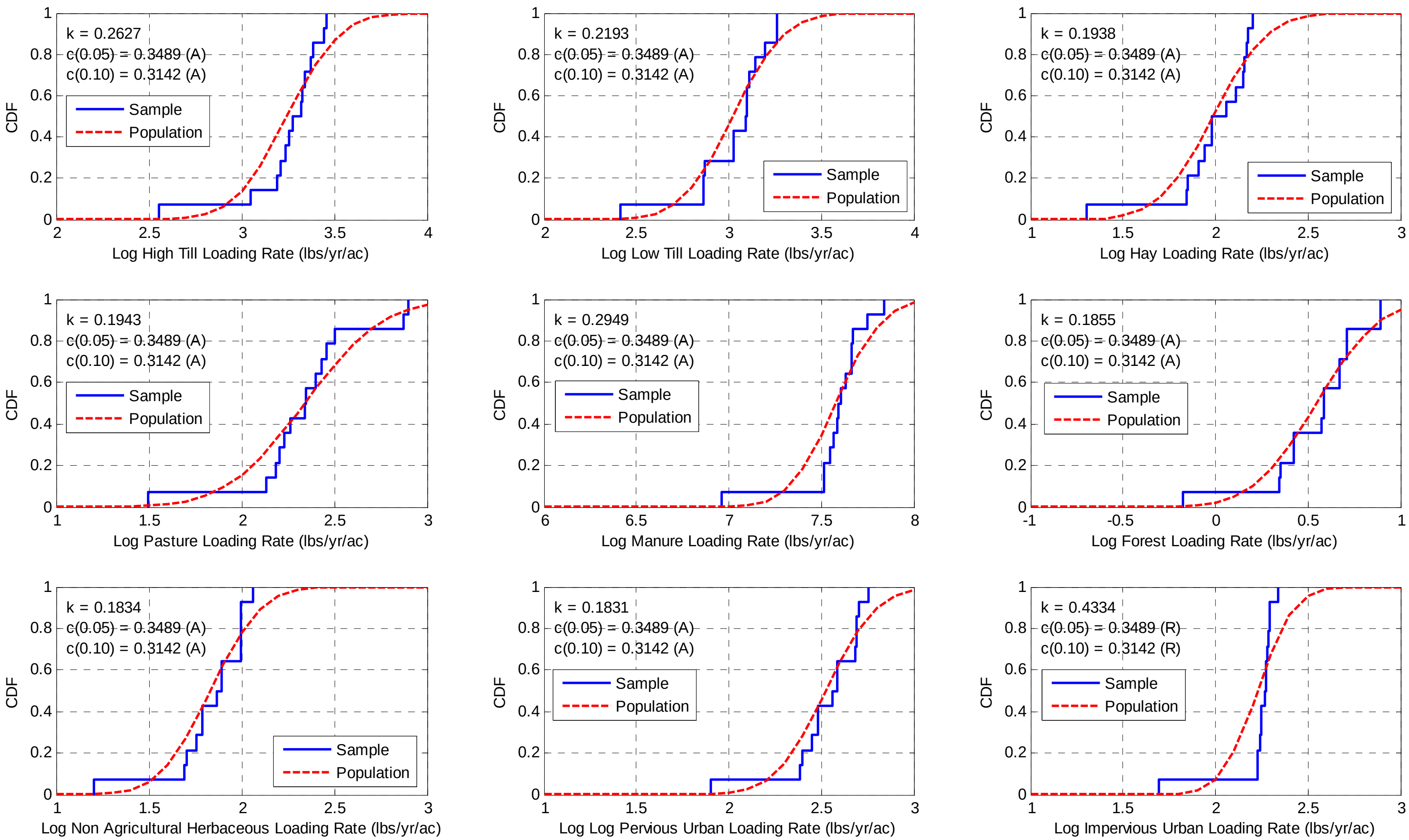


Figure 3-14: Log-normal cumulative distribution function for the Lake Linganore watershed.
Note: k = observed maximum difference; $c(0.05)$ = critical value at the 5 percent level of significance; $c(0.10)$ = critical value at the 10 percent level of significance; A = accepted the null; R = rejected null.

The loading rate samples, for both the Current condition and Tributary Strategy condition, are assumed to have normal distributions defined by a local loading rate at a watershed centroid and a nearest neighbor standard deviation. The evaluation of the all state segments associated with a non-zero loading rate reveals that the probability distributions for the loading rates can follow either a normal or log-normal probability distribution. However, when analyzed with a smaller sample size for local conditions, a normal distribution is better than a log-normal distribution. This decision is supported by the fact that, on average, the KS-1 statistic (k) is smaller for the normal distribution, compared to the log-normal distribution.

A similar study done on event mean concentrations (EMCs) using Nationwide Urban Runoff Program (NURP) data found that the probability distribution of EMCs follows a log-normal probability distribution (Novotny 1994). The difference in conclusions between this thesis and the NURP study may be due to the difference in the defined study location and sample size. Although the assumed normal distribution may not be true, the small sample size and averaged loading rate data sets are not robust enough to come to a statistically stronger distribution.

3.3.2.3 Calculation of a Load Normal Distribution

A total annual average load distribution was calculated for each pixel in a digitized watershed stream network. The major assumption is that loading rates are normally distributed as determined in Section 3.3.2.2. The normal distribution mean and standard deviation for each set of pixel nitrogen loads was, therefore, calculated as follows:

$$ML_j = \sum_{i=1}^{10} mc_i A_i \qquad 3\text{-}12$$

$$SL_j = \sqrt{\sum_{i=1}^{10} (sc_i A_i)^2} \qquad 3\text{-}13$$

where ML_j is the mean load (lb/yr/ac) for the normal distribution at pixel j in the digitized watershed stream network; i is one of 10 land use categories; mc_i is the assumed mean loading rate (lb/yr/ac), always identified as the local loading rate at the centroid of the watershed, for land use i; SL_j is the standard deviation load (lb/yr/ac) for the normal distribution at pixel j in the digitized watershed stream network; and sc_i is the calculated standard deviation (lb/yr/ac) of the set of adjacent and local loading rates; A_i is the relative area (dimensionless) of land use i, which is defined as the accumulated land use areas (Equation 3-1 through Equation 3-5) divided by the total drainage area at pixel i in the stream. Depending on the accumulated land use at a particular pixel location, a pixel may have a higher or lower probability of being in or out of compliance compared to pixels at other locations.

Figure 3-15 shows a differentiation in results by individual land use categories for the Current condition load calculation for the Lake Linganore watershed. The loading rate normal distribution mean and standard deviation were determined based on values reported in Table 3-10.

Using Equations 3-12 and 3-13, the mean Current condition load at the watershed outlet pixel was calculated as 11.2 lb/yr/ac with a standard deviation load of 1.0 lb/yr/ac, respectively. This calculation of the mean Current condition load is not much different from the earlier basic load calculation of 11.3 lb/yr/ac (Table 3-5). The mean load calculation in Equation 3-12 is only slightly changed from basic load calculation in Equation 3-7. The differences between the two equations are: (1) a single local loading rate is used instead of state segment specific loading rates, and (2) a dimensionless area quantity is used instead of land use area in acres. The calculations for Equations 3-12 and 3-13 were repeated using loading rate normal distributions for the Tributary Strategy condition. The outlet Tributary Strategy condition mean load and standard deviation load are 6.7 lb/yr/ac and 1.1 lb/yr/ac, respectively. This calculation of the mean Tributary Strategy condition load is exactly equal to the earlier basic load calculation of 6.7 lb/yr/ac (Table 3-6). The agreement between the basic load calculation and the normal distribution calculation is not surprising given that the load calculation process is linear.

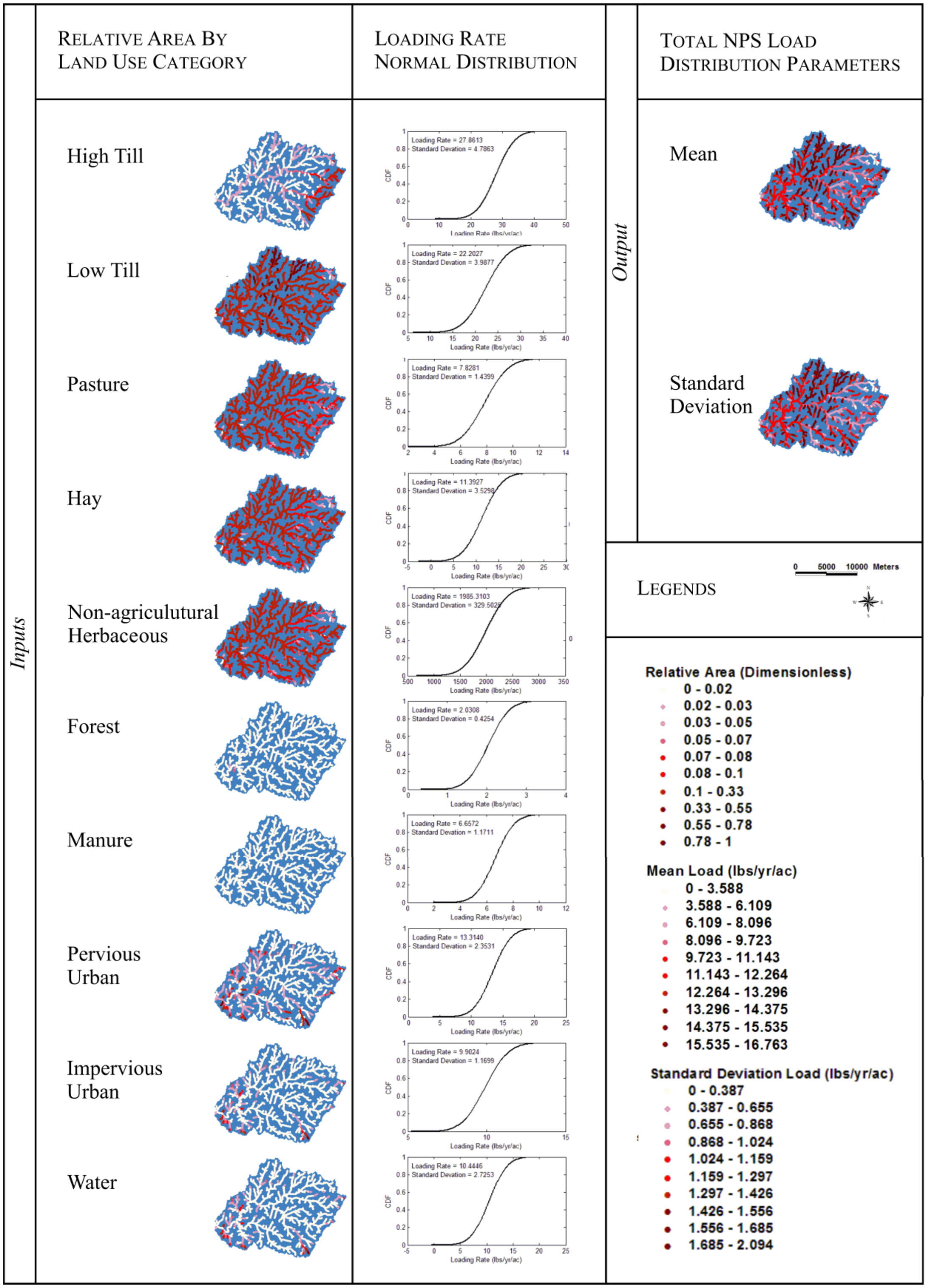


Figure 3-15: Load normal distribution calculation inputs and outputs for the Lake Linganore watershed.

3.4 Interpretation of Watershed Compliance with MDE/USEPA Standards

3.4.1 Watershed Selection

In order to investigate different ways of measuring compliance, a set of 35 watersheds were selected throughout Maryland. A watershed was selected if it had: (1) a comparable MDE/USEPA load; (2) either a Total Maximum Daily Load (TMDL) report or a Water Quality Analysis (WQA) report; (3) a complete set of GIS data; (4) a drainage outlet contained within Maryland. Watersheds with a TMDL for nitrogen were assumed to be noncompliant and had reported LAs that were used as a water quality criterion. Watersheds with WQA reports were assumed to be compliant because the MDE/USEPA report that the current monitoring information provides “sufficient justification to revise Maryland’s 303(d) list to remove nutrients as an impairing substance” in relation to the water body (*e.g.*, MDE 2002). Watersheds with WQA reports, therefore, lacked a NPS load allocation; the average value of all available LAs, therefore, was used as an assumed water quality criterion. Lastly, watersheds that had a TMDL report or WQA report for total phosphorus but did not have a TMDL or WQA report for nitrogen were considered. Occasionally, the TMDL report for these watersheds stated that the watersheds were phosphorus limited; meaning that the phosphorus load, not the nitrogen load, was causing the impairment. The phosphorus impaired watersheds also assumed a water quality criterion from an average value of all available nitrogen LAs. The set of 35 watersheds were delineated within the GIS and are listed in Tables 3-11 and 3-12, which summarize the information associated with each of the watersheds.

Table 3-11: Watershed identification numbers and background collected from available MDE/USEPA reports.

Id	Basin Name	Basin Code	Physiographic Province	Impairing Nutrient	Designated Use	Report Type
1	Lower Wicomico River	2130301	E	TN/TP	I/II	TMDL
2	Wicomico Creek	2130303	E	TN/TP	I	TMDL
3	Chicamicomico River	2130308	E	TN/TP	I	TMDL
4	Corsica River	2130507	E	TN/TP	II	TMDL
5	Middle Chester River	2130509	E	TN/TP	II	TMDL
6	Upper Chester River	2130510	E	TN/TP	II	TMDL
7	Bohemia River	2130602	E	TN/TP	I	TMDL
8	Northeast River	2130608	E (P)	TN/TP	I	TMDL
9	Worton Creek	2130611	E	TN/TP	I	TMDL
10	Fairlee Creek	2130611	E	TN/TP	I/II	TMDL
11	Still Pond Creek	2130611	E	TN/TP	I	TMDL
12	Swan Creek	2130706	W (P)	TN/TP	I	TMDL
13	Back River	2130901	W (P)	TN/TP	I	TMDL
14	Breton Bay	2140104	W	TN/TP	II	TMDL
15	Langford Creek	2130506	E	TN/TP	II	WQA
16	Bynum Run	2130704	W(P)	TN/TP	III	WQA
17	Middle Patuxent River	2131106	W (P)	TN/TP	IP	WQA
18	Saint Mary's Lake	2140103	W	TN/TP	I	WQA
19	Needwood Lake	2140206	P	TN/TP	IV	WQA
20	Lake Bernard Frank	2140206	P	TN/TP	IV	WQA
21	Little Seneca Lake	2140208	B (P)	TN/TP	IVP	WQA
22	Antietam Creek	2140502	B	TN/TP	IIIP	WQA
23	Savage River	2141006	A	TN/TP	IIIP	WQA
24	Piney Run Reservoir	2130908	P	TS/TP	IIIP	WQA
25	Southeast Creek	2130508	E	TP	I	TMDL
26	Clopper Lake	2140208	B (P)	TS/TP	I	TMDL
27	Lake Linganore	2140302	P	TP/TS	IVP	TMDL
28	Lake Habeeb	2141002	A	TP	IIIP	TMDL
29	Adkins Pond	2130203	E	TP/TS	I	TMDL
30	Tony Tank Lake	2130301	E	TP/TS	I	TMDL
31	Johnson Pond	2130304	E	TP/TS	I	TMDL
32	Urieville Lake	2130509	E	TP/TS	I	TMDL
33	Loch Raven Reservoir	2130805	P	TP/TS	IIIP	TMDL
34	Prettyboy Reservoir	2130806	P	TP	IIIP	TMDL
35	Centennial Lake	2131105	P	TP/TS	I	TMDL

Table 3-12: Watershed identification numbers and GIS identified watershed scale characteristics and land use.

Id	Reported Area (ac)	GIS Area (ac)	Area Error (%)	Stream Length (m)	Land Use (%) Calculated using CBPO Equations 3-1 through 3-5			
					Forest	Agricultural	Urban	Water
1	108,074	108,343	0.2	744,430	39	30	30	2
2	19,961	19,962	0.0	140,050	48	30	20	2
3	33,017	34,770	5.3	250,250	47	36	17	1
4	25,000	23,951	-4.2	131,760	26	60	9	6
5	36,060	38,254	6.1	235,550	16	68	11	5
6	113,485	113,849	0.3	711,510	34	56	9	1
7	35,544	31,536	-11.3	206,350	22	49	24	4
8	45,557	44,425	-2.5	300,010	41	26	23	11
9	11,656	9,774	-16.1	37,650	25	56	9	9
10	8,470	8,586	1.4	54,876	27	62	8	4
11	15,018	14,275	-4.9	90,259	27	46	6	21
12	16,127	14,950	-7.3	109,740	43	27	27	3
13	39,075	39,467	1.0	246,850	8	2	79	11
14	35,418	35,112	-0.9	231,010	56	21	17	5
15	27,027	27,318	1.1	160,460	20	62	6	12
16	14,358	14,871	3.6	103,220	33	25	42	0
17	37,052	36,916	-0.4	237,670	41	30	28	0
18	5,632	5,537	-1.7	36,250	80	9	7	4
19	8,192	8,130	-0.8	50,042	31	28	40	1
20	7,808	7,947	1.8	50,744	34	19	46	1
21	13,312	18,564	39.5	123,940	40	30	27	3
22	676	700	3.6	3,170	87	5	2	6
23	74,215	74,357	0.2	395,320	84	9	5	0
24	6,656	7,078	6.3	39,325	33	44	20	4
25	34,994	34,732	-0.7	205,000	28	63	7	2
26	1,830	1,861	1.7	11,394	14	5	76	4
27	51,904	56,287	8.4	341,670	36	50	14	0
28	5,632	5,636	0.1	31,797	79	12	6	3
29	13,824	13,479	-2.5	79,925	45	34	22	0
30	8,836	9,166	3.7	60,197	29	29	41	1
31	24,993	25,245	1.0	175,650	35	28	35	0
32	5,200	5,717	9.9	31,813	12	79	9	0
33	193,920	194,788	0.4	1,230,000	48	27	22	2
34	51,200	51,063	-0.3	319,070	42	37	17	3
35	2,221	2,350	5.8	12,540	35	36	28	2

The MDE/USEPA reports identified areas at the Maryland eight-digit watershed level. This level was usually the area of interest in MDE/USEPA reports, even though the areas were probably too large to successfully address with a comprehensive watershed management plan. As a TMDL or WQA report was developed, the MDE/USEPA occasionally focused on smaller subareas to demonstrate a water quality or habitat improvement. These subareas were identified within the GIS using road maps and stream network maps provided in MDE/USEPA reports.

Differences between the MDE/USEPA reported drainage area and the GIS delineated drainage area were used to identify the watershed outlet for poorly defined watershed boundaries. According to Moglen and Hartman (2001), GIS delineated drainage areas greater than approximately 2,220 ac can be expected to have a less than five percent error when using 30-meter DEM data. However, if this meant that an entire MDE/USEPA mapped reach was eliminated within the GIS, an error in drainage area was overlooked. A large error in drainage area meant that the MDE/USEPA and the delineated GIS outlet may not agree. The affects of a large error in drainage area on the interpretation of watershed compliance are discussed in the results section.

The watersheds examined in this thesis are distributed across five physiographic provinces: (1) Appalachian Plateau; (2) Ridge and Valley Province; (3) Blue Ridge Province; (4) Piedmont Plateau Province; (5) Eastern Coastal Plain Province, and Western Coastal Plain Province. The 35 watershed locations are shown in Figure 3-16. The Coastal Plains and Piedmont Provinces contain the majority of reported watersheds, with heavier emphasis on the Eastern Coastal Plain Province compared to the Western Coastal Plain Province. Both the Eastern Coastal Plain Province and the Piedmont

Provinces are heavily agricultural. The watersheds with nutrient WQA reports are distributed throughout all five provinces with emphasis on the Western Coastal Plain Province. The Western Coastal Plain Province has a smaller percentage of agricultural land cover compared to the percentages of urban and forest land cover. The watersheds reported in the Appalachian Plateau and Blue Ridge Provinces have larger percentages of forest land cover, relative to the other land covers.

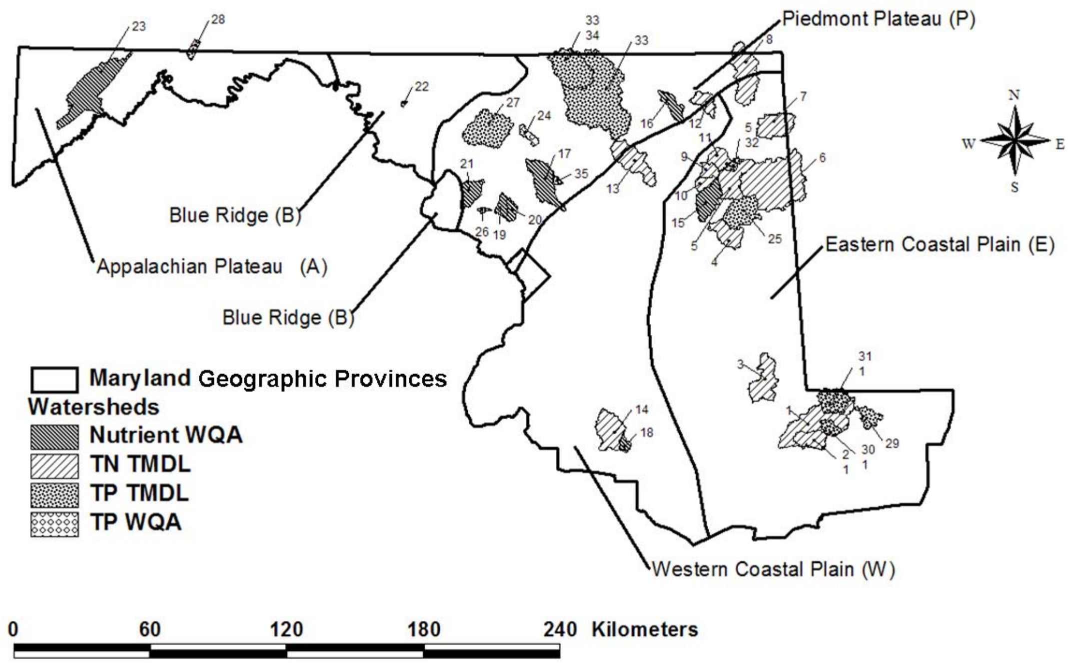


Figure 3-16: Watershed identification numbers located within the five Physiographic Provinces of Maryland.

3.4.1.1 Problems Identified During Watershed Selection

There were three limitations to the watershed selection process. The first limit was that the GIS resources prevented some large watersheds from being modeled. The second limit was that equivalent MDE/USEPA reported areas could not be replicated. The first two limits prevented the selection of the Lower Susquehanna River (Basin Code 02120201), Upper Pocomoke River (Basin Code 02130203), Manokin River

(Basin Code 02130208), Baltimore Harbor (Basin Code 02130903), Upper Patuxent River (Basin Code 02131104), Port Tobacco River (Basin Code 02140109), Town Creek (Basin Code 02140512), and Upper North Branch Potomac River (Basin Code 02141005). The third limit was that CBPO state and county segments were unavailable for peripheral areas within Maryland. The third limit prevented the inclusion of watersheds within the eight-digit basin code 02130103, specifically: Herring Creek, Bishopville Prong, Turville Creek, Shingle Landing Prong, and Saint Martin River. The fourth limit was that the agricultural area was misrepresented in CBPO land cover to land use conversions for certain county segments; this problem originates from assumed loading rates developed by the CBPO. The fourth limit prevented the inclusion of the Town Creek (Basin Code 2130403), Mattawoman (Basin Code 2140111), and Bird River (Basin Code 2130704) watersheds.

3.4.2 Load Criteria for Water Quality Compliance Interpretations

Numeric criteria provide definite interpretations of compliant and noncompliant conditions, establish a base goal for water quality measurements, and reduce ambiguity for management decisions. Despite these advantages, however, Maryland does not have a methodology for listing waters impaired by nutrients based solely on numeric nutrient criteria (USEPA 2004; Dalmasy, pers. comm., 2007). The lack of numeric criteria creates difficulties in the assessment of river and stream conditions, and the development of protective water quality standards, thus hindering the water quality manager's ability to implement management strategies. Pending development of nutrient criteria, MDE uses concentrations for dissolved oxygen and chlorophyll a as indicators that unacceptable concentrations of nutrients are present. Compliance of calculated load distributions, therefore, could not be interpreted based on water quality criteria in units of mass per volume for nitrogen. Following a recommendation provided by the U.S. EPA (USEPA 2007), a set of watershed specific load criteria was collected from available TMDL reports. An average of all available load criteria was assumed for watersheds without a TMDL report.

3.4.2.1 Set of Watershed Specific Criteria collected from TMDL Reports

Nitrogen load criteria were collected from all 23 available nitrogen TMDL reports, of which 13 reports were specific to watersheds selected for modeling (Table 3-13). The Bohemia River watershed (7) was not included in this set because the reported TMDL was for a seasonal average instead of an annual average and would have caused a bias in the results of this thesis. Only the load allocation (LA) of the TMDL Equation 2-4 was used as the criterion for comparison with modeled NPS loads. The waste load allocation (WLA), the margin of safety (MOS), and the future allocation (FA) were not considered during criteria development. The waste load allocation was excluded because it represents point source loads, which were not accounted for in the calculated load distributions. The margin of safety and future load allocations were not incorporated into the criteria development because these values were inconsistent in MDE /USEPA methods and were not always reported.

The watershed LA (lb/yr) criteria reported in Table 3-14 apply to their respective watershed outlets. The LA criteria were, therefore, divided by their drainage area (ac) as shown in Table 3-14. This step assumed that area relative LA (lb/yr/ac) criteria could be applied to stream pixels upstream of a watershed outlet. The area relative LA criterion provided a tool for gauging whether modeled NPS loads were compliant or noncompliant compared to the long-term TMDL NPS load allocations and, by inference, water quality standards.

Table 3-13: Nitrogen Total Maximum Daily Load (TMDL) Allocations

		Loads from Equation 2-4				
ID	Basin Name	TMDL (lb/yr)	LA (lb/yr)	WLA (lb/yr)	MOS (lb/yr)	FA (lb/yr)
1	Lower Wicomico River	1,266,530	832,460	409,130	24,940	
2	Wicomico Creek	104,584	101,538	0	3,046	
3	Chicamicomico River	203,608	197,500	0	6,108	
4	Corsica River	287,670	268,211	7,598	10,327	1,534
5	Middle Chester River	275,437	217,447	47,567	10,424	
6	Upper Chester River	614,612	561,653	26,452	26,507	
8	Northeast River	168,344	74,749	84,268	3,498	5,829
9	Worton Creek	18,016	17,476	0	540	
10	Fairlee Creek	83,420	79,490	260	2,650	1,020
11	Still Pond Creek	34,918	33,901	0	1,017	
12	Swan Creek	252,094	121,907	124,092	6,095	
13	Back River	1,773,100	26,323	1,737,626	9,151	
14	Breton Bay	187,195	119,902	62,580	4,713	
*	Town Creek	6,471.7	144.1	5,620.80	706.8	
*	Mattawoman Creek	217,986	116,699	85,784	5,814	9,689
*	Herring Creek	9,547	8,592	0	955	
*	Turville Creek	26,272	23,645	0	2,627	
*	Bishopville Prong	64,946	61,699	0	3,247	
*	Shingle Landing Prong	104,700	71,644	29,285	3,771	
*	St. Martin River	222,110	141,453	73,212	7,445	
*	Manokin River	353,680	301,890	42,730	9,060	
*	Baltimore Harbor	5,323,963	1,246,036	4,042,625	35,302	
*	Port Tobacco River	243,310	190,470	24,920	5,840	22,080

Note: TMDL = Total Maximum Daily Load; LA = Load Allocation (Nonpoint-source); WLA = Waste Load Allocation (Point Source); MOS =Margin of Safety; FA = Future Allocation; * Watershed was not assigned an ID because it is not among the 35 watersheds selected for analysis but was included in the average TMDL criterion.

Table 3-14: Watershed specific load allocation (LA) criteria obtained from MDE/USEPA TMDL reports.

ID	Basin Name	Area (ac)	LA (lb/yr)	*y* (lb/yr/ac)	$\hat{y}$ (lb/yr/ac)	*e* (lb/yr/ac)	*e/y*
1	Lower Wicomico River	108074	832460	7.7	4.9	-2.8	-0.4
2	Wicomico Creek	19961	101538	5.1	4.7	-0.3	-0.1
3	Chicamicomico River	33017	197500	6.0	4.8	-1.2	-0.2
4	Coresica River	25000	268211	10.7	4.8	-6.0	-0.6
5	Middle Chester River	36060	217447	6.0	4.8	-1.3	-0.2
6	Upper Chester River	113485	561653	4.9	4.9	0.0	0.0
8	Northeast River	45557	74749	1.6	4.8	3.2	2.0
9	Fairlee Creek	8470	79490	9.4	4.7	-4.7	-0.5
10	Worton Creek	11656	17476	1.5	4.7	3.2	2.1
11	Still Pond Creek	15018	33901	2.3	4.7	2.5	1.1
12	Swan Creek	16127	121907	7.6	4.7	-2.8	-0.4
13	Back River	39075	26323	0.7	4.8	4.1	5.9
14	Breton Bay	35418	119902	3.4	4.8	1.4	0.4
*	Town Creek	597	144	0.2	4.7	4.5	22.5
*	Mattawoman Creek	62474	116699	1.9	4.8	3.0	1.6
*	Herring Creek	3016	8592	2.8	4.7	1.9	0.7
*	Turville Creek	6046	23645	3.9	4.7	0.8	0.2
*	Bishopville Prong	10817	61699	5.7	4.7	-1.0	-0.2
*	Shingle Landing Prong	11832	71644	6.1	4.7	-1.3	-0.2
*	St. Martin River	26110	141453	5.4	4.8	-0.7	-0.1
*	Manokin River	52351	301890	5.8	4.8	-1.0	-0.2
*	Baltimore Harbor	268671	1246036	4.6	5.2	0.6	0.1
*	Port Tobacco River	28000	190470	6.8	4.8	-2.0	-0.3

Note: LA = Load Allocation (Nonpoint-source); y = Load Allocation divided by Area; $\hat{y}$ = Equation 3-13; *e* = residuals ($\hat{y}$ –y); *e/y* = relative residuals; * Watershed was not assigned an ID because it is not among the 35 watersheds selected for analysis but was included in the average TMDL criterion.

3.4.2.2 A Watershed Generic Criterion for Watersheds without TMDL reports

Two alternatives were evaluated for a generic criterion to use for watersheds that did not have a TMDL report: (1) fit a regression equation to the set of 23 reported area relative LA and their respective drainage areas; (2) average the set of 23 LA criteria. A linear bivariate structure was assumed for the first alternative

$$\hat{y} = ax + b \tag{3-12}$$

where $\hat{y}$ (lb/yr/ac) is the LA divided by the drainage area, x (ac) is the drainage area, and coefficients a and b are fitted constants. The coefficients were fitted to the set of 23 areas and LA values (Table 3-14) using a least squares objective function. The fitted coefficients $a = 1.7 \times 10^{-6}$ and $b = 4.7$ yielded the following prediction equation

$$\hat{y} = 1.7 * 10^{-6}x + 4.7 \tag{3-13}$$

The coefficients used in Equation 3-13 had the following goodness-of-fit statistics for estimating area relative LA criteria: correlation coefficient $R = 0.03$; coefficient of multiple determination $R^2 = 0.001$; and standard error of estimate $S_e = 2.8$ lb/yr/ac; standard error ratio $S_e/S_y = 1.0$. The coefficient of multiple determination (R^2) is a more informative statistic compared to the correlation coefficient (R) because it describes the percent of total variation explained by least-squares fitting. For Equation 3-13 only 0.1 percent of the total variation in area relative LA is explained by watershed drainage area. The standard error ratio indicates that the likely error of prediction of Equation 3-13 is worse relative to the accuracy of prediction when using the 4.8 lb/yr/ac average value of the area relative LA criteria (Table 3-14). Additionally, the relative residuals (Table 3-14) were exceptionally large, exceeding a value of 0.5 lb/yr/ac for seven watersheds. The linear bivariate Equation 3-13 was, therefore, abandoned for the

4.8 lb/yr/ac average criterion value. Predicted values for Equation 3-13 and the averaged criterion value are compared to the observed area relative LA and their respective drainage areas in Figure 3-17.

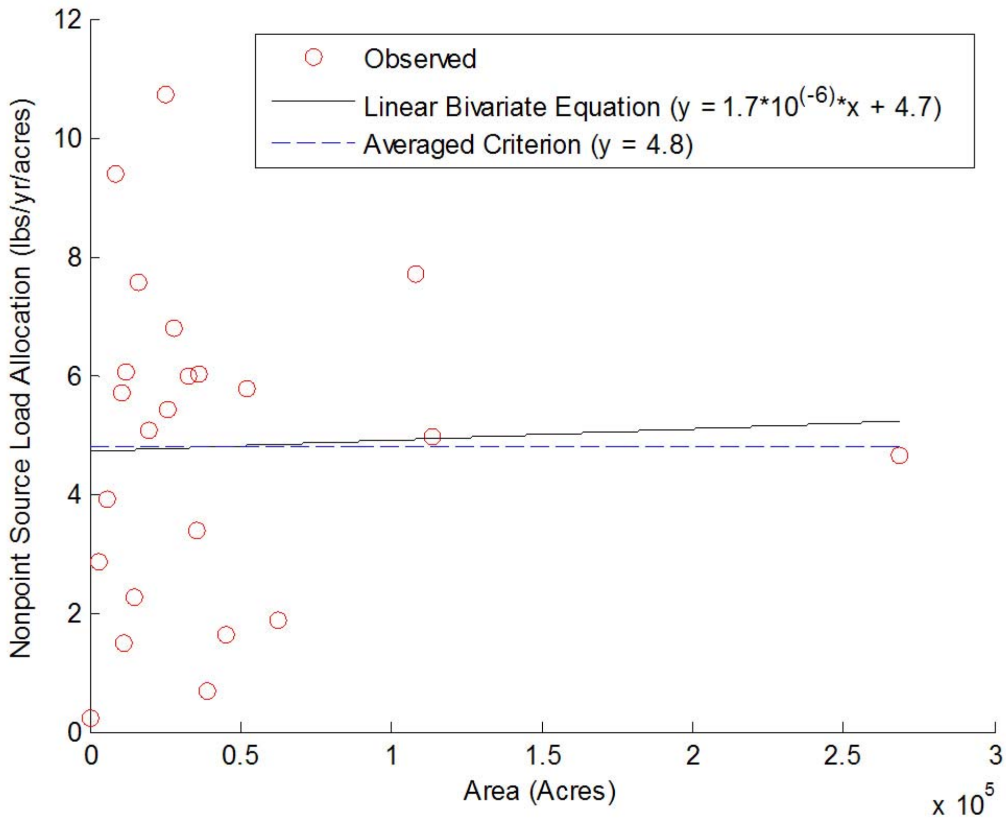


Figure 3-17: Two estimation methods for area relative load allocations (LA) versus watershed drainage area.

Therefore, the remaining selected watersheds that did not have an MDE/USEPA reported annual LA were assumed to have an averaged criterion value of 4.8 lb/yr/ac. The Urieville Lake watershed (35) was an exception because its drainage areas overlapped the Middle Chester River watershed (6); therefore, both watersheds 35 and 6 were given an area relative LA of 6.0 lb/yr/ac. The Tony Tank Lake (30) and Johnson Pond (31) watersheds were exceptions because their drainage areas overlapped the Lake Wicomico watershed (1); therefore, watershed 30, 31, and 1 were given an area relative LA of 7.7 lb/yr/ac.

3.4.3 Perspective One: Outlet Mean Load Comparison

The area-relative, TMDL-based LA (lb/yr/ac) was compared to the mean load (lb/yr/ac) at each watershed outlet. The watershed compliance was determined as shown in Figure 3-18.

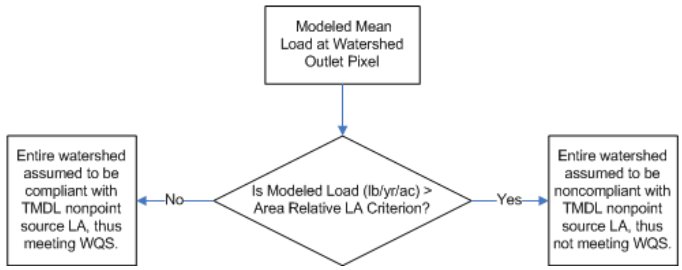


Figure 3-18: Outlet mean annual load comparison decision flow chart.

If the outlet mean load was greater than the area-relative LA criterion, then the entire watershed was assumed to be noncompliant with the TMDL NPS load allocation. The watershed, therefore, was assumed to not meet water quality standards. Alternatively, if the outlet mean load was less than or equal to the area relative LA criterion, then the entire watershed was assumed to be compliant with the TMDL NPS load allocation and, thus, was assumed to meet water quality standards.

For example, the Lake Linganore watershed (27) outlet had a Current condition mean load of 11.2 lb/yr/ac. The watershed (27) was listed as impaired for phosphorus and sediment, and not for nitrogen; therefore, a nitrogen TMDL LA was not available and an area relative LA criterion of 4.8 lb/yr/ac was assumed. A comparison of the two loads showed that the mean load at the watershed outlet is greater than the criterion load. The watershed (27) outlet pixel has a Tributary Strategy condition mean load of 6.7 lb/yr/ac, which is also greater than the load criterion. The watershed (27) is, therefore, designated as noncompliant with the TMDL NPS load allocation for both the Current condition and the Tributary Strategy condition.

In contrast, the Saint Mary's Lake watershed (18) outlet pixel had Current condition and Tributary Strategy condition mean loads of 3.3 lb/yr/ac and 2.7 lb/yr/ac, respectively. Because the watershed (18) was listed as being compliant for nitrogen, an area relative LA criterion of 4.8 lb/yr/ac was assumed. Both condition mean loads are less than the load criterion and, therefore, are assumed to be compliant with the TMDL NPS load allocation.

As demonstrated, the outlet mean load comparison uses a straightforward interpretation of the LA portion of the TMDL Equation 2-4. This first perspective is a nominal comparison between a mean annual load and a maximum allowable load at a watershed outlet (Section 3.4.3). This perspective assumes that the mean annual load conditions at the outlet always represent all upstream conditions along a watershed stream network. This perspective, however, may not fully represent the variation in accumulated NPS loads at the outlet pixel resulting from the spatial variation in land use activities located upstream from that pixel. Therefore, this thesis evaluated a second perspective that utilizes a load normal distribution to determine the probability of a load exceeding a maximum allowable load at a watershed outlet (Section 3.4.4).

3.4.4 Perspective Two: Watershed Outlet Probability Comparison

The watershed outlet probability perspective uses the mean and standard deviation of the calculated load distribution at the watershed outlet. This perspective accounts for the spatial variation in the land use activities and assumes that the land use categories remain constant from year to year. This perspective assumes that a watershed is noncompliant with TMDL NPS load allocations if an area relative LA criterion has a probability of being exceeded greater than 10 percent. Alternatively, a watershed is assumed compliant of TMDL NPS load allocations if the load criterion had a probability of being exceeded less than or equal to 10 percent. Figure 3-19 summarizes how watershed compliance was determined.

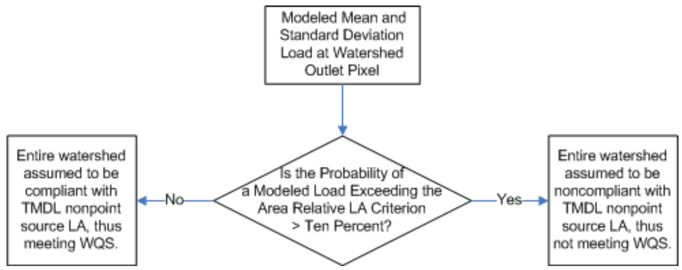


Figure 3-19: Outlet exceedance probability comparison decision flow chart.

The 10 percent criterion was based on a USEPA (2000a, 2000b) recommendation that if State observations are averaged over the year, the average should not exceed the criterion. In particular, no more than 10 percent of the observations used in calculating that average should exceed the criterion. This standard refers to a load distribution in time. If calculated load normal distribution of this thesis represents the uncertainty in the load estimate, some of that uncertainty may come from temporal variability in annual loads. Therefore, the 10 percent criterion was adopted for evaluating the second compliance perspective.

In this case, the Lake Linganore watershed (27) outlet has a mean load of 11.2 lb/yr/ac and standard deviation load of 1.1 lb/yr/ac, which were used to derive an assumed normal distribution for the Current condition. A second distribution was derived for the Tributary Strategy condition (with a mean of 6.7 lb/yr/ac and a standard deviation of 1.1 lb/yr/ac). Figure 3-20 shows that the Current condition and the Tributary Strategy condition have respective 100 percent and 96 percent probabilities of exceeding the 4.8 lb/yr/ac LA criterion. Because both probabilities are greater than 10 percent, the Lake Linganore watershed is designated as noncompliant.

Similarly, two distributions were derived for the Current condition (with a mean of 3.3 lb/yr/ac and a standard deviation of 0.1 lb/yr/ac) and Tributary Strategy condition (with a mean of 2.7 lb/yr/ac and a standard deviation of 0.1 lb/yr/ac) for the Saint Mary's Lake watershed (18) outlet. Figure 3-21 shows that both the Current condition and Tributary Strategy condition have a zero percent probability of exceeding the 4.8 lb/yr/ac LA criterion. Because both probabilities were less than 10 percent, the Saint Mary's Lake watershed is designated as compliant.

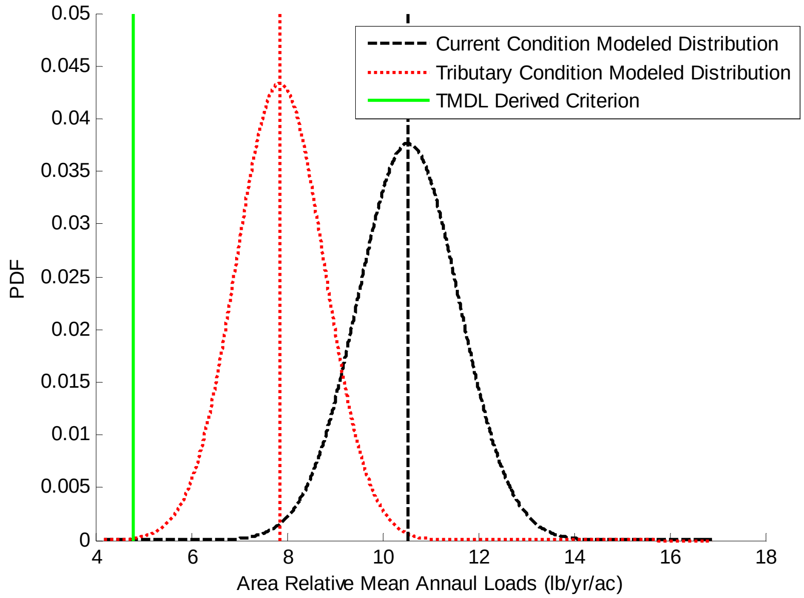


Figure 3-20: Lake Linganore watershed (27) probability distributions and area relative LA criterion.

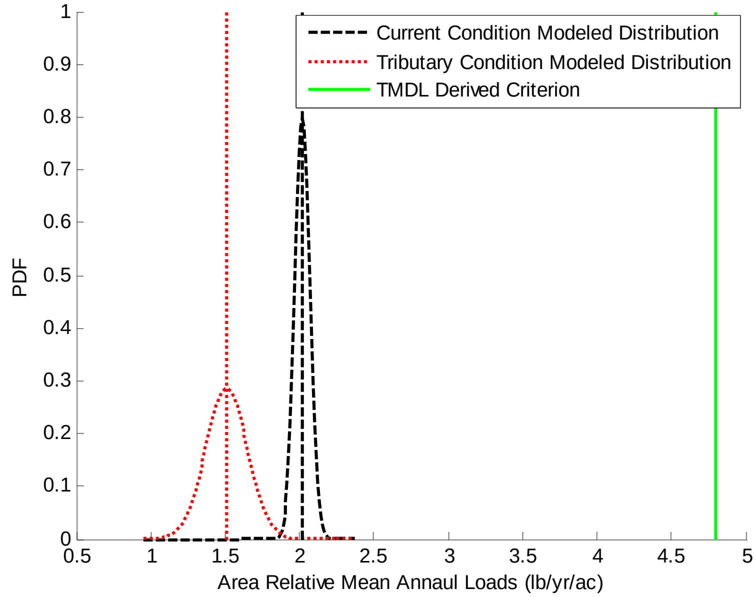


Figure 3-21: Saint Mary's Lake watershed (18) probability distributions and area relative LA criterion.

Although the compliance decisions for both the outlet mean load comparison and the outlet exceedance probability agree in the above examples, there is a possibility for decisions to disagree. This hypothetical scenario describes a watershed which is compliant because the mean is close to the LA criterion. For example, assume a mean annual load distribution defined by a mean of 4.7 lb/yr/ac and a standard deviation of 0.2 lb/yr/ac. Figure 3-22 shows that the area relative load is less than the 4.8 lb/yr/ac LA criterion. Comparison of the LA criterion with the outlet mean load, therefore, determines the watershed as compliant. The probability of exceeding the LA criterion, however, is 30.9 percent, which is greater than 10 percent; the exceedance probability comparison, therefore, would determine the watershed as noncompliant. The later decision contrasts with the original decision. This thesis evaluates the frequency of which these two contrasting compliance interpretations occur within the 35 selected watersheds.

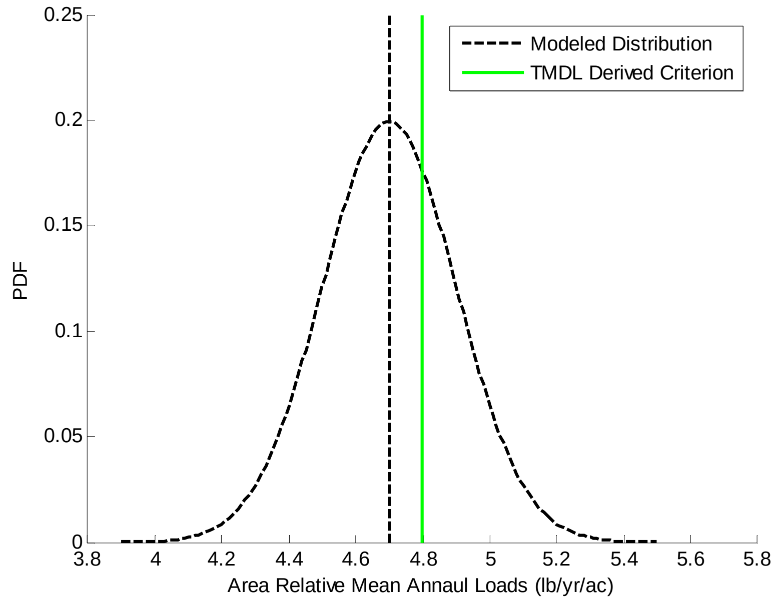
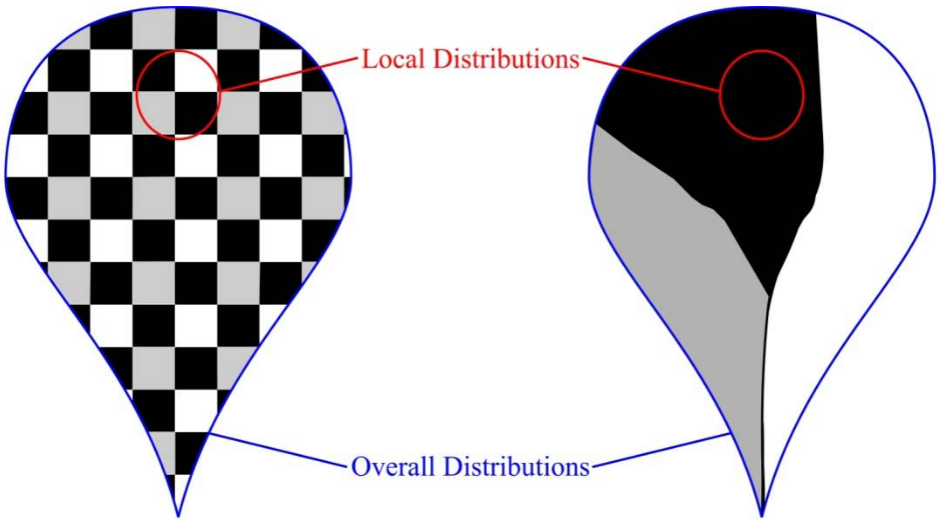


Figure 3-22: Outlet mean annual load compliant but outlet probability of exceedance noncompliant.

3.4.5 Perspective Three: Percent Stream Length Comparison

A problem with the two types of outlet comparisons is that, neither comparison accounts for the spatial variability of mean annual loads at stream locations upstream of a watershed outlet. Some watersheds may be spatially distributed in their land use and, therefore, are represented by their outlet compliance decision. For example, Figure 3-23(a) shows a watershed where the local distribution of three land use categories is approximately the same as the overall watershed distribution of those same three land use categories. On the other hand, some watersheds may have spatially concentrated single land use activities that result in subareas that are not represented by their watershed outlet compliance decision. Figure 3-23(b) shows a watershed where the local distribution is represented by a single land use category; however, the overall distribution includes three land use categories.



(a) Spatially Distributed (b) Spatially Concentrated

Figure 3-23: Differences in local versus overall spatial distributions for heterogeneous land use.

The outlet exceedance probability comparison used by perspective two, therefore, was applied at every point along the watershed stream network. To do this, the mean and standard deviation of the modeled NPS load were collected and used to calculate load distributions at every stream pixel upstream of the watershed outlet. This comparison used the same 10 percent probability of exceedance scenario shown in Figure 3-19 to determine the compliance of each individual stream pixel.

An understanding of the compliance of each pixel in the stream was used to develop a measure of the health of each part of the watershed. This was, in part, accomplished by comparing the Current condition to the Tributary Strategy condition to place stream pixels into one of the following three categories: always noncompliant;

noncompliant for Current conditions, but compliant for Tributary Strategy conditions; and always compliant. Three stream length percentages were calculated from the division of total stream length between each of the three categories. The whole watershed was designated to be compliant if at least 70 percent of the total stream length was compliant for both conditions.

The whole watershed compliance with water quality standards decisions, where at least 70 percent of the total stream length has loads that do not exceed the LA criterion more than 10 percent, was arbitrarily chosen. Currently, guidance does not exist to define the length in kilometers that is necessary for a spatial stream network to meet water quality standards. The idea, however, that 100 percent compliance with water quality standards for any given stream network length seems unreasonable. Therefore, the 70 percent criterion was loosely applied such that watersheds with between 50 to 90 percent compliant stream lengths were still said to be overall compliant with water quality standards.

The Lake Linganore watershed (27) is an example with uniform heterogeneous land use as shown in Figure 3-24. The land use distribution comprises 36 percent forest, 50 percent agriculture, 14 percent urban, and 0 percent water. The watershed (27) had a total stream length of 341,670 m, where 1 percent was compliant for both conditions, 3 percent was noncompliant for Current conditions but compliant for Tributary Strategy conditions, and 96 percent was noncompliant for both conditions. The watershed (27), therefore, was noncompliant for 99 and 96 percent of the total stream length for the Current and Tributary Strategy conditions, respectively. Applying the 70 percent criterion, the whole watershed (27) was determined to be noncompliant. This is a reasonable conclusion because Figure 3-24 shows that the compliant stream lengths occur in limited sections of upstream first order streams.

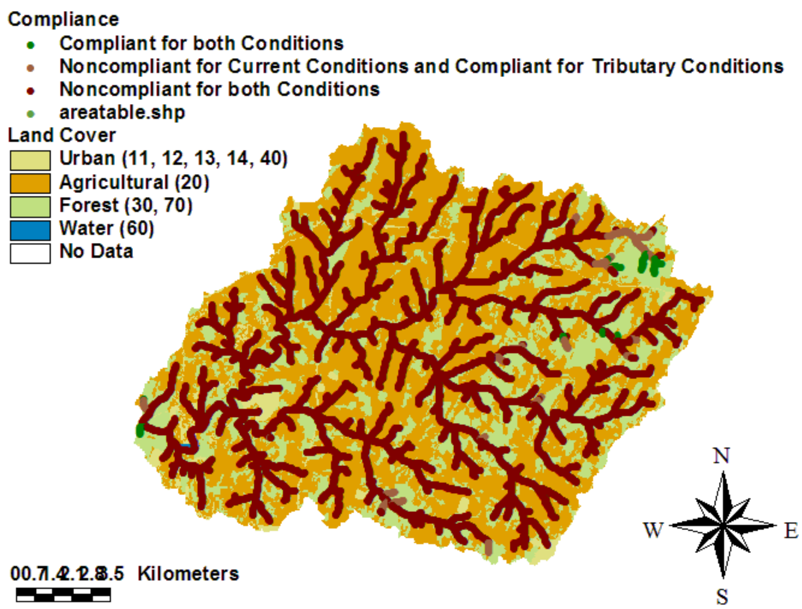


Figure 3-24: Third perspective using percent compliant stream length for Lake Linganore (27).

The Saint Mary's Lake watershed (18) is an example with large sections of homogeneous land use shown in Figuer 3-25. The land use distribution comprises 80 percent forest, 9 percent agriculture, 7 percent urban, and 4 percent water. The watershed (18) has a total stream length of 36,250 m, where 80 percent is found to be compliant for both conditions, 9 percent compliant for Tributary Strategy conditions, but noncompliant for Current conditions, and 11 percent noncompliant for both conditions. The watershed (18), therefore, is noncompliant for only 20 and 11 percent of the total stream length for the Current condition and the Tributary Strategy conditions, respectively. Applying the 70 percent criterion, the whole watershed (18) is determined to be compliant for both conditions. Figure 3-25 shows that the compliant stream lengths follow the longest flow path of the Saint Mary's Lake watershed and several of the main reaches of the stream network. However, the noncompliant stream lengths occupy five isolated subareas within these watersheds that could be managed on an individual basis. This scenario is different compared to the compliant stream lengths in the Lake Linganore watershed (27), where the compliant stream lengths occupy less than 1 to 3 percent of the total stream length, and are distributed in numerous locations throughout the watershed.

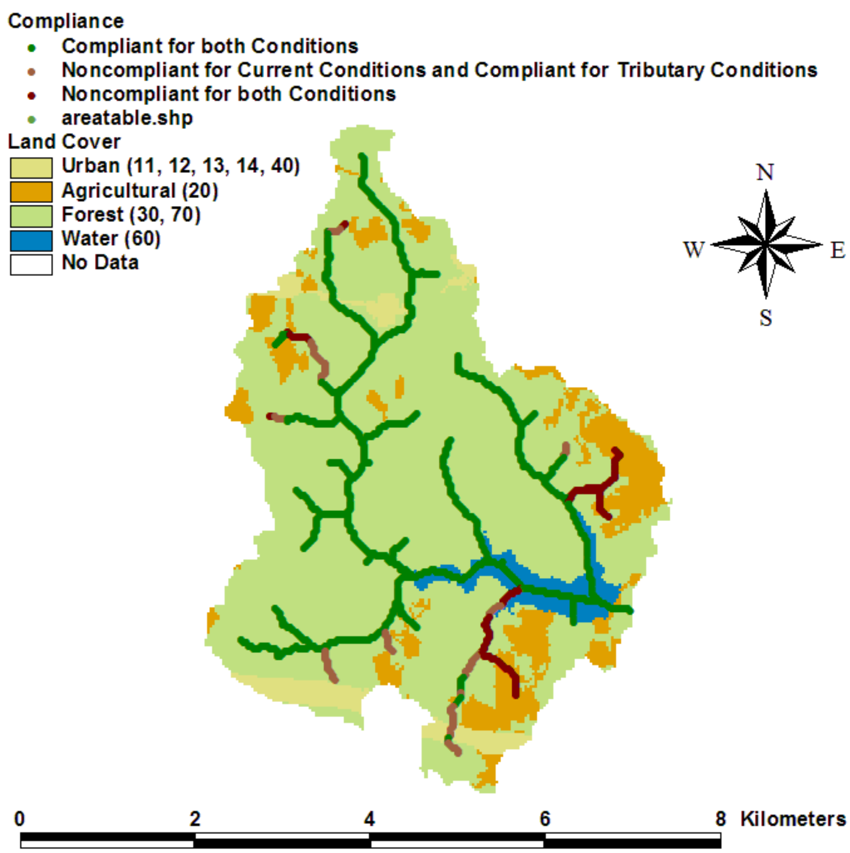


Figure 3-25: Third perspective using percent compliant stream length for Saint Mary's Lake (18).

<u>3.5 Monitoring and Management Considerations</u>

The monitoring objective seeks to employ the compliance status and the load variation within the watershed to recommend the most effective use of monitoring resources to measure conditions in the watershed. To fulfill this object two tools are presented, the first being a compliance map. The second tool is the semivariogram for the graphical representation of the load variance within a stream, which is described in the later part of this section.

3.5.1 Compliance Maps

The development of compliance maps (*e.g.*, Figure 3-24 and Figure 3-25) and three compliance perspectives have been described. These compliance maps are demonstrated as tools to (1) aid in prioritizing watersheds for monitoring, and (2) aid in the selection of new monitoring sites. The benefit of the compliance maps is that they provide a visual representation on the relationship between stream network structure, LCLU, and NPS loadings. Appropriate loading criteria can be developed and applied to these maps such that more informative compliance interpretations can be made.

One recommendation is that monitoring sites could be placed within watershed subareas that display the greatest potential to changes in BMP mitigated loadings as displayed by the Tributary Strategy condition loading rates. These subareas were previously described as being compliant for Tributary Strategy conditions but noncompliant for Current conditions in the whole watershed comparison. Because these areas are most vulnerable to water quality problems, these monitoring sites can act as a warning system for potential watershed scale water quality problems.

Applying the whole watershed comparison to the compliance maps provides insights regarding alternative courses of watershed management. Given limited resources, some local water quality managers might want to focus attention on watersheds that are less severely impaired in order to meet a policy objective to protect relatively healthy waters before turning attention to more severely impaired waters. Other managers might choose the reverse priority. The examples of the Lake Linganore watershed (27) and Saint Mary's Lake watershed (18) demonstrate these possibilities.

The watershed (27) would be an example of a severely impaired water body, which does not significantly improve even under the Tributary Strategy condition. From a water quality management perspective, mitigating watershed (27) would be an expensive endeavor that would have to involve the entire stream network, especially considering that the agricultural land use is distributed throughout the area. The watershed (27) was not reported by the MDE/USEPA in a TMDL report as noncompliant or in a WQA report as compliant. The pervasiveness of the noncompliant stream pixels could be an indication that a management decision was made to address more controllable water quality problems first.

In contrast, the Saint Mary's watershed (18) would meet the objective of protecting relatively healthy waters. The watershed (18) was identified as a compliant watershed by the MDE/USEPA in a WQA report. However, a local water quality management effort could reasonably use the compliance map to select four or five monitoring sites with the objective of developing a water quality improvement strategy to reduce the length of noncompliant streams.

3.5.2 Monitoring Site Range of Influence and Prediction Standard Error

The development of a model to calculate NPS load distributions for an entire watershed stream network has been described. An important feature of the varying NPS load data is that they are spatially dependent. Since each stream sample point includes the area and NPS load from the next upstream sample point, an inherent local structure exists. From this local structure, a point value at an unmonitored location can be predicted from observations of its value at nearby outlet locations. However, the point value at some maximum distance may not be related to that at a monitoring site.

The semivariogram is a tool that characterizes the variability in loading and thus (1) indicates the physical extent of the local structure, and (2) estimates the accuracy with which a monitoring site can predict values where no data have been collected. The purpose of this section is only to make the analysis of spatial NPS loadings better known to water quality managers by describing the methods to develop a semivariogram. A more developed application of semivariogram analyses than what is presented here needs to be investigated in future research.

The semivariogram analysis was an experimental demonstration of a geostatistical method that has not been previously applied to loads at stream points. The appropriateness of applying this method to mean annual loads at stream points should be evaluated. These mean annual loads are correlated by their accumulative nature and do not represent independent observations on a random variable. However, the semivariogram concept is based on the assumption that points are related by their closeness to each other. It may be more valid to apply the semivariogram technique to incremental loads downstream. In this way, the loads would still be related by their proximity to one another based on the likelihood that local land use areas are spatial related.

3.5.2.1 Semivariogram Analyses

The semivariogram is used to graphically describe the spatial relatedness in a set of NPS loads collected over a stream length. The following demonstrates that semivariograms can be used as an exploratory tool to detect spatial dependence in a stream length and to characterize different patterns of spatial variability in NPS loadings in single stream length. The semivariogram is demonstrated for a length of stream where a single sample point at a downstream location is used to predict a single point at an upstream location. This simplified approach eliminates the need to analyze the spatial variability within the dendritic structure of a stream network; where a stream network is defined as the combination of all stream lengths accumulating to a watershed outlet.

3.5.2.2 Equations and Background

The semivariogram is a graph that has the set of distances between sample points, or lag distances, on the x-axis and the corresponding set of variances, or the squared differences, between sample points on the y-axis. The typical structure of a semivariogram is such that, as the separation distance between pairs of upstream points and downstream sampling points increase, the corresponding semivariogram values will also generally increase. Eventually, however, an increase in the separation distance no longer causes a corresponding increase in the average squared difference between pairs of values and the variogram reaches an asymptote at a specific variance. The distance at which the variogram reaches this asymptote is called the range of influence (r). The asymptote that the variogram reaches at the range of influence is called the sill (γ_r).

Monitoring procedures rarely manage to locate samples exactly at desired locations. Therefore, the following semivariogram equation reflects the fact that pairs of sample points do not have to be separated by an exact distance. The semivariogram is computed as half the average squared difference between the paired sample points such that

$$\gamma(h) = \frac{1}{2n(h)} \sum_{(i,j)|h_{ij} \approx h} (v_i - v_j)^2 \tag{3-14}$$

in which $\gamma(h)$ is the sampling variance ($lb^2/yr^2/ac^2$); $n(h)$ is the number of pairs of sample points i and j; h_{ij} is the distance (m) between sample points i and j approximately equal to a specified lag h; and v_i and v_j are the sample values (lb/yr/ac) collected for points i and j, respectively. The allowable range in h is determined by a certain tolerance on the distance and another tolerance on the direction. This research assumed that the direction of any particular separation vector h_{ij} was unimportant as long as the vector followed the stream flow direction. With all possible directions combined into a single variogram, only the magnitude of h_{ij} is important.

3.5.2.3 Distance Lag and Tolerance Considerations

The lag h parameter needed to be chosen for the distance between successive sample points, sometimes referred to as the lag increment. Usually the GIS-based sampling pattern, located on a regular grid, would have suggested a reasonable lag increment of 30 m. In drawing samples from the GIS, however, there was disagreement between the actual lag distance and the specified lag distance. Although a 30 m grid cell was used, points located diagonally adjacent to each other could have a separation distance as large as $30\sqrt{2} \cong 42.43$ m (Figure 3-26). Accumulated across several grid cells, the error between the actual lag and the specified lag could potentially affect the determination of the range of influence. The true distance between sample points, therefore, could not be represented by a 30 m grid. The chosen lag spacing was estimated by the average spacing between adjacent sample points. The average spacing between adjacent points was computed as the stream length (m) divided by the number of points sampled in the stream.

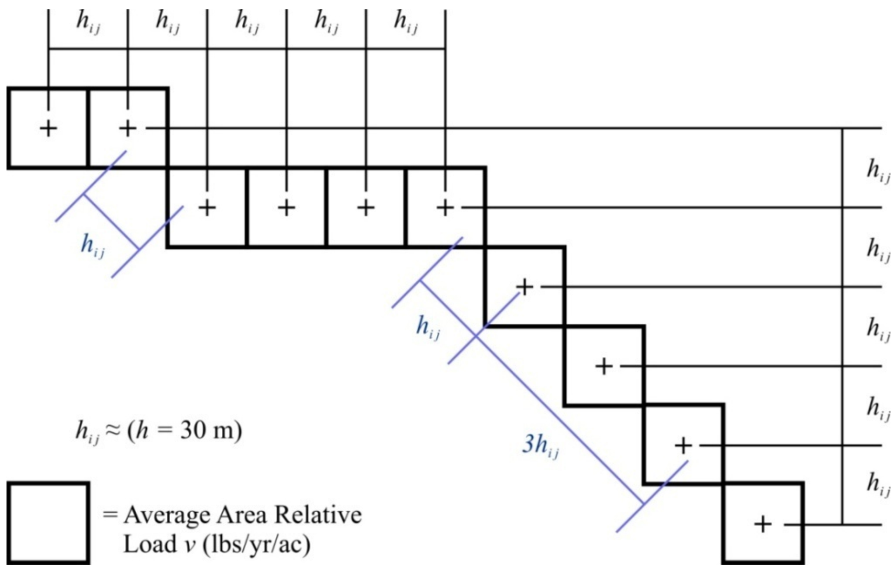


Figure 3-26: Relationship between the 30 m lag parameter and diagonal pairs of grid cells. Note that the sample value of a grid cell is averaged over a (30 m)^2 area.

A lag tolerance to account for the error in the lag calculation was not addressed. In addition to the error in the lag increment, there is considerable uncertainty in the DEM-mapped stream networks due to potential elevation errors within a particular watershed (Lindsay and Evans 2008). Some tolerance in the specified lag, however, was present because each area relative load estimate applies to a (30 m)^2 area. Perfect alignment with the centroid of each grid cell, therefore, was not necessary.

Other considerations included selecting the number of pairs of points for any one variogram point and the maximum number of lags. The semivariogram should be computed from lags with a minimum of 30 pairs of points for any one variogram point

(Cressie 1993). The semivariogram should not be computed beyond a maximum number of lags. The product of the maximum number of lags and the lag increment should be no more than half the largest distance among all points; when necessary, the maximum number of lags was subjectively selected based on the divergence of the sampling variance from the expected spherical structure (Section 3.5.2.4).

3.5.2.4 Subjectively Optimizing a Spherical Model

A spherical model was fit to the semivariogram using subjective optimization. This procedure required a data matrix containing each pair of sample variance and lag distance. An initial radius and sill for the semivariogram was chosen by inspection. After a few iterations, a final range and sill was chosen based on the relative bias ($\bar{e}/\bar{y}$), standard error ratio (S_e/S_y), and coefficient of multiple determination (R^2) reported in the optimization program. The spherical model had the form

$$\gamma(h) = \begin{cases} \left(\frac{3h}{r} - \frac{h^3}{r^3}\right)\frac{\gamma_r}{2} & \text{for } h \leq r \\ \gamma_r & \text{for } h > \text{r} \end{cases} \tag{3-15}$$

in which $\gamma(h)$ is the sampling variance (lb^2/yr^2/ac^2); h is the approximate lag distance (m) between sample points; r is the range of influence (m); γ_r is the sill (lb^2/yr^2/ac^2).

The following is an example of the fitted spherical model for the Saint Mary's watershed (18). The variogram was calculated from 113 values in the sample data set. Successive lags are 39.6 m apart. Although the maximum number of lags was equal to 257 for a maximum possible distance of 10,170 m, the sampling variation diverges from the intended spherical shape at a distance of approximately 5,000 m. The semivariogram, therefore, was fitted using 128 sampling squared difference calculations for a maximum lag distance of 5,000 m. The r and γ were optimized to reduce $\bar{e}/\bar{y}$ and S_e/S_y. The final values included r = 4,179 m, γ = 0.22 (lb/yr/ac)^2, $\bar{e}/\bar{y}$ = 0.0019, S_e/S_y = 0.16, and an R^2 = 0.98. Repeating the subjective optimization procedure for the Tributary Strategy condition produced a semivariogram with a r = 4,116 m, γ = 0.11 (lb/yr/ac)^2, $\bar{e}/\bar{y}$ = 0.005, S_e/S_y = 0.15, and an R^2 = 0.98. Both semivariograms had approximately the same range of influence. The sill (Figure 3-27) for Current conditions, however, is reduced from the sill (Figure 3-28) for Tributary Strategy conditions.

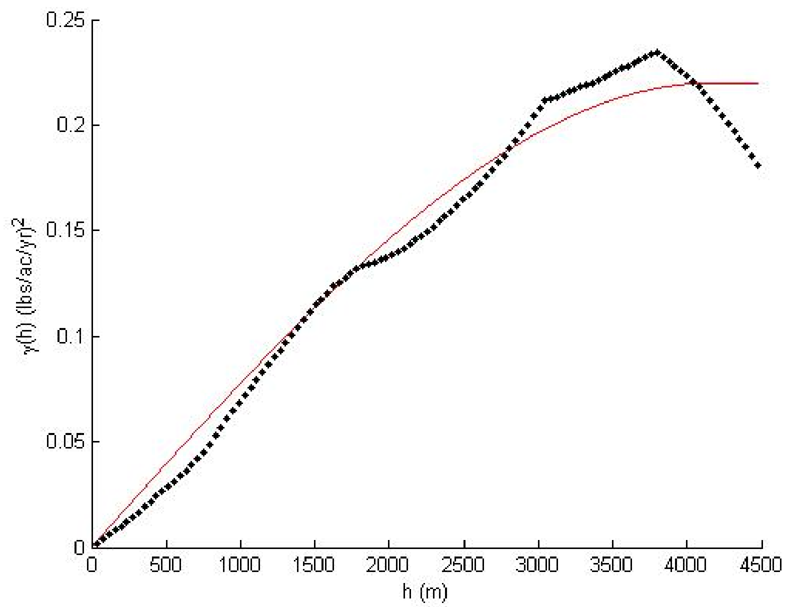


Figure 3-27: Semivariogram characterizing the variation in Current condition NPS loadings. Semivariogram is calculated from sample points along a compliant stream length within the Saint Mary's Watershed (18).

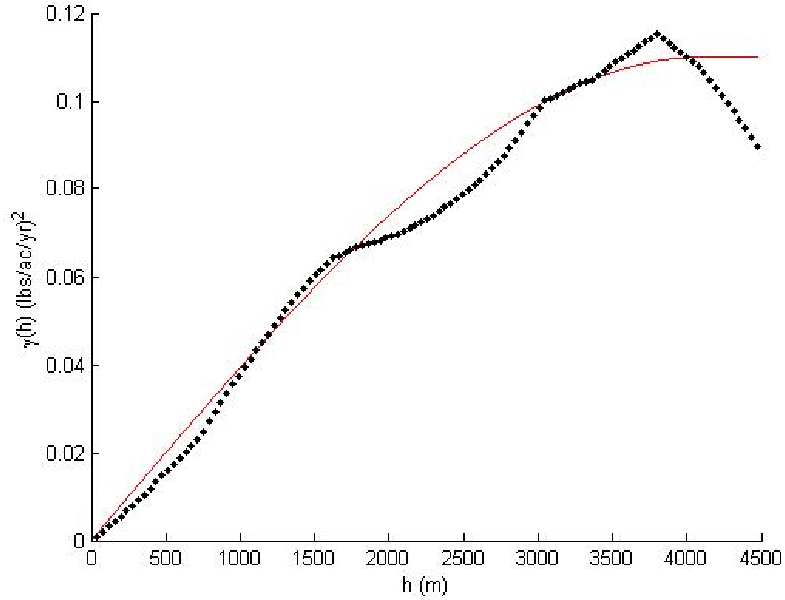


Figure 3-28: Semivariogram characterizing the variation in Tributary Strategy condition NPS loadings. Semivariogram is calculated from sample points along a compliant stream length within the Saint Mary's Watershed (18).

3.5.2.5 Point Predictions using the Semivariogram and Compliance Maps

The selection of monitoring sites should be based on the accuracy by which the monitored sample points predict upstream unmonitored sample points. Assume that the NPS data from this thesis can be represented by a spherical semivariogram with a sill of γ and a range of influence *r*. Then for a single sample measurement, the best estimate of the NPS load at an unmonitored upstream location is the sample value taken at the downstream monitored site as follows:

$$\hat{y} = y \tag{3-16}$$

where $\hat{y}$ is the predicted value for the unmonitored upstream point; and y is the value of the downstream monitored point.

The standard error of estimate can be computed with the equation

$$S_e = [2\bar{\gamma}(s, y) - \bar{\gamma}(y, y) - \bar{\gamma}(s, s)]^{0.5} \tag{3-17}$$

where $\bar{\gamma}(y, y)$ is the variation in the downstream monitored value *y* and $\bar{\gamma}(s, s)$is the variation in the unmonitored value *s*, which are assumed to be zero for point values; $\bar{\gamma}(s, y)$ is the variation between the two point values *s* and *y*, which can be computed with the semivariogram Equation 3-15.

Continuing the example of the Saint Mary's watershed (18), the predicted value at the downstream point was equal to $\hat{y}$ = 3.3 lb/yr/ac. Figure 3-29 and Figure 3-30 shows the set of standard errors calculated from Equation 3-17 for a range of distances between 0 m and 4,500 m for the Current condition and the Tributary Strategy condition, respectively. The standard error is compared to the still for a set of $S_e/\sqrt{\gamma_r}$ ratios. Figure 3-29 and Figure 3-30 show that at distances of 153 m and 75 m, respectively, the ratios begin to exceed a value of 0.5, which indicates that estimated values past these distances become inaccurate.

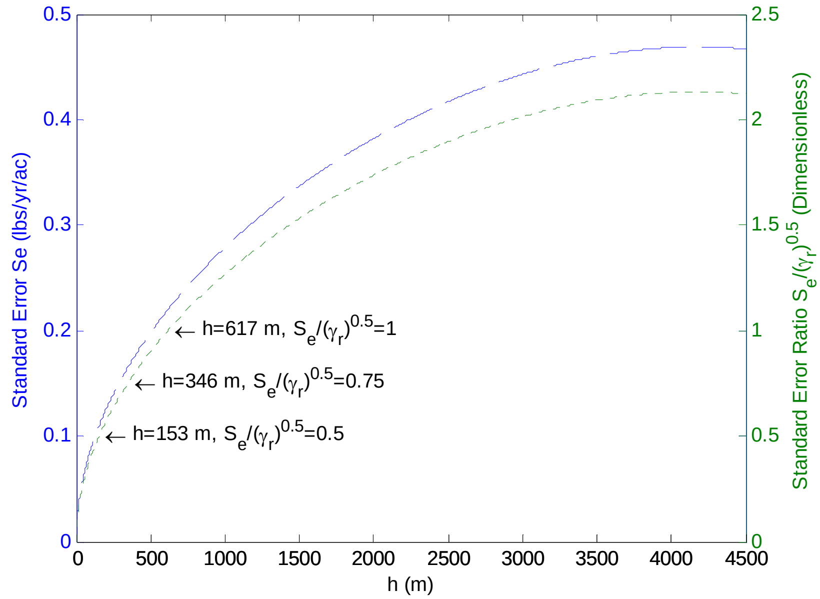


Figure 3-29: Standard errors and standard error ratios for predicting upstream points a distance h from a downstream monitored point for the Current condition. Semivariogram is calculated from sample points along a compliant stream length within the Saint Mary's Watershed (18).

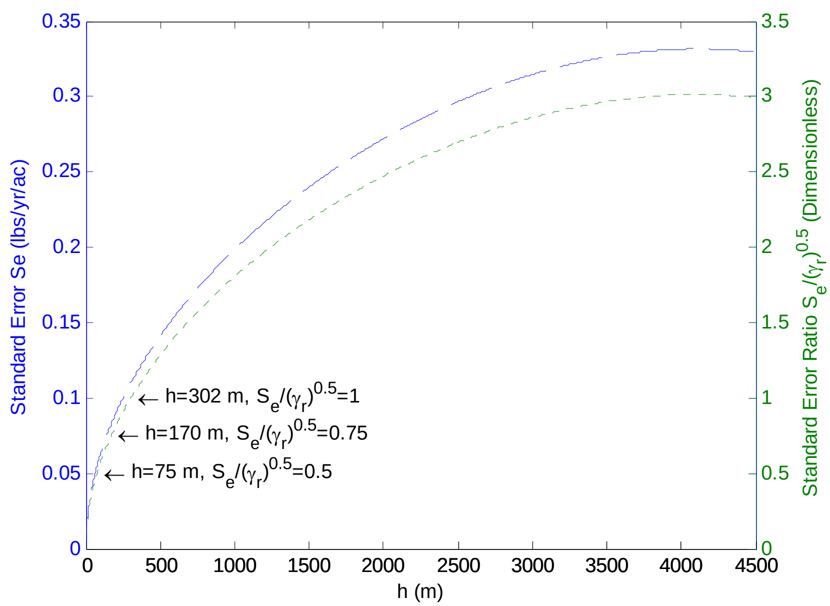


Figure 3-30: Standard errors and standard error ratios for predicting upstream points a distance h from a downstream monitored point for the Tributary Strategy

condition. Semivariogram is calculated from sample points along a compliant stream length within the Saint Mary's Watershed (18).

The above Saint Mary's Watershed example demonstrates that as the load variation becomes reduced by BMP mitigation efforts, the extent of the local structure also becomes reduced. More importantly the distance at which downstream sample points can accurately estimate upstream conditions becomes reduced. These findings suggest that noncompliant watersheds with small load variation due to low mean loads may be misrepresented by downstream monitoring sites. Choosing monitoring sites for the purpose of developing a semivariogram for a stream length may be a more informative measure of upstream conditions than considering monitoring sites individually. In the case of Figures 3-29 and 3-30 the spherical semivariogram shows a difference in load variation between Current and Tributary Strategy conditions. Sample designs for the purpose of estimating semivariograms for a maximum lag distance could potentially use differences in load variation as an indicator of changes in load conditions for the whole watershed.

Chapter 4: Results and Discussion

4.1 Introduction

The GIS methods for calculating load scenarios as described above were used to develop a complete population for NPS nitrogen loads for each of the 35 watersheds. This chapter first establishes a level of acceptance for the modeled NPS loads. Second, a comparison is made between the two perspectives in detecting watershed outlet compliance based on two generally understood interpretations of the LA of the TMDL Equation 2-4. A third, alternative perspective in detecting compliance regions within the whole watershed is then addressed. The modeled loads for Tributary Strategy conditions were used to recommend whether the watershed can be practically improved. In other words, Tributary Strategy conditions helped identify areas within the watershed that can be brought into compliance following the Tributary Strategy Plan. Finally, the semivariogram is presented as a tool to characterize the spatial variability and local loading structure within whole watershed compliance maps. The change in the local loading structure is evaluated between the two loading conditions.

4.2 Modeled Loads versus MD/USEPA Reported Loads

The mean watershed outlet loads for modeled Current conditions were compared to mean watershed outlet loads reported by MDE/USEPA to estimate how well the modeled loads represent accepted values. The 35 modeled Current condition loads were matched using their basin code with MDE/USEPA reported loads that were estimated directly from the Chesapeake Bay Program's Phase IV Watershed Model (WSM). The modeled loads were calculated for drainage areas reported in their respective TMDL report or WQA report. The two sets of 35 loads, however, did not always match at the watershed outlet. Additionally, the MDE/USEPA reported loads include point and nonpoint sources of nitrogen. The two sets of 35 loads, therefore, had to be considered as two independent samples. Figure 4-1 plots the modeled loads against the MDE/USEPA reported loads with a 45 degree line of agreement for comparison.

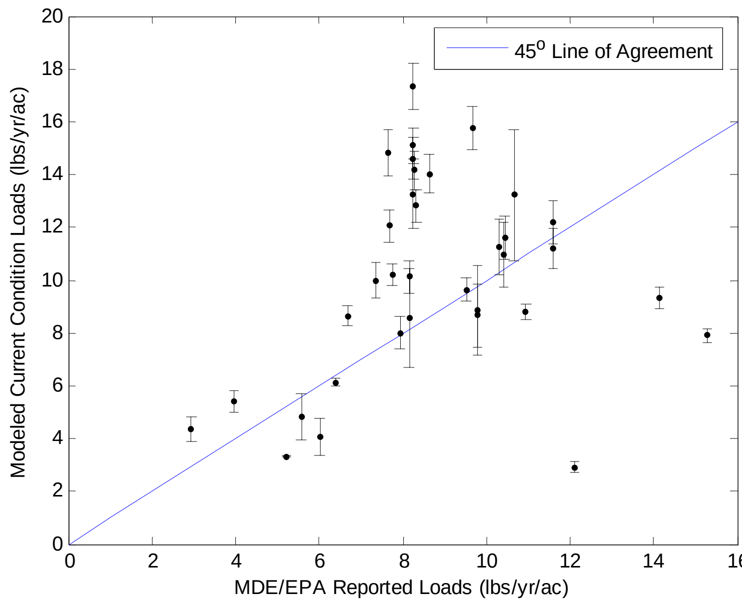


Figure 4-1: Modeled Current condition loads plus or minus one standard deviation versus MDE/USEPA reported loads along a 45 degree line of agreement.

4.2.1 The Kolmogorov-Smirnov Two-Sample (KS-2) Test

The Kolmogorov-Smirnov two-sample (KS-2) test was used to test the null hypothesis that two independently drawn samples (*i.e.*, the modeled Current condition loads versus the MDE/USEPA reported loads) are not different in distribution characteristics. The test is sensitive to differences in any of the following distribution characteristics: central tendency or location, dispersion or scale, and shape. Only the two-tailed alternative was used at the five and one percent levels of significance.

The KS-2 hypothesis test using a two-tailed alternative was applied to the two distributions of equal size ($n \leq 35$). For small samples of equal size, histograms are tabulated for both samples and then converted to cumulative form. Because the sample size was adequately large, the cumulative distribution was converted to cumulative probability form by dividing by a sample size of 35. The cumulative probability histogram for sample 1, MDE/USEPA reported loads (lb/ac/yr), and sample 2, modeled Current condition loads (lb/ac/yr), are denoted as $C_1(x)$ and $C_2(x)$, respectively. For the two-tailed alternative, the value of the test statistic, D, is the largest absolute difference D between corresponding ordinates of the cumulative probability histogram:

$$D = max|C_1(x) - C_2(x)| \tag{4-1}$$

The null hypothesis is rejected if the computed D of Equation 4-1 is greater than the critical values $D_{0.05}$ or $D_{0.01}$ of Equations 4-2 and 4-3.

$$D_{0.05} = 1.36\sqrt{\frac{n_1 + n_2}{n_1 n_2}} \tag{4-2}$$

$$D_{0.01} = 1.63\sqrt{\frac{n_1 + n_2}{n_1 n_2}} \tag{4-3}$$

where the critical value of the test statistic depends on the sizes of sample 1 and sample 2, which are denoted as n_1 and n_2, the level of significance $D_{0.05}$ or $D_{0.01}$, and on the fact that the test is two-tailed.

Figure 4-2 graphically shows the KS-2 cumulative probability distributions. The cumulative probabilities and absolute differences are given in Table 4-1. Values for modeled Current condition loads and MDE/USEPA reported loads are given in Table 4-2 of the following section. The MDE/USEPA reported loads show a tendency to have slightly larger loads compared to the modeled Current condition loads; this is probably due to the inclusion of point and nonpoint sources in the MDE/USEPA reported load. The maximum absolute difference between the two distributions was equal to 0.31 lb/yr/ac. The null hypothesis was accepted at both five percent and one percent levels of significance for critical values of 0.33 lb/yr/ac and 0.39 lb/yr/ac, respectively. The final interpretation is that the distribution of the modeled Current condition loads is not significantly different from the distribution of the MDE/USEPA reported loads, which supports the decision to assume that the modeled Current condition loads agree with accepted values. Based on the outcome of this statistical test, the remaining inferences made from the modeled Current condition loads at both the watershed outlet and upstream from the watershed outlet will be accepted.

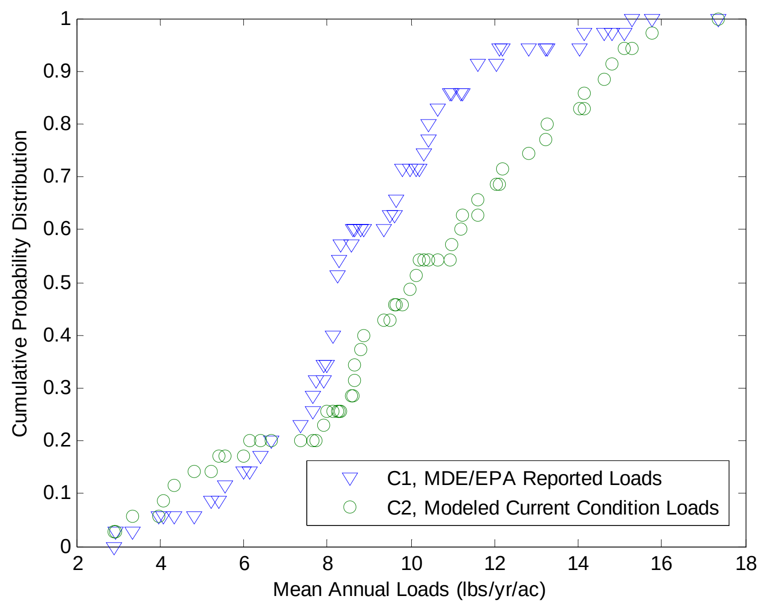


Figure 4-2: KS-2 test on MDE/USEPA reported load distribution and modeled Current condition load distribution. Loads of both compliant and noncompliant watersheds were included.

Table 4-1: KS-2 test on MDE/USEPA load distributions and modeled Current condition load distributions

Bin	C_1	C_2	D	Bin	C_1	C_2	D	Bin	C_1	C_2	D
2.92	0.00	0.03	0.03	8.25	0.51	0.26	0.26	10.96	0.86	0.57	0.29
2.94	0.03	0.03	0.00	8.28	0.54	0.26	0.29	11.19	0.86	0.60	0.26
3.33	0.03	0.06	0.03	8.32	0.57	0.26	0.31	11.24	0.86	0.63	0.23
3.96	0.06	0.06	0.00	8.57	0.57	0.29	0.29	11.59	0.91	0.63	0.29
4.07	0.06	0.09	0.03	8.63	0.60	0.29	0.31	11.60	0.91	0.66	0.26
4.34	0.06	0.11	0.06	8.65	0.60	0.31	0.29	12.06	0.91	0.69	0.23
4.81	0.06	0.14	0.09	8.67	0.60	0.34	0.26	12.11	0.94	0.69	0.26
5.22	0.09	0.14	0.06	8.80	0.60	0.37	0.23	12.20	0.94	0.71	0.23
5.42	0.09	0.17	0.09	8.86	0.60	0.40	0.20	12.82	0.94	0.74	0.20
5.57	0.11	0.17	0.06	9.34	0.60	0.43	0.17	13.24	0.94	0.77	0.17
6.01	0.14	0.17	0.03	9.52	0.63	0.43	0.20	13.26	0.94	0.80	0.14
6.13	0.14	0.20	0.06	9.63	0.63	0.46	0.17	14.02	0.94	0.83	0.11
6.40	0.17	0.20	0.03	9.66	0.66	0.46	0.20	14.14	0.97	0.83	0.14
6.68	0.20	0.20	0.00	9.79	0.71	0.46	0.26	14.16	0.97	0.86	0.11
7.36	0.23	0.20	0.03	9.99	0.71	0.49	0.23	14.61	0.97	0.89	0.09
7.65	0.26	0.20	0.06	10.13	0.71	0.51	0.20	14.81	0.97	0.91	0.06
7.67	0.29	0.20	0.09	10.20	0.71	0.54	0.17	15.11	0.97	0.94	0.03
7.75	0.31	0.20	0.11	10.30	0.74	0.54	0.20	15.28	1.00	0.94	0.06
7.90	0.31	0.23	0.09	10.41	0.77	0.54	0.23	15.76	1.00	0.97	0.03
7.93	0.34	0.23	0.11	10.44	0.80	0.54	0.26	17.34	1.00	1.00	0.00
8.00	0.34	0.26	0.09	10.66	0.83	0.54	0.29				
8.15	0.40	0.26	0.14	10.94	0.86	0.54	0.31				

Note: Bin = nitrogen loads (lb/yr/ac); C = cumulative probability distribution; 1 = MDE/USEPA reported loads; 2 = Modeled Current condition loads; D = absolute difference between C_1 and C_2.

4.3 The Two Watershed Outlet Perspectives

The first outlet perspective looked at the mean annual loads at the outlet of each watershed (Section 3.4.3). The watershed compliance was determined by asking the question "Is the mean annual load observed at the outlet greater than the load allocation (LA) of the watershed TMDL?" If the answer was no, then the watershed was compliant with water quality standards; otherwise, if the answer was yes, then the watershed was noncompliant with water quality standards. Alternative to the mean annual value, a probability of exceeding the LA less than or equal to 10 percent was used to identify a compliant watershed; a probability of exceeding the LA greater than 10 percent was used to identify a noncompliant watershed (Section 3.4.4). The following table lists the results based on both the mean annual load at the watershed outlet and the probability of exceeding the LA value at the watershed outlet. The outlet compliance decision and the LA critical value used for each watershed are given in Table 4-2.

Table 4-2: Total nitrogen NPS loads and outlet compliance interpretation

ID	MDE/USEPA		Current condition			Tributary Strategy		
	Criterion (lb/yr/ac)	Mean (lb/yr/ac)	Mean (lb/yr/ac)	Standard Deviation (lb/yr/ac)	Exceedance Probability (%)	Mean (lb/yr/ac)	Standard Deviation (lb/yr/ac)	Exceedance Probability (%)
1	7.7	11.59 (N)	11.19 (N)	0.76	100 (N)	5.06 (Y)	0.47	0 (Y)
2	5.1	7.36 (N)	9.99 (N)	0.69	100 (N)	4.35 (Y)	0.48	6 (Y)
3	6.0	7.75 (N)	10.20 (N)	0.43	100 (N)	5.42 (Y)	0.37	6 (Y)
4	10.7	8.63 (Y)	14.02 (N)	0.73	100 (N)	7.11 (Y)	0.72	0 (Y)
5	6.0	9.66 (N)	15.76 (N)	0.80	100 (N)	7.88 (N)	0.81	99 (N)
6	4.9	8.32 (N)	12.82 (N)	0.63	100 (N)	6.43 (N)	0.65	99 (N)
7	4.8	7.67 (N)	12.06 (N)	0.62	100 (N)	6.19 (N)	0.37	100 (N)
8	1.6	7.93 (N)	8.00 (N)	0.60	100 (N)	4.83 (N)	0.27	100 (N)
9	9.4	8.25 (Y)	14.61 (N)	0.78	100 (N)	6.47 (Y)	0.59	0 (Y)
10	1.5	8.25 (N)	15.11 (N)	0.67	100 (N)	6.38 (N)	0.47	100 (N)
11	2.3	8.25 (N)	13.26 (N)	1.31	100 (N)	6.41 (N)	1.06	100 (N)
12	7.6	15.28 (N)	7.90 (N)	0.26	88 (N)	5.33 (Y)	0.26	0 (Y)
13	0.7	10.66 (N)	13.24 (N)	2.49	100 (N)	8.06 (N)	1.40	100 (N)
14	3.4	6.40 (N)	6.13 (N)	0.15	100 (N)	4.61 (N)	0.35	100 (N)
15	4.8	7.65 (N)	14.81 (N)	0.88	100 (N)	7.63 (N)	0.85	100 (N)
16	4.8	10.94 (N)	8.80 (N)	0.28	100 (N)	5.67 (N)	0.26	100 (N)
17	4.8	6.68 (N)	8.65 (N)	0.38	100 (N)	6.20 (N)	0.52	100 (N)
18	4.8	5.22 (N)	3.33 (Y)	0.05	0 (Y)	2.71 (Y)	0.14	0 (Y)
19	4.8	9.79 (N)	8.86 (N)	1.71	99 (N)	5.93 (N)	1.67	75 (N)
20	4.8	9.79 (N)	8.67 (N)	1.21	100 (N)	5.92 (N)	1.71	74 (N)
21	4.8	8.15 (N)	8.57 (N)	1.87	98 (N)	6.21 (N)	1.28	86 (N)
22	4.8	12.11 (N)	2.92 (Y)	0.20	0 (Y)	2.45 (Y)	0.17	0 (Y)
23	*4.8*	*2.94 (Y)*	*4.34 (Y)*	*0.46*	*16 (N)*	*3.53 (Y)*	*0.43*	*0 (Y)*
24	4.8	9.52 (N)	9.63 (N)	0.43	100 (N)	6.29 (N)	0.57	100 (N)
25	4.8	8.28 (N)	14.16 (N)	0.72	100 (N)	7.04 (N)	0.74	100 (N)
26	4.8	8.15 (N)	10.13 (N)	0.62	100 (N)	6.37 (N)	2.10	77 (N)
27	4.8	10.30 (N)	11.24 (N)	1.05	100 (N)	6.70 (N)	1.09	96 (N)
28	4.8	3.96 (Y)	5.42 (N)	0.42	93 (N)	3.95 (Y)	0.39	1 (Y)
29	*4.8*	*10.41 (N)*	*10.96 (N)*	*1.24*	*100 (N)*	*4.67 (Y)*	*0.55*	*41 (N)*
30	7.7	11.59 (N)	12.20 (N)	0.83	100 (N)	5.58 (Y)	0.50	0 (Y)
31	7.7	10.44 (N)	11.60 (N)	0.81	100 (N)	5.27 (Y)	0.48	0 (Y)
32	6.0	8.25 (N)	17.34 (N)	0.89	100 (N)	8.40 (N)	0.92	100 (N)
33	*4.8*	*6.01 (N)*	*4.07 (Y)*	*0.71*	*15 (N)*	*2.53 (Y)*	*0.55*	*0 (Y)*
34	*4.8*	*5.57 (N)*	*4.81 (Y)*	*0.87*	*51 (N)*	*2.90 (Y)*	*0.66*	*0 (Y)*
35	4.8	14.14 (N)	9.34 (N)	0.40	100 (N)	6.75 (N)	0.58	100 (N)

Note: Shading shows disagreements between perspectives. (Y) = Yes. Watershed is compliant with LA criterion; (N) = No. Watershed is noncompliant with LA criterion.

4.3.1 Perspective One: Outlet Mean Annual Load Compliance Interpretation

When using the outlet mean annual load comparison, 28 of the 35 compliance interpretations agreed between the modeled Current condition loads and the MDE/USEPA reported loads. Twenty-seven of the interpretations were identified as noncompliant. This observation can only be used to highlight the severity of the nutrient problem within Maryland. Because the two sets of watersheds do not share the same watershed outlet, further comparison is not informative. The MDE/USEPA loads were often reported for watershed areas much larger than the modeled watershed areas. The modeled watershed areas were matched with the areas associated with TMDL reports and WQA reports, and not with the areas associated with MDE/USEPA reported mean annual loads. Although, the loads were area normalized, the discrepancy in areas may still have affected the load prediction agreements due to the addition or subtraction of tributary contributions.

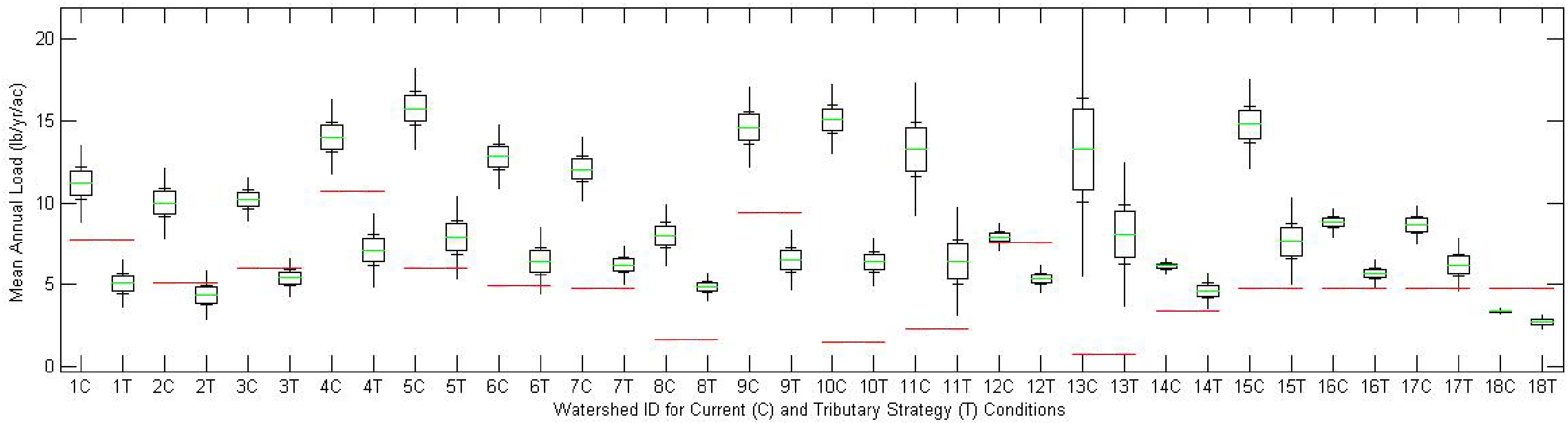
The outlet mean annual load comparison between the modeled Current condition loads and the modeled Tributary Strategy loads had three compliance interpretations: noncompliant, compliant, and potentially (or sometimes) compliant. Twenty noncompliant watersheds had mean annual loads for both the Current condition and the Tributary Strategy condition greater than their respective LA critical values. Five compliant watersheds (18, 22, 23, 33, and 34) had mean annual loads for both the Current condition and the Tributary Strategy condition less than their respective LA critical values; Watersheds 18, 22, and 23 were reported in their respective WQA report as nitrogen compliant. Ten potentially compliant watersheds (1-4, 9, 12, and 28-31) had mean annual loads for the Current condition greater than their respective LA critical values, but had mean annual loads for the Tributary Strategy condition less than their respective LA critical values. This result is counter to what was expected for watersheds 15 through 22, which were all reported in their WQA reports as nutrient compliant.

Watersheds 24 through 35 were reported in their respective WQA reports as phosphorus limited based on the total nitrogen to total phosphorus ratios for these watersheds; thus, MDE/USEPA placed efforts on phosphorus to manage nutrients. The MDE/USEPA reports did not specifically say if the watershed is nitrogen compliant. As mentioned earlier, Maryland's water quality standards presently do not place a limit on the concentration of nutrients in the water column. Rather, Maryland manages nutrients indirectly by limiting their effects expressed in terms of excess algal growth and low dissolved oxygen. As a result some of these watersheds did not have adequate nitrogen data (*e.g.*, watershed 33 was reported in a TMDL report as not having data on organic nitrogen concentrations in the reservoir). All but watersheds 33 and 34, of the phosphorus limited watersheds, were identified as nitrogen noncompliant for Current conditions by the modeled loads. Watersheds 28-31 show a potential to become compliant based on the compliance of Tributary Strategy loads.

The fact that most of the watersheds were detected as noncompliant by modeled Current condition loads is not unreasonable for two reasons. The first reason is that it is possible that the assumed LA critical value of 4.8 is stricter than the true value, thus causing more watersheds to be marked as noncompliant compared to what is documented in TMDLreports and WQA reports. The second reason is that it is possible that these watersheds were nutrient limited such that their designated uses were not impaired by nitrogen (this may be the case with watersheds 24 through 35). In general, ratios of total nitrogen to total phosphorus in the range of 5 to 10 indicate that neither phosphorus nor nitrogen are associated with plant growth being limited (Chianudani and Vighi 1974). If the ratio is greater than 10, phosphorus tends to be limiting, and if the ratio is less than 5, nitrogen tends to be limiting. A future research may identify nutrient limited regions within a watershed, such that monitoring objectives could choose to sample phosphorus versus nitrogen constituents to conserve on funds.

4.3.2 Perspective Two: Probability of Exceedance Outlet Compliance Interpretation

Figure 4-3 summarizes the comparison between mean annual load distributions and probabilities of exceeding LA criteria at watershed outlets for Table 4-2 by using a modified box-plot. Respective LA criterion are plotted across both the Current condition and Tributary Strategy condition mean annual outlet load distributions for comparison. Note that Figure 4-3 represents the assumed normal distribution for each of the 35 watersheds, rather than the traditional quartile representation of the data. The central bar represents the mean annual load. When the LA criterion is above the central bar, the watershed is compliant when using the first watershed outlet perspective rules. The box upper and lower sides represent one standard deviation away from the mean load. The upper and lower bars represent the 80 percent confidence limits. The 80 percent confidence limits allows for a comparison between the LA criteria and the 10 percent probability of exceeding those criteria. When the LA criterion is between the upper 80 percent confidence line and the upper tail end of the distribution, the watershed is compliant when using the second watershed outlet perspective rules. The tails represent the 99.8 percent confidence limits on the assumed normal distribution of the watershed mean outlet loads.



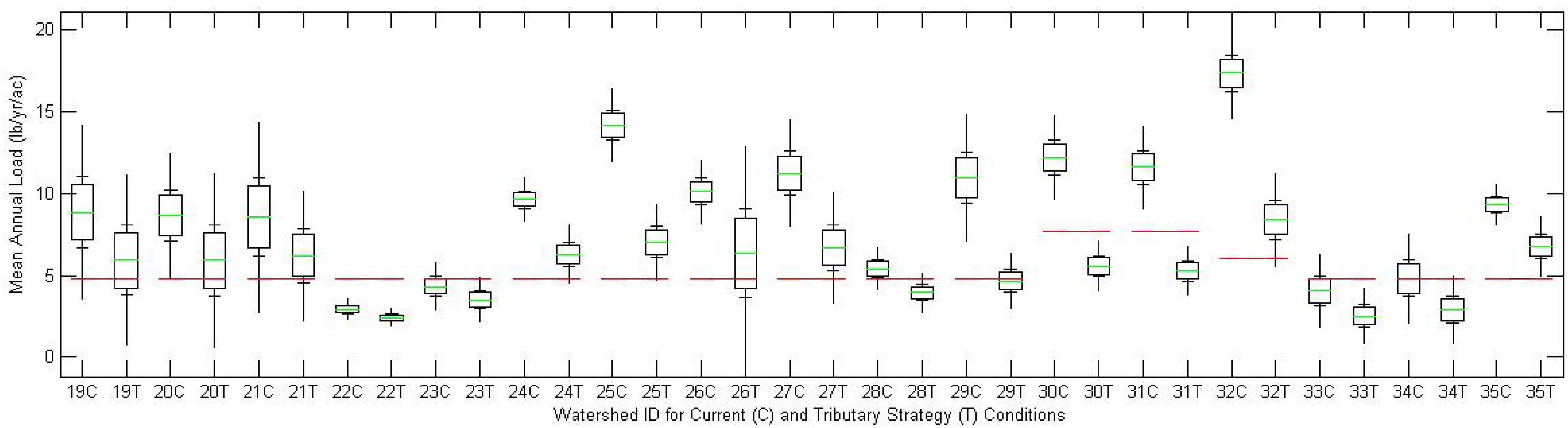


Figure 4-3: Normal distribution of mean annual load estimates for watershed outlets compared to their respective LA critical value. The definition for the boxes and whiskers is described earlier in Section 4.3.2.

Figure 4-3 shows five watershed conditions: 20 watersheds were noncompliant for all conditions; 2 watersheds (18 and 22) were compliant for all conditions; 9 watersheds (1-4, 9, 12, 28, 30, and 31) were noncompliant for Current conditions but had the potential to be compliant for Tributary Strategy conditions for both outlet interpretations; 3 watersheds (23, 33, and 34) were designated special case a; one watershed (29) was designated special case b. The majority of the compliance interpretations, therefore, were unmistakably compliant or noncompliant. Special case a conditions and special case b conditions, however, were examples where the compliance interpretation can be ambiguous.

The special case a scenario describes watersheds that were compliant for the outlet mean annual load comparison but noncompliant for the outlet probability comparison for Current conditions; watershed Tributary Strategy conditions were compliant for both outlet perspectives. On average, these watersheds meet the mean annual load requirement for compliance; there is an occasional chance, however, that the requirement is not met. Watersheds 23, 33, and 34 match this compliance description (Figure 4-4). As described earlier, these watersheds are compliant because the mean falls close below the LA critical value. For example, Savage River's mean annual load distribution for the Current condition is defined by a mean of 4.34 lb/yr/ac and a standard deviation of 0.46 lb/yr/ac. Figure 4-4 shows that the outlet Current condition mean load is less than the LA critical value. Under the outlet mean annual load comparison, therefore, watershed 23 is determined to be compliant for the Current conditions at the watershed outlet. However, the probability of exceeding the LA critical value is 16 percent for the outlet Current condition, which is greater than the 10 percent requirement. Using the 10 percent probability of exceeding the LA critical value comparison, watershed 23 is determined to be noncompliant for Current conditions at the watershed outlet. The later decision contrasts with the original decision. By comparing the Tributary Stategy condition distribution for Savage River (with a mean of 3.53 lb/yr/ac and a standard deviation of 0.43 lb/yr/ac) it is shown that watersheds under the special case a are the most likely to have their impairment addressed by the Tributary Strategy Plan; in contrast, the watersheds that were previously described as potentially compliant must undergo a larger reduction in mean annual loads to reach a similar level of compliance (Figure 4-3). However, special case a designated watersheds are also the watersheds that are most likely to be overlooked if a mean annual load perspective is used at the watershed outlet.

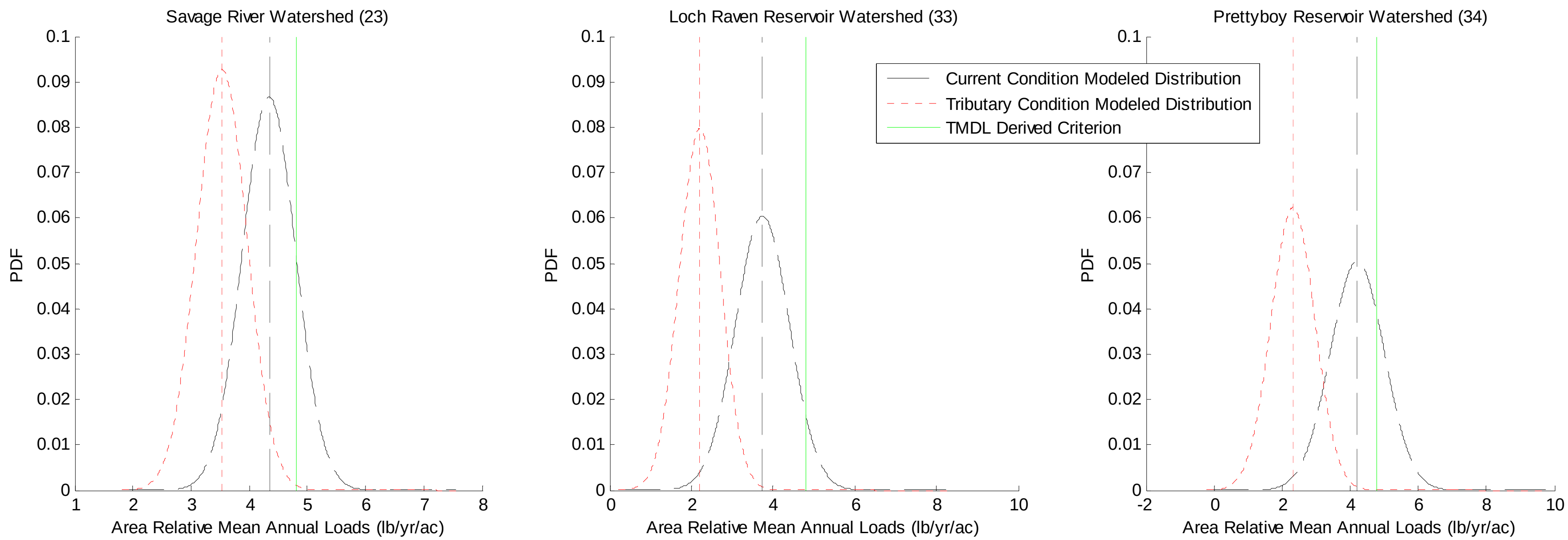


Figure 4-4: Assumed normal distributions for the probability of exceedance compliance interpretation for the Savage River (23), Loch Raven Reservoir (33), and Prettyboy Reservoir (34) watersheds with contradicting compliance interpretations.

The special case b scenario describes watersheds that were compliant for the mean outlet load comparison but noncompliant for the probability comparison for Tributary Strategy conditions; Current conditions were noncompliant for both outlet interpretations. On average, these watersheds had potential to be compliant; there is a probability, however, that the LA requirement is not met under the Tributary Strategy. The Adkins Pond watershed (29) was the only watershed designated as special case b. The mean annual load distribution for the Current condition is defined by a mean of 10.96 lb/yr/ac and a standard deviation of 1.24 lb/yr/ac. Figure 4-5 shows that the outlet mean Current condition load is greater than the LA critical value of 4.8 lb/yr/ac. The probability of exceeding the LA critical value is 100 percent for the outlet Current condition, which is greater than the 10 percent requirement. Both perspectives, therefore, determine watershed 29 as noncompliant for the Current condition at the outlet. By comparing the Tributary Strategy condition distribution for Adkins Pond (with a mean of 4.67 lb/yr/ac and a standard deviation of 0.55 lb/yr/ac) it is shown that on average the watershed has the potential to have its impairment addressed by the Tributary Strategy Plan; there is, however, a 41 percent probability that the Tributary Strategy condition loads will exceed the LA critical value. Watersheds with characteristics of the special case b scenario, therefore, must undergo close monitoring after BMP establishment so that compliance can be maintained. In other words, special case b watersheds are most likely to return to a noncompliant state after their impairment has been addressed.

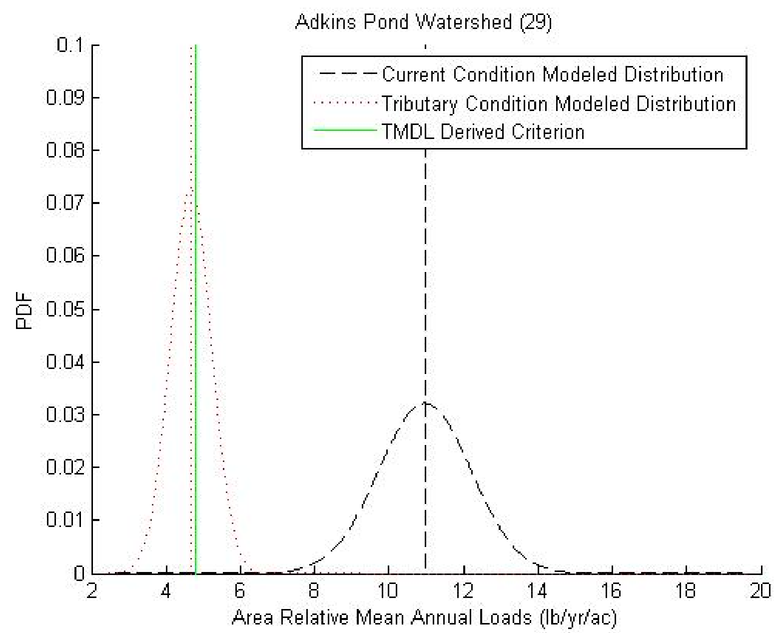


Figure 4-5: Assumed normal distributions for the probability of exceedance compliance interpretation for Adkins Pond watershed (29) with contradicting compliance interpretations.

4.4 The Stream Network Perspective

The objective of this section is to determine if the two perspectives in detecting compliance with water quality standards at a watershed outlet are representative of mean annual loads at each stream location within the whole watershed. The calculation of whole watershed loading distributions were regulated by the spatial distribution of land use, digital elevation, stream junctions, and loading rates related to the availability of BMPs for Current conditions and Tributary Strategy conditions. The specific combinations of these factors can cause different decisions in terms of compliance at each 30 meters of stream length such that the compliance interpretation at the watershed outlet may not adequately represent the health of the entire watershed.

4.4.1 Perspective Three: Percent Compliant Stream Length Approach

The outlet exceedance probability comparison, used in Table 4-2 for Current conditions and Tributary Strategy conditions, was applied to each stream location within the watershed. If a location was compliant for both conditions, then the location was designated as always compliant. If a location was compliant for Tributary Strategy condition and noncompliant for Current conditions, then the location was designated as sometimes compliant. If a location was noncompliant for both conditions, then the pixel was designated as never compliant. The lengths of the stream for of each of the three categories were summed and reported as a percent of the total stream length for the watershed. The decisions made on watershed stream length compliance with LA critical values for each respective watershed in the study are given in Table 4-3. A summary on the agreement between Table 4-2 and Table 4-3 is also provided.

Table 4-3: Stream lengths and whole watershed compliance interpretation

ID	Total Stream Length				Table 4-2 Agreement	
	Total Length (m)	Always Compliant (%)	Sometimes Compliant (%)	Never Compliant (%)	Current condition/ Always	Tributary Strategy/ Sometimes
1	744431	19 (N)	65 (Y)	17 (P)	AM/AP	AM/AP
2	140051	16 (N)	52 (Y)	32 (P)	AM/AP	AM/AP
3	*250248*	*12 (N)*	*32 (N)*	*56 (N)*	*AM/AP*	*DM/DP*
4	131757	13 (N)	87 (Y)	0 (P)	AM/AP	AM/AP
5	235545	0 (N)	1 (N)	99 (N)	AM/AP	AM/AP
6	711511	7 (N)	16 (N)	77 (N)	AM/AP	AM/AP
7	206350	0 (N)	1 (N)	99 (N)	AM/AP	AM/AP
8	300015	0 (N)	0 (N)	100 (N)	AM/AP	AM/AP
9	59078	2 (N)	97 (Y)	1 (P)	AM/AP	AM/AP
10	54876	0 (N)	0 (N)	100 (N)	AM/AP	AM/AP
11	90259	0 (N)	0 (N)	100 (N)	AM/AP	AM/AP
12	109739	32 (N)	57 (Y)	11 (P)	AM/AP	AM/AP
13	246845	0 (N)	0 (N)	100 (N)	AM/AP	AM/AP
14	231005	14 (N)	7 (N)	79 (N)	AM/AP	AM/AP
15	160455	2 (N)	1 (N)	97 (N)	AM/AP	AM/AP
16	103216	3 (N)	8 (N)	89 (N)	AM/AP	AM/AP
17	237669	1 (N)	3 (N)	95 (N)	AM/AP	AM/AP
18	36250	80 (Y)	9 (Y)	11 (Y)	AM/AP	AM/AP
19	50042	1 (N)	3 (N)	96 (N)	AM/AP	AM/AP
20	50744	1 (N)	0 (N)	99 (N)	AM/AP	AM/AP
21	123937	2 (N)	2 (N)	97 (N)	AM/AP	AM/AP
22	3170	92 (Y)	5 (Y)	3 (Y)	AM/AP	AM/AP
23	*395321*	*41 (N)*	*28 (Y)*	*31 (P)*	*DM/AP*	*AM/AP*
24	40485	0 (N)	2 (N)	98 (N)	AM/AP	AM/AP
25	205000	1 (N)	3 (N)	96 (N)	AM/AP	AM/AP
26	11394	3 (N)	0 (N)	97 (N)	AM/AP	AM/AP
27	341665	1 (N)	3 (N)	96 (N)	AM/AP	AM/AP
28	31797	36 (N)	38 (Y)	25 (P)	AM/AP	AM/AP
29	*79925*	*6 (N)*	*18 (N)*	*76 (N)*	*AM/AP*	*DM/AP*
30	60197	9 (N)	70 (Y)	21 (P)	AM/AP	AM/AP
31	175647	15 (N)	65 (Y)	20 (P)	AM/AP	AM/AP
32	31813	0 (N)	0 (N)	100 (N)	AM/AP	AM/AP
33	*1230026*	*27 (N)*	*59 (Y)*	*14 (P)*	*DM/AP*	*AM/AP*
34	*319068*	*13 (N)*	*69 (Y)*	*18 (P)*	*DM/AP*	*AM/AP*
35	14031	4 (N)	2 (N)	95 (N)	AM/AP	AM/AP

Note: Shaded entries show disagreements. (Y) = Yes. Watershed is compliant; (N) = No. Watershed is noncompliant; (P) = Possible. Watershed is not currently compliant, but is compliant with Tributary Strategies implemented; AM = Agrees with outlet mean; DM = Disagrees with outlet mean; AP = Agrees with outlet probability of exceedance; DP = Disagrees with outlet probability of exceedance.

Among the total 35 watersheds, 32 watersheds agreed across all three compliance perspectives for the Current condition. The considerable agreement between the three perspectives using the modeled loads suggests that the outlet perspective represents the overall watershed compliance perspective most of the time. These watersheds were identified as having an 88 percent or higher probability of exceeding or not exceeding the LA critical value; in other words, the outlet was unmistakably different from the LA critical value.

Three of the whole watershed (23, 33, and 34) compliance interpretations disagreed with Current condition mean load interpretations at the outlet, but agreed with Current condition probability interpretations at the outlet. These three watersheds were designated earlier as special case a, which were found to be most receptive to having their impairment addressed by the Tributary Strategy Plan.

One of the whole watershed (29) compliance interpretations disagreed with the Tributary Strategy condition mean load interpretation at the outlet, but agreed with the Tributary Strategy condition probability interpretation at the outlet. This particular watershed was designated earlier as special case b, which was most likely to return to a noncompliant state. Although watershed 3 was not designated as special case b, the relation of the distribution to the LA critical value is borderline compliant for Tributary Strategies compared to that of watershed 29 (*i.e.*, the probability of exceeding the LA critical value is 6 percent for watershed 3 compared to the 41 percent for watershed 29; the requirement for compliance is 10 percent or less). This should be a reminder that the definitions for compliance and noncompliance are imperfect.

From a monitoring perspective, the mean annual load at the watershed outlet cannot be used to identify watersheds that have a potential to switch between compliant and noncompliant states for either Current conditions or Tributary Strategy conditions. The outlet perspective only identifies the extreme compliant or noncompliant states, which have respective high probabilities of exceeding or not exceeding a LA criterion value. The mean annual load at the outlet reduces the compliance issue to a nominal solution. In contrast, the probability of exceeding a LA critical value at the outlet can capture some of the variability in the two compliance states that occurs upstream from that point. The whole watershed perspective, however, allows for the health of the watershed to be determined more on a case by case basis, such that cases like watershed 3 can be better understood.

4.4.2 Compliance Maps

The whole watershed perspective produced a set of 35 compliance maps shown in Appendix A.1. The benefit of the compliance maps is that they provide a visual representation on the relationship between stream network structure, LCLU, and NPS loadings. These maps assisted in the identification of stream lengths that are homogeneously compliant for either Current conditions or Tributary Strategy conditions. These stream lengths may not represent a compliant watershed, but could be monitored individually to improve the health of a subsection of the watershed. Watersheds 3, 23, 29, 33, and 34 have already been identified as having stream lengths receptive to improvement by the Tributary Strategy Plan. The compliance maps identified watersheds 6, 14, and 28 as also having isolated lengths of stream that can potentially be improved.

The Upper Chester watershed (6) was identified as noncompliant for all three perspectives for both Current conditions and Tributary Strategy conditions. However, 23 percent of stream lengths are compliant under Tributary Strategy conditions (Table 4-3). The compliance map shows that the upper portion of the watershed stream lengths have the potential to be compliant under the Tributary Strategy Plan (Figure 4-6). The difference in compliance between upper and lower portions of the watershed is due to the larger contribution of forested area in the upper portion of the watershed. However, this is not represented in the two outlet perspectives or the 70 percent criterion used to summarize observations for the third perspective.

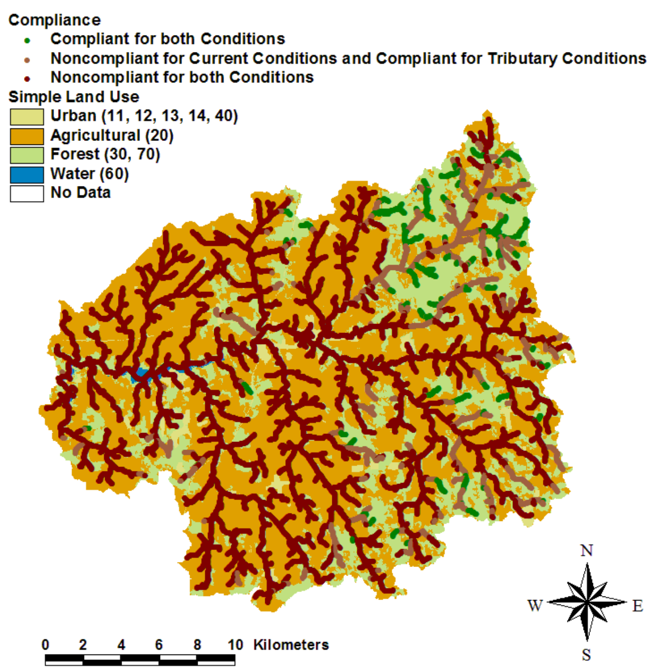


Figure 4-6: Map of stream compliance with the LA critical value for the Upper Chester River watershed (6).

The Breton Bay watershed (14) was identified as noncompliant for all three perspectives for both Current conditions and Tributary Strategy conditions. In this case 21 percent of the total stream length is compliant under Tributary Strategy conditions (Table 4-3). The map of compliance shows that one length of stream in the upper portion of the watershed could easily address the nitrogen impairment under the Tributary Strategy Plan (Figure 4-7). The difference in compliance between upper and lower portions of the watershed is due to the larger contribution of forested area along that particular stream length. Again, this is not represented in the two outlet perspectives or the 70 percent criterion used to summarize observations for the third perspective.

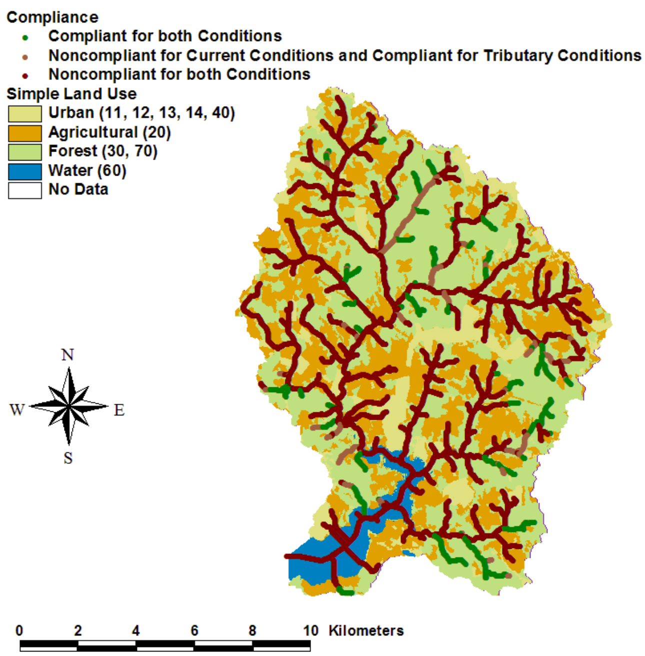


Figure 4-7: Map of stream compliance with the LA critical value for the Breton Bay watershed (14).

The Lake Habeeb watershed (28) was identified as noncompliant for all three perspectives for just Current conditions; the watershed was identified as compliant when considering Tributary Strategy conditions. However, 36 percent of the total stream length is compliant under Current conditions (Table 4-3). The compliance map shows that several lengths of streams along the main channel of the watershed are compliant (Figure 4-8); the main channel is noncompliant. The difference in compliance between the main channel and the other streams is due to load contributions from concentrated agricultural land use. The streams local to the concentrated agricultural land use are the most noncompliant compared to the rest of the watershed. Overall the watershed is forested; therefore, compliant levels of NPS runoff accumulate to smaller streams. Again, these observations are not represented in the two outlet perspectives or the 70 percent criterion used to summarize observations for the third perspective.

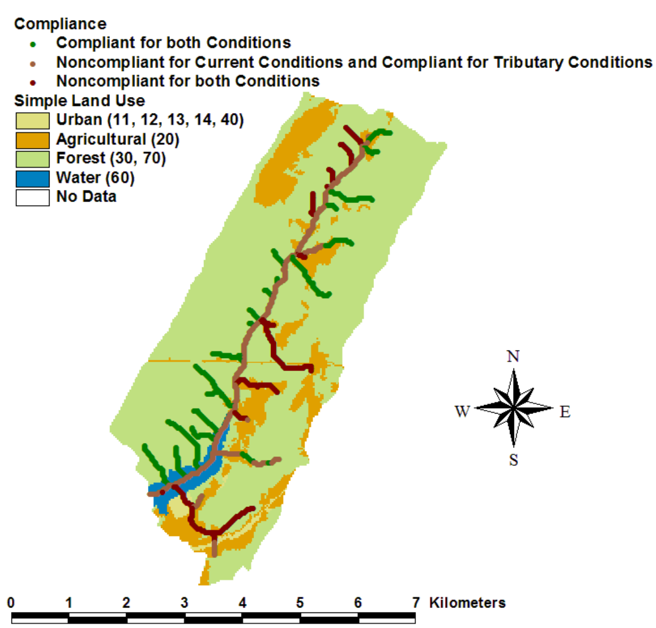


Figure 4-8: Map of stream compliance with the LA critical value for the Lake Habeeb watershed (28).

4.5 Relationship Between Land Use Spatial Distributions and Compliance

A review of the LCLU data associated with the estimation of the load samples explains differences in the load samples between the set of 35 watersheds. Additional variation also occurred due to loading rate conditions applied to specific state segments.

The LCLU classification results for each watershed are given earlier in Table 3-12. The LCLU classifications are simplified to include: agriculture (A), urban (U), forest (F), and water (W). Agriculture is the sum of high till, low till, hay, pasture, and manure. Urban is the sum of pervious urban, impervious urban surfaces, and non-agricultural spaces such as golf courses. The classifications show that, when cumulated, non-forest classes dominate the majority of the 35 watersheds. The LCLU information revealed variation in spatial patterns of LCLU distributions among the watersheds.

To test for LCLU variability in watershed loading distributions, simplified land use classes were ordered by increasing area relative mean annual load at each of the 35 watershed outlets. Figure 4-9(b, d, f, and h) shows a boxplot representation of the spread of LCLU within each watershed in comparison to Figure 4-9(a, c, e, and g), which shows a boxplot for the respective spread of area relative mean annual loads within each watershed. Figure 4-9 uses the traditional quartile representation of a box and whisker plot. The central bar represents the median of the data, which was determined as the middle value of a set of order-ranked data for all stream locations within a watershed. The box upper and lower sides represent upper and lower quartiles of the data. The upper and lower bars represent the largest and smallest data values. The length of the whiskers was specified as 1.5 times the interquartile range. The dots represent data that fall outside the range of the other values, otherwise known as outliers. The outliers were not included in the whisker because loads are not dispersed throughout the whole range from the quartile to the outlier. Figure 4-9 is based on pairs of mean annual loads and land use proportions, collected from the set of mean loads that were calculated at every 30 m by 30 m stream pixel within each watershed.

In most cases the differences between proportions of LCLU were not large, but loading distribution medians did show a relation to the proportions of forested areas and agricultural areas, with highest percent forest occurring for minimum loadings and highest percent agriculture occurring for maximum loadings. In some cases, there were large differences in the proportions of LCLU classes between watersheds. For example, the proportion of forested areas range from a maximum of 0.97 percent to a minimum 0.04 percent, where the respective Current condition loads range from a minimum of 1.86 lb/yr/ac and a maximum of 18.78 lb/yr/ac. The respective Tributary Strategy condition loads range from a minimum of 1.67 lb/yr/ac to a maximum of 9.05 lb/yr/ac. Similar differences for other LCLU classes can also be observed.

In each watershed, Figure 4-9 shows that forest, agricultural, urban, and water classes contributed to an observed increase in nitrogen loading. Figure 4-9 suggests that forest contributes smaller nitrogen loads compared to the other classes, and as the proportion of forests inside the watershed increases, NPS loads downstream remain small. Figure 4-9 identifies agricultural areas as strong contributors of NPS loads.

The urban areas have been identified as less important contributors compared to agriculture; urban areas usually occurred over smaller land areas overall.

Another important factor associated with differences in NPS loads among streams is the land use proportions in smaller order streams. The earlier compliance maps showed that in some of the watersheds, forests occupy large portions of areas upstream to smaller order streams. These forested areas tend to contribute compliant levels of NPS loads. In contrast, when agriculture occupies upstream locations, the smaller order streams are noncompliant. Section 4.4.2 includes three examples of compliance maps that illustrate the effects of forest and agricultural land use on loads.

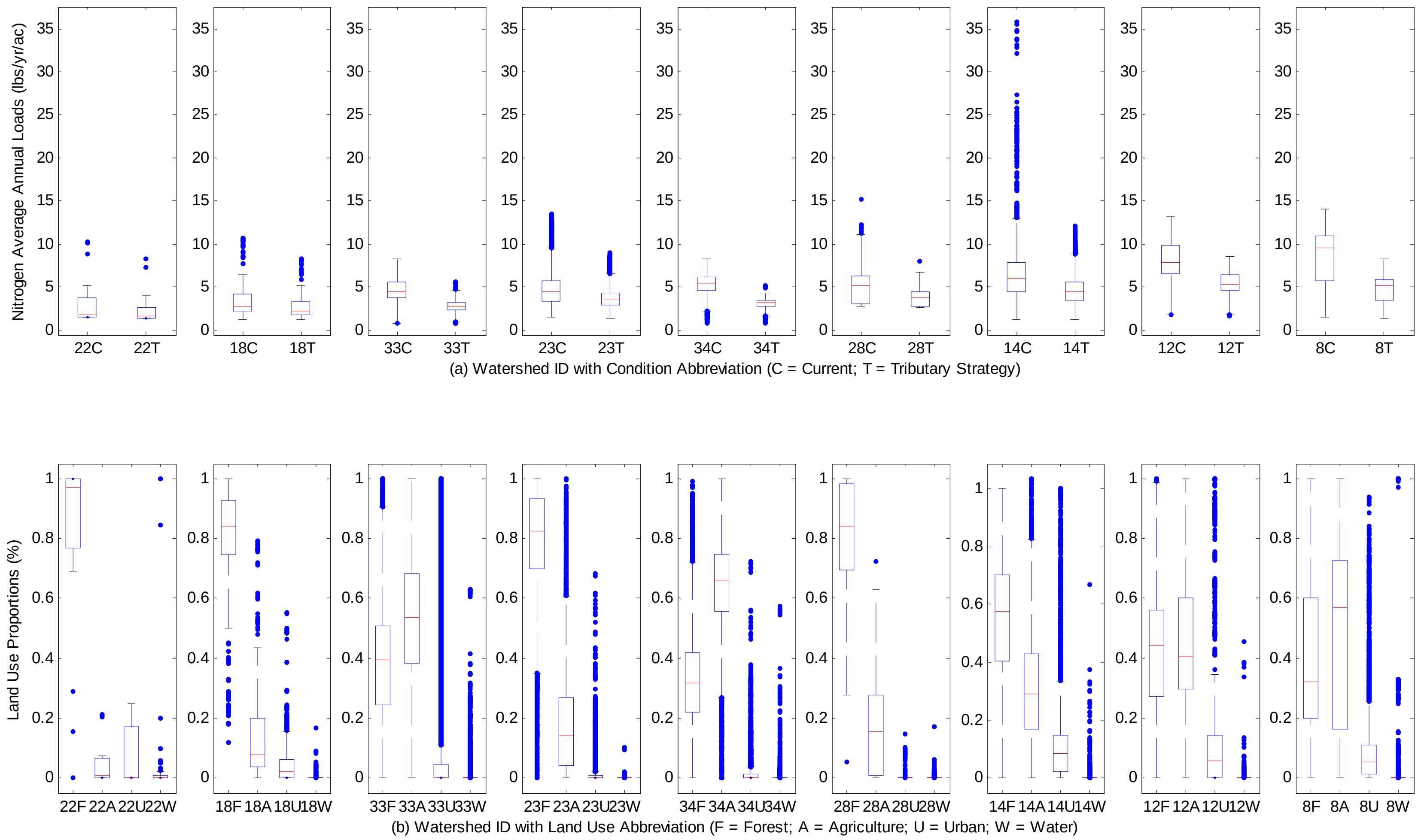


Figure 4-9: Boxplots comparing LCLU classifications and mean annual loads between watersheds. The data were collected for every stream pixel.

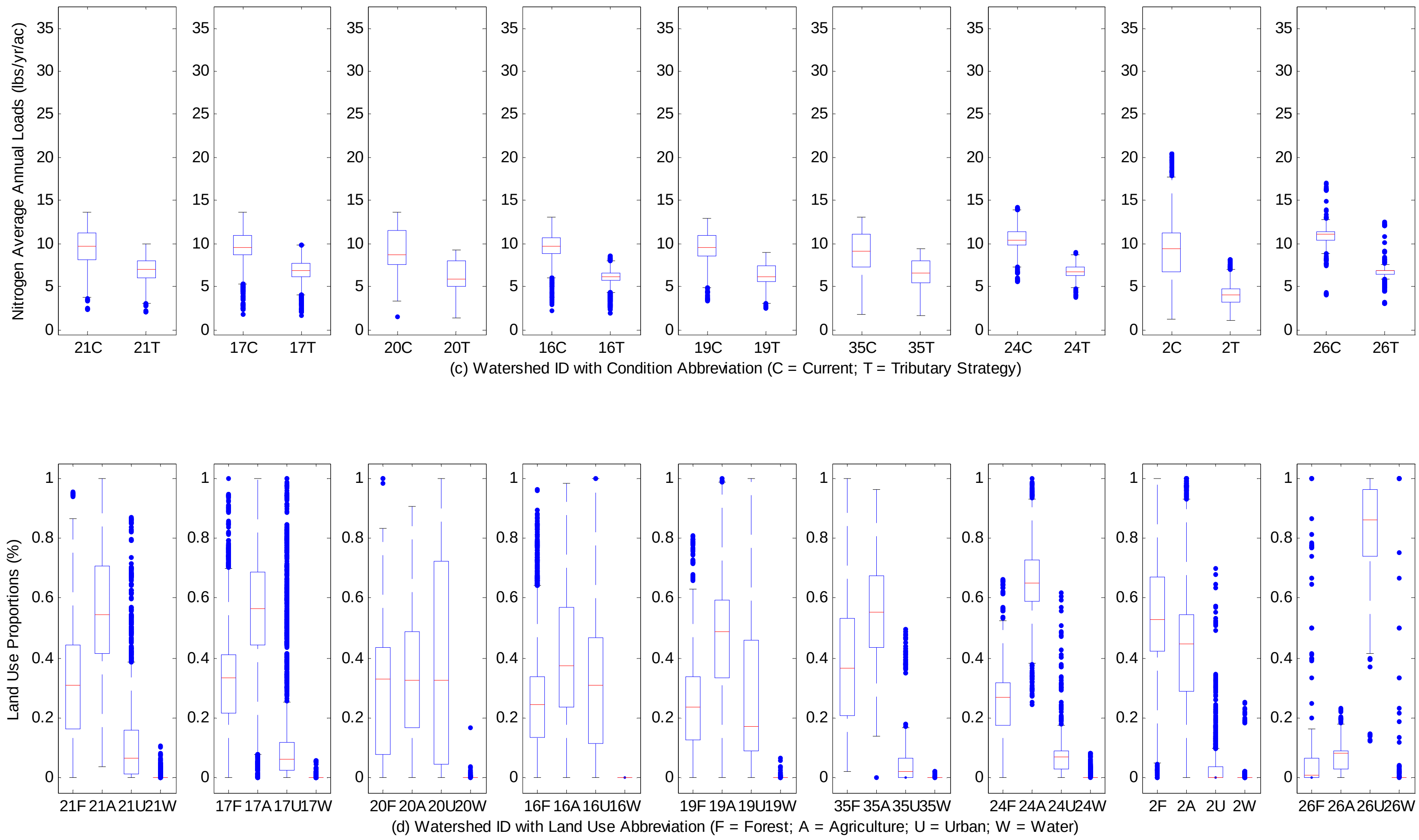


Figure 4-9 (continued): Boxplots comparing LCLU classifications and mean annual loads between watersheds. The data were collected for every stream pixel.

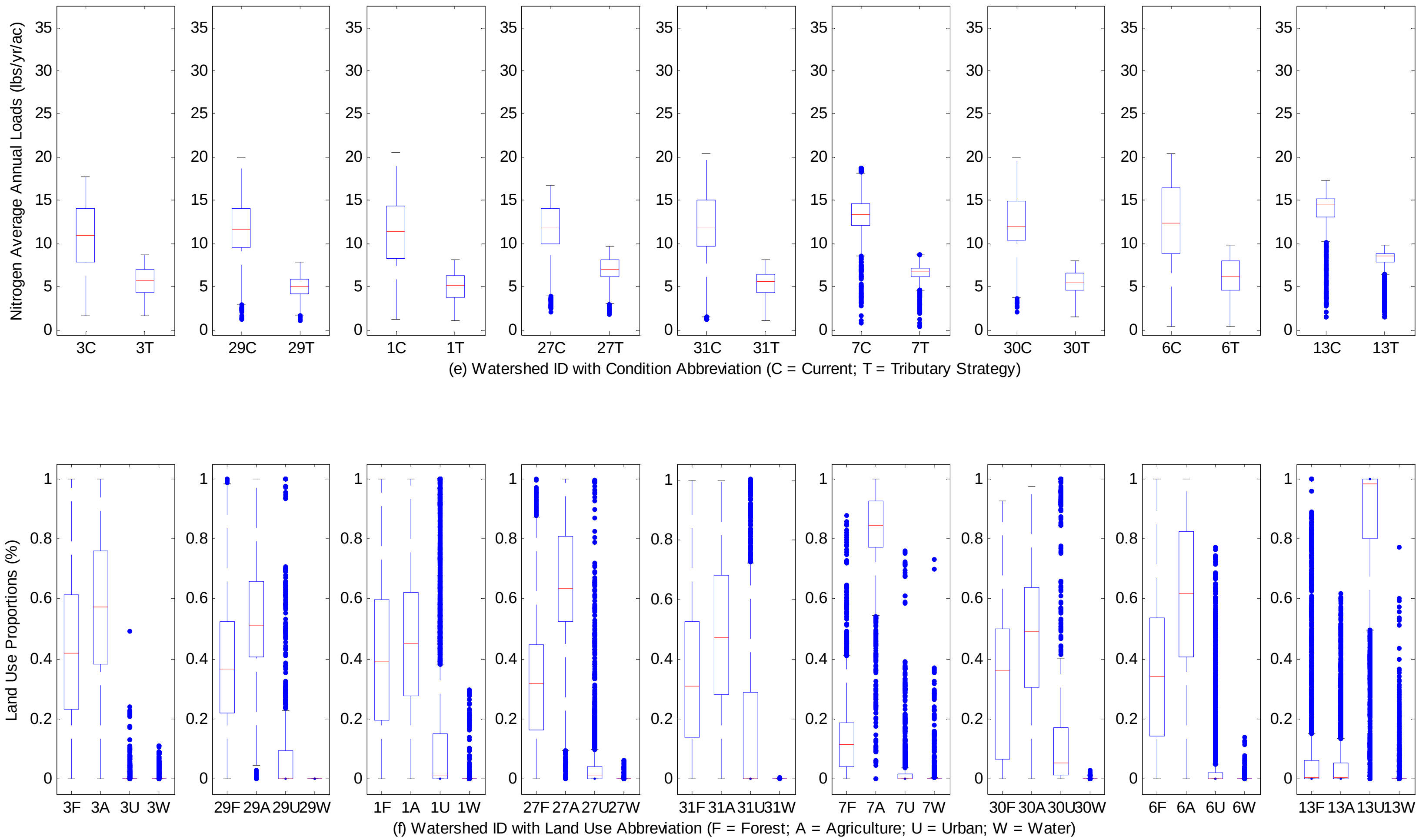


Figure 4-9 (continued): Boxplots comparing LCLU classifications and mean annual loads between watersheds. The data were collected for every stream pixel.

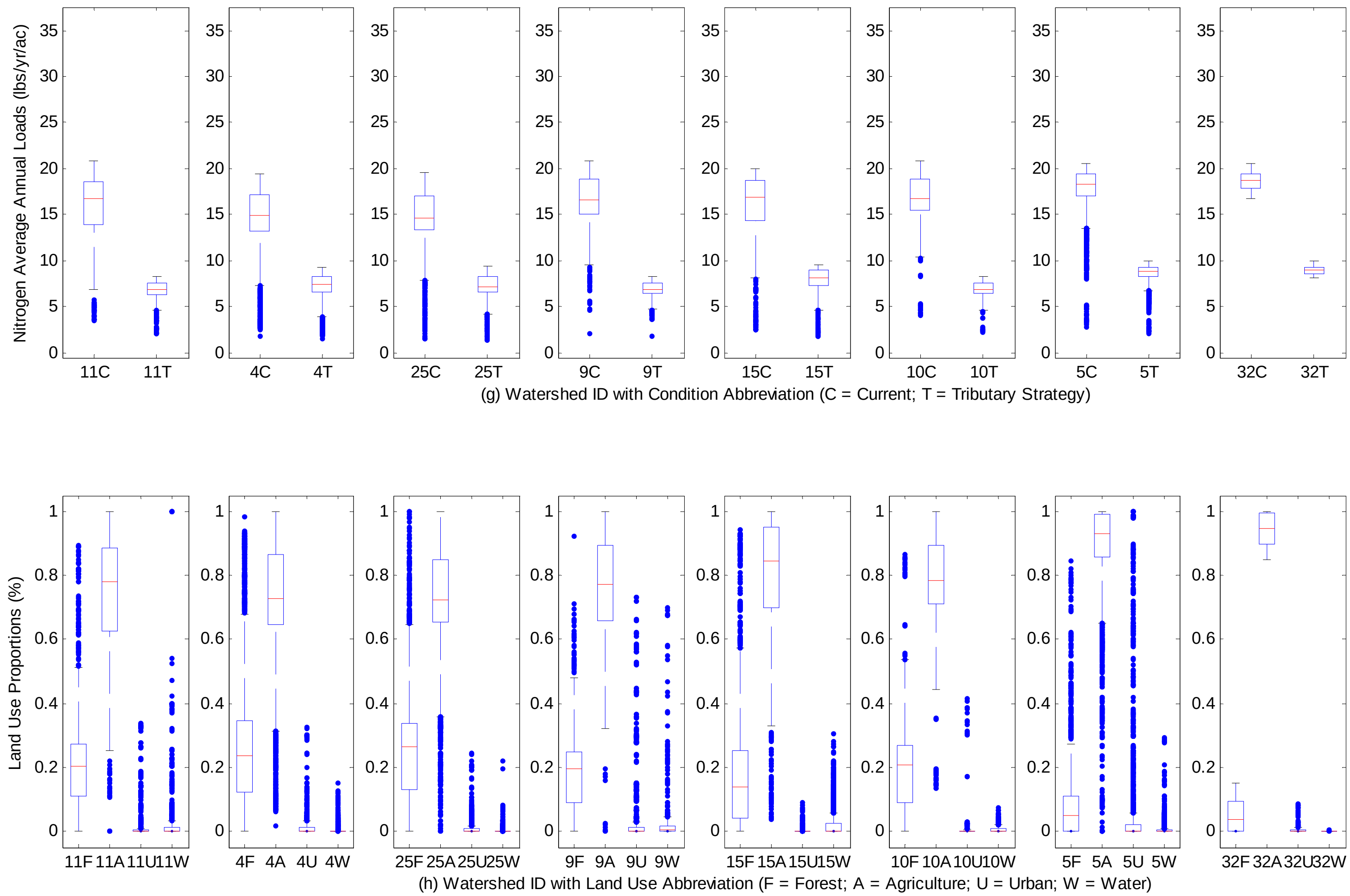


Figure 4-9 (continued): Boxplots comparing LCLU classifications and mean annual loads between watersheds. The data were collected for every stream pixel.

The compliant watersheds are located in the Appalachian Plateau and Blue Ridge, and Western Coastal Plain provinces of Maryland. Based on the observations made for Figure 4-9, the reduced loading may be attributed to the fact that these regions have areas with higher forest LCLU and are less heterogeneous compared to the Piedmont and Eastern Coastal Plain provinces of Maryland. The loading rates by land use for forest are smaller compared to other land use loading rates (Figure 3-8) and combined with the greater available forested areas, the loads in these provinces are relatively small. These observations are consistent with MDE/USEPA reports, which focused mostly on watersheds located in the Piedmont province, where most of the LCLU is less forested. Watersheds located in the Piedmont and Eastern Coastal Plain provinces tend to be listed for nutrients by MDE/USEPA, where watersheds located in the Appalachian Plateau, Blue Ridge, and Western Coastal Plain provinces tend to be delisted for nutrients.

Additionally, the larger variance in sampling due to the more heterogeneous LCLU would suggest that the out of compliance problem is largely due to large variance, rather than the large mean values. The literature review indicated that the spatial variation of NPS pollution is the main problem in reducing nutrient loads. The remainder of the discussion examines the spatial variability in loadings in relation to semivariogram analyses.

4.6 Evaluation of the Tributary Strategy Plan's Reduction in Loads

This thesis examined compliance from the following three perspectives: Perspective one evaluated compliance as a mean annual load nominal comparison with a LA criterion (Section 4.3.1). Perspective two evaluated compliance as a probability of exceeding a LA criterion (Section 4.3.2). Perspective three evaluated watershed compliance as a percent compliant stream length (Section 4.4.1). These three perspectives identified few watersheds as compliant. Although the Tributary Strategy condition loading rates were reduced from the Current condition loading rates, less than half of the total 35 watersheds were evaluated as compliant under Tributary Strategy conditions (Table 4-4).

Table 4-4: Number of Watersheds Identified as Compliant.

Condition	Perspective One	Perspective Two	Perspective Three
Current	5	2	2 (2-1)
Tributary Strategy	15	14	11 (13-4)

Table 4-4 shows that perspective one identified more watersheds as compliant with water quality standards compared to the number of compliant watersheds for perspectives two and three. Perspective one, therefore, is the least stringent in enforcing water quality standards. In contrast, perspectives two and three identified approximately the same number of compliant watersheds. Perspective three is shown with a range in possible compliance determinations. When the required compliant stream length was assumed to equal 70 percent, perspective three identified two and 11 watersheds as being compliant for Current and Tributary Strategy conditions, respectively. When the required compliant stream length was reduced to 50 percent, two and 13 watersheds were identified as compliant for Current and Tributary Strategy conditions, respectively. When the required compliant stream length was increased to 90 percent, one and 4 watersheds were identified as compliant for Current and Tributary Strategy conditions, respectively.

4.7 Monitoring Application

The spatial variability of NPS runoff poses a serious problem in identifying compliant and noncompliant watersheds within the State of Maryland. The variability determines, for example, the confidence with which a monitoring location can reliably detect upstream NPS contributions. If a specific level of confidence is required for such comparisons, then it would be beneficial to know how far away the monitoring point can be located from the NPS. Additionally, a watershed with high spatial variability and long range in local structure means that fewer samples are required in order to make such comparisons at a given level of confidence than would be the case if the variability was much lower and the range in local structure was shorter. In essence therefore, there is a need to ensure that the choice of monitoring sites do not assume unacceptable errors in upstream prediction estimates. An initial step in understanding data from streams is discerning non-random patterns along the length of the flow direction.

4.7.1 Semivariogram Analyses

A review of the variance associated with reduced loads between the Current and Tributary Strategy conditions explains differences in the load samples between the set of 35 watersheds. To analyze spatial patterns in variance, spatial statistics were applied using semivariograms for chosen stream lengths within each watershed. A range and sill were found for a spherical model and are shown in Tables 4-5 and 4-6. Watersheds not represented in the two tables (*e.g.*, 5, 9, 11, 22, 26, and 32) did not produce a clear spherical structure and are omitted from this comparison.

A large set of compliant streams was not available from the 35 watersheds to conduct a statistically significant test on compliant versus noncompliant conditions. However, if the Tributary Strategy loads are assumed to represent reasonably reduced loads then a comparison between all Current condition loads and all Tributary Strategy conditions loads can be made to evaluate the change in variation that can be expected as loads approach compliant levels.

Table 4-5: Noncompliant spherical semivariogram parameters and statistics

			Current condition					Tributary Strategy Condition				
ID	n	h	γ_r	r	$\bar{e}/\bar{y}$	S_e/S_y	R^2	γ_r	r	$\bar{e}/\bar{y}$	S_e/S_y	R^2
1	130	42.4	0.42	1322	0.0047	0.56	0.69	0.052	1247	0.0045	0.58	0.66
2	61	40.5	3.47	2125	0.0093	0.13	0.98	0.54	2160	0.0077	0.13	0.98
3	291	41.2	2.13	8570	0.0110	0.13	0.98	0.44	8628	0.0111	0.13	0.98
4*	62	38.5	0.82	1446	-0.0040	0.24	0.94	0.16	1420	-0.0035	0.24	0.94
6	319	38.6	1.57	9567	-0.0005	0.09	0.99	0.31	9560	-0.00069	0.09	0.99
7	217	37.2	0.39	3930	0.0034	0.09	0.99	0.08	3610	0.0022	0.12	0.99
8	449	40.6	0.97	15690	-0.0228	0.22	0.95	0.39	19746	-0.0085	0.14	0.98
10	85	37.8	1.80	3672	0.0298	0.20	0.96	0.22	3204	0.0303	0.21	0.96
13	303	39.6	0.39	9815	0.0081	0.18	0.97	0.11	11061	0.0067	0.16	0.97
14	38	41.6	0.15	1116	-0.0042	0.12	0.99	0.058	972.8	-0.0061	0.20	0.96
15	142	42.1	0.97	4777	0.0213	0.17	0.97	0.20	4866	0.0224	0.17	0.97
16	74	40.1	0.11	2145	0.0086	0.14	0.98	0.045	2110	0.0027	0.08	0.99
17	62	39.8	0.02	1658	-0.0027	0.17	0.97	0.014	1736	-0.0092	0.19	0.97
19	167	41.9	2.4	7312	0.0065	0.11	0.99	1.09	7498	0.0083	0.11	0.99
20	166	42.0	0.96	6850	0.0119	0.10	0.99	0.57	8777	0.0061	0.07	0.99
21	60	41.6	0.41	2013	0.0091	0.10	0.99	0.18	1765	0.008	0.14	0.98
24	86	40.5	0.41	3626	-0.0131	0.15	0.98	0.15	3557	-0.0103	0.13	0.98
25	100	39.7	0.39	2193	0.0080	0.14	0.98	0.07	2217	0.0076	0.14	0.98
27	248	40.2	1.72	10385	0.0250	0.15	0.98	0.50	10399	0.026	0.16	0.98
29	258	38.7	2.9	7934	0.0050	0.12	0.99	0.59	11096	0.015	0.13	0.98
31*	206	41.4	2.13	3345	0.0091	0.60	0.65	0.30	3617	0.0094	0.39	0.85
33*	61	39.1	0.02	2451	0.0160	0.14	0.98	0.004	2302	0.0111	0.13	0.98
34*	61	38.9	0.03	1504	0.0112	0.21	0.96	0.01	1445	0.01	0.25	0.94
35	63	38.1	2.46	1836	0.0104	0.10	0.99	1.13	1764	0.01	0.12	0.99

Note: * Sometimes compliant loads based on Tributary Strategy conditions;
ID = watershed identification number; n = number of variogram values used to fit the spherical model; h = lag increment; γ_r = sill; r = range of influence; $\bar{e}/\bar{y}$ = relative bias; S_e/S_y = standard error ratio; R^2 = coefficient of determination;

Table 4-6: Compliant spherical semivariogram parameters and statistics

			Current condition					Tributary Strategy Condition				
ID	n	h	γ_r	r	$\bar{e}/\bar{y}$	S_e/S_y	R^2	γ_r	r	$\bar{e}/\bar{y}$	S_e/S_y	R^2
12	79	37.7	0.51	2742	0.0080	0.11	0.99	0.17	2652	0.007	0.12	0.99
18	113	39.6	0.22	4179	0.0019	0.16	0.98	0.11	4116	0.005	0.15	0.98
23	249	40.0	0.18	7201	-0.00090	0.15	0.98	0.07	7195	-0.001	0.13	0.98
28	119	42.4	0.39	3022	-0.011	0.32	0.90	0.07	2816	-0.012	0.37	0.86
30	48	37.4	0.99	820	-0.0066	0.28	0.92	0.12	727	-0.0080	0.13	0.98

Note: ID = watershed identification number; n = number of variogram values used to fit the spherical model; h = lag increment; γ_r = sill; r = range of influence; $\bar{e}/\bar{y}$ = relative bias; S_e/S_y = standard error ratio; R^2 = coefficient of determination;

4.7.1.1 Difference in Sample Site Range of Influence

The ranges of influence were not significantly different between the Current condition and the Tributary Strategy condition loads for all compliance states. A KS-2 test was conducted where the sample size, n, was equal to 29. The null hypothesis for the two-tailed alternative was that the cumulative frequency distributions for the range of influence are not significantly different between the two conditions. The maximum difference between the cumulative frequency distributions for the two conditions was equal to 3 (Figure 4-10). The null hypothesis was accepted because the maximum difference is less than the critical values 11 and 13 at the 5 percent and 1 percent levels of significance, respectively.

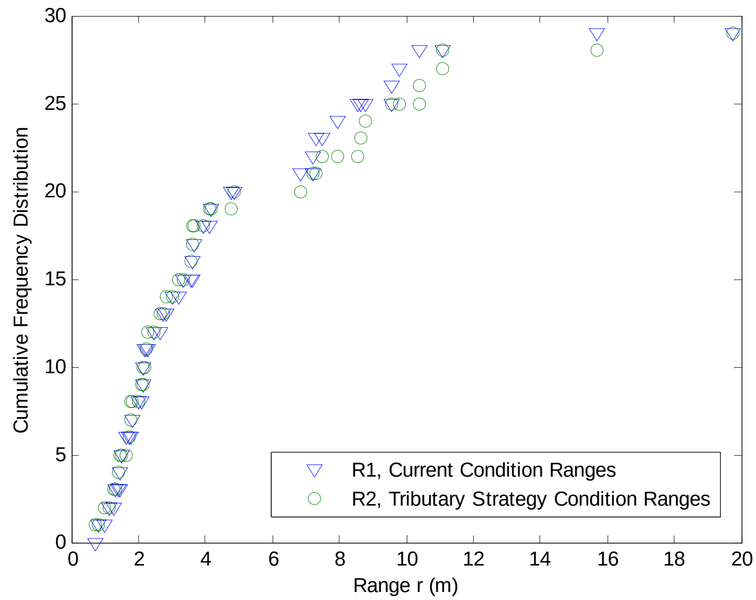


Figure 4-10: Cumulative probability distribution for two sets of 29 ranges for the Current condition and Tributary Strategy condition.

4.7.1.2 Difference in Sample Site Sill

The sills are significantly different between the Current condition and the Tributary Strategy condition loads for all conditions. A KS-2 test was conducted where the sample size, n, was equal to 29. The null hypothesis was the same as before but for the one-tailed alternative, where the alternative hypothesis was that the cumulative frequency distribution for the Current condition sill is significantly greater than the cumulative probability distribution for the Tributary Strategy condition sill. The maximum difference between the two cumulative frequency distributions is equal to 14 (Figure 4-11). The one-tailed alternative hypothesis is accepted because the maximum difference is greater than the critical values 10 and 12 at the 5 percent and 1 percent levels of significance, respectively.

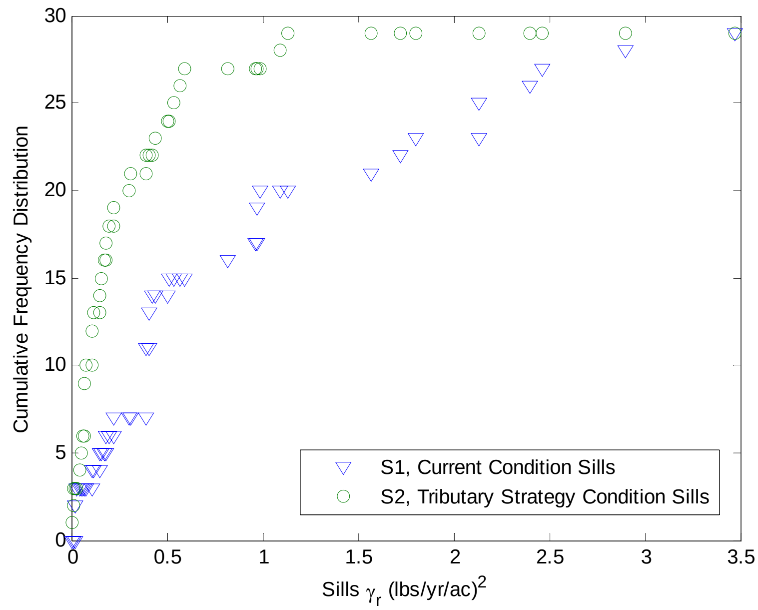


Figure 4-11: Cumulative frequency distributions for two sets of 29 sills for the Current condition and Tributary Strategy condition.

4.7.2 Implications of Loading Variance

The results indicate that the semivariogram Equation 3-14 are informative of prediction accuracy based on changing loads. The range of influence remained constant for all watershed conditions. However, the Tributary Strategy condition sills were reduced relative to the Current condition sills. As illustrated in Section 3.5.2.5 for the Saint Mary's watershed (18), these results indicate that as loading conditions become reduced, the monitoring point's accuracy in predicting upstream conditions becomes reduced. The reduced accuracy is due to the reduced spatial structure of the data points. As the Tributary Strategy conditions are approached, the load variation approaches values closer to random noise, or natural variation. Understanding the natural variation, therefore, could be a more informative measure of stream compliance with water quality standards than the three compliance perspectives that were described earlier.

The semivariograms are provided here to illustrate the utility of semivariograms as a first step in detecting spatial variation and to encourage monitoring designs to explore patterns of load variability in the design of monitoring programs in stream networks. The dependence of the value of the sill on the mean of the data values for each stream length is apparent in the above hypothesis test between the sills for the Current condition and the sills for the Tributary Strategy condition. Other studies have considered alternatives to Equation 3-14 which take into account effects of changing mean loads within a stream network (Ganio *et al.* 2005). These alternative methods can graphically describe a clear spatial structure for the entire stream network of a watershed. The semivariogram methods presented in this thesis, therefore, are not fully developed and are still in exploration stages.

Chapter 5: Summary and Conclusions

5.1 Summary of the Research

Nonpoint-source (NPS) pollution monitoring studies seldom have the ability to locate sources of pollution and determine the best strategic plan to minimize pollution from those different sources. While there have been previous efforts to evaluate the effectiveness of land cover/land use (LCLU) in the identification of NPS pollution, no single example has sought to evaluate the effectiveness of specific monitoring perspectives. Specifically, this thesis evaluated the performance of three perspectives in detecting watershed compliance with water quality standards, the first being a nominal comparison between a mean annual load and a maximum allowable load at a watershed outlet (Section 3.4.3). The second perspective utilized a loading distribution to determine the probability of a mean load exceeding a maximum allowable load at a watershed outlet (Section 3.4.4). The third perspective evaluated the loading distribution for the entire watershed stream network to determine the percentage of total stream length that exceeds water quality requirements (Section 3.4.5). In order to compare the performance of the three perspectives 35 watershed loading scenarios were calculated within a GIS environment (Section 3.2 and Section 3.3) and compared with a combination of MDE/USEPA recommended criterion values and reasonably assumed criterion values (Section 3.4.2).

Watershed compliance interpretations using the three perspectives showed that the current implementation of total maximum daily load criterion at a watershed outlet is inadequate in the identification of watersheds whose designated uses are threatened. This conclusion is supported by the fact that the nominal mean annual load outlet perspective was only representative of upstream water quality conditions for watersheds whose loading scenarios clearly differed from the maximum load allocation criterion; this means that total maximum daily loads applied at the outlet tended to only identify watersheds that are undoubtedly impaired or are high quality waters (Section 4.3.1). Compliance maps generated in the GIS showed that these noncompliant watersheds are typically characterized by LCLU distributions that are comparable at both the smaller stream-scale and the larger-watershed scale; this observation would indicate that land use categories cannot assist in targeting large contributing sources of pollution within these watersheds (Section 3.5.1, Section 4.4.2, and Section 4.5). An examination of the percentage of compliant stream length within each of the calculated watershed loading scenarios (Table 4-3, Section 4.4) showed that the probability of exceeding a threshold at the watershed outlet (Section 4.3.2) is more representative of conditions upstream of a watershed outlet compared to the nominal annual average load perspective (Section 4.3.1).

Combination of the two outlet perspectives aids in the identification of threatened watersheds (Figure 4-3 and Figure 4-4, Section 4.3.2). Threatened watersheds are defined as watersheds whose compliance interpretation for the nominal annual average load comparison identifies the watersheds as compliant but their loading distributions have high probabilities of exceeding maximum load allocations. In other words, on average, threatened watersheds are compliant with load allocations, however, variations within their loading distributions are large enough that noncompliant conditions persist enough to pose threats to their designated uses.

Additionally, an examination of load variation upstream of a watershed outlet utilizing semivariogram techniques was demonstrated (Section 3.5.2). Statistical comparisons between semivariograms for the Current loading condition and the Tributary Strategy loading condition showed that as loading conditions become reduced, a monitoring point's accuracy in predicting upstream conditions becomes reduced (Section 4.7.2).

The GIS calculated loading scenarios also provide an efficient way to identify specific locations or regions where elevated levels of nitrogen loadings may be expected (Section 3.5.1, Section 4.4.2, and Section 4.5). In particular, this thesis has shown that watersheds with a large percentage of their area occupied by agricultural lands tend to have locations where elevated nutrient levels can be expected. Urban land use also tends to elevate nutrient levels but generally at smaller spatial scales. Monitoring programs can use compliance maps to focus on subareas, particularly at the transitional stream lengths between compliant and noncompliant loads.

5.2 Significance of the Load Calculation Methodology

This thesis developed a loading calculation methodology that is of greatest value to monitoring network design, specifically at the site selection stage. Because the methodology used readily available LCLU data and pollutant loading rates, the methodology may be applied to any unmonitored location. For example, the research was performed across 35 watersheds within the State of Maryland. Utilization of the compliance map and site loading distributions can aid in the identification of monitoring sites that are representative of upstream loading conditions. Additionally, application of semivariogram techniques within a GIS can estimate the expected load variation at points upstream from a selected monitoring site. Understanding a monitoring site's potential change in load variation is possibly more important from a monitoring perspective than understanding a site's change in mean annual load. This thesis demonstrated the examination of both load variation and mean annual loads.

5.3 Limitations and Future Work

The semivariogram analysis was an experimental demonstration of a geostatistical method that has not been previously applied to loads at stream points. The appropriateness of applying this method to mean annual loads at stream points should be evaluated. These mean annual loads are correlated by their accumulative nature and do not represent independent observations on a random variable. However, the semivariogram concept is based on the assumption that points are related by their closeness to each other. It may be more valid to apply the semivariogram technique to incremental loads downstream. In this way, the loads would still be related by their proximity to one another based on the likelihood that local land use areas are spatial related.

A limitation on the semivariogram analysis was that load sample points were collected along a single stream length. In reality loads vary along an entire branched network of stream lengths. Future research should develop a semivariogram for all non-Euclidean distances between points everywhere in the watershed. Euclidean distance is defined as the shortest straight line between any two points (Rathbun 1998). The term non-Euclidean, in this context, refers to lag distances that are omnidirectional along stream network paths only and do not cross into land topography (Ganio *et al.* 2005). Additionally, the current implementation of semivariogram analyses was dependent on the mean of the data values for each local stream length. For example, the Current condition sills were larger compared to the Tributary Strategy condition sills because the mean of the data collected for the Current condition was larger than the mean of the data collected for the Tributary Strategy condition. Alternative analyses should evaluate relative semivariograms to scale the semivariogram to some local mean value. In future extension, the semivariogram technique may allow a single semivariogram to be applied anywhere within a watershed compared to just a single stream length.

Loading rate standard deviations based on equal weights are assumed within the current implementation of the GIS calculated loading scenarios. This assumption may have caused unnecessary bias in the model. For example, a watershed may overlap two county segments. The majority of the watershed may overlap one county segment, while only a corner of the watershed may overlap the other county segment. The county segments report a mean loading for each land use. Assuming that there is an equal weight for each county segment could bias the predictions if there is a large difference between the two loading rates. A future extension of this research should assess effects of distance or area weighted standard deviation calculations on the estimation of loading distributions. Within this assessment, the validity of the normal distribution assumption should be tested.

Loading contributions from the entire watershed land area are currently assumed. This assumption is not representative of the fact that the actual area of land that contributes to storm runoff, and thus nutrient and sediment transport, can be relatively small and dynamic (Eshleman *et al.* 1993). This "variable source area concept" (Black 1991) is usually applied at the event scale for relatively small watersheds. Others have suggested, however, that this concept can be applied to large watersheds to explain processes such as nutrient cycling (Naiman *et al.* 1992). This concept would be appropriate in trying to determine nutrient and sediment loading from NPSs in a similar context. Results from Sorrano *et al.* (1996) suggest that the area of the watershed that contributes most of the loading is much less than the total watershed area and is strongly dependent on precipitation. Remotely sensed soil and precipitation data should be evaluated in the identification of contributing areas. Using available infiltration equations, it may be possible to differentiate between land areas that contribute to runoff and land areas that absorb all precipitation. An alternative method could calculate a ratio between the drainage area and slope (Moglen and Bras 1994). This ratio could then be compared to a threshold to select specific contributing areas. Only the land areas that contribute to runoff would then be used in load calculations. Within this alternative method, it may also be necessary to calculate new loading rates.

The order by which land use accumulates downstream within a watershed is not currently being considered. The effects of forest land use as a nonpoint source sink have been widely studied and have been shown to limit the amount of NPS pollution that is passed on to the next land use class. In particular, best management practices such as riparian zones next to agricultural lands are being advocated because forest land use can attenuate some of the nonpoint source load that is leaving the agricultural land use. Future research should evaluate the use of an additional attenuation coefficient to limit downstream nonpoint source load contributions depending on the upstream land use.

Future research should also identify nutrient limited regions within a watershed, such that monitoring objectives could choose to sample phosphorus versus nitrogen constituents to conserve on funds. Ratios of nitrogen loads to phosphorus loads can be evaluated using available phosphorus loading rates in conjunction with the nitrogen loading rates used in this thesis. The final GIS outcome could include the following three maps: a map of nitrogen compliant streams; a map of phosphorus compliant streams; a map of nutrient limited streams. When overlaid, these maps could be coupled with professional judgment in the identification of areas where the effects of excess nutrients are being realized.

Integration of a daily time step should be included. Disaggregation of annual average loads into daily loads was investigated early on in the work contributing to this thesis. A Maryland daily to annual discharge ratio curve was developed and a composite model regression curve was fit to the data. This curve was omitted from the final thesis mainly because the accuracy of pollutant loading estimates would have been reduced. This curve, however, could be used to disaggregate the total maximum daily load distribution. The 90th percentile could then be used as a representative daily load criterion, following the recommendation of the USEPA (2007). This could then be compared to disaggregated annual stream pixel average loads. This way a more complete spatiotemporal statement about the water quality compliance of a watershed could be made. The current application, however, does not consider variations within years, the currently application only attempts to calculate loading from year to year.

Finally, the origin of the loading rates used in this thesis is in a Chesapeake Bay Program Office tool to interpolate loads that are equivalent with Phase 4.3 of the Chesapeake Bay Watershed Model (WSM). This tool was intended to be used for nonpoint-source load accounting purposes. As monitoring data are acquired for the entire state of Maryland, proper validation of the model in this thesis should be completed to understand the model's predictability of actual observed loads. Until this validation process is completed the results of the loading calculated scenarios should only be used as planning tools and should not be accepted as observed loads or observed variations in loads.

Appendices

A.1 Compliance Maps and Maryland State Plane Coordinates for Outlet

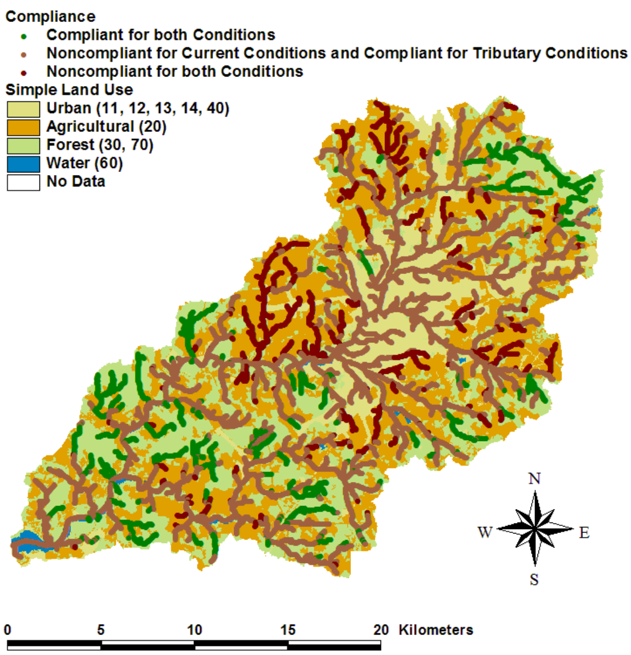


Figure A-1: Lower Wicomico River watershed (1) and outlet (502395.2, 65876.7).

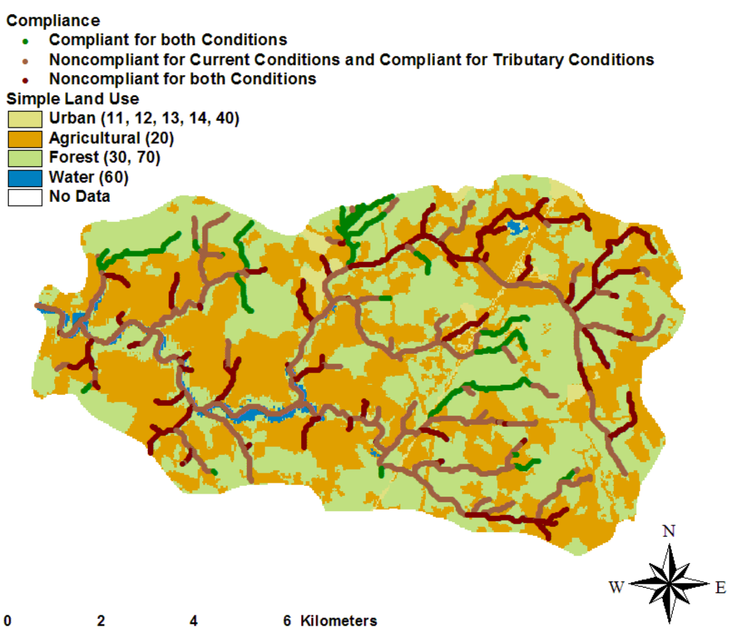


Figure A-2: Wicomico Creek watershed (2) and outlet (508626.7, 69522.8).

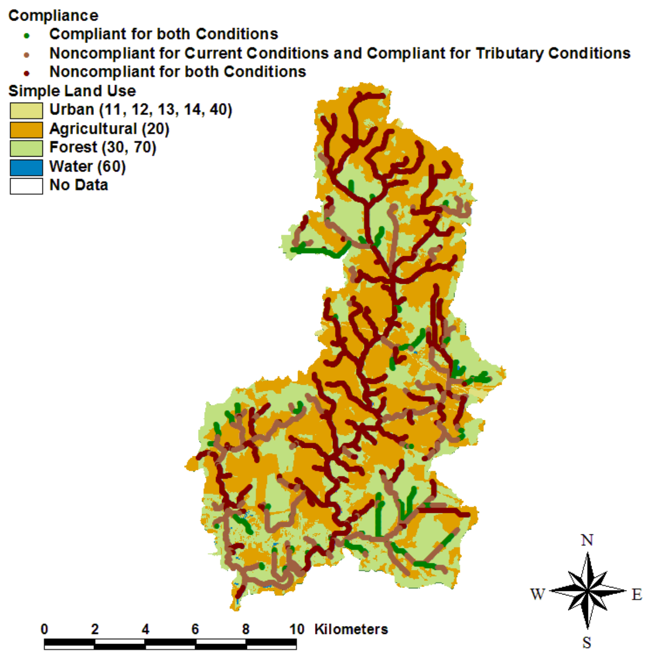


Figure A-3: Chicamicomico River watershed (3) and outlet (491626.4, 85308.8).

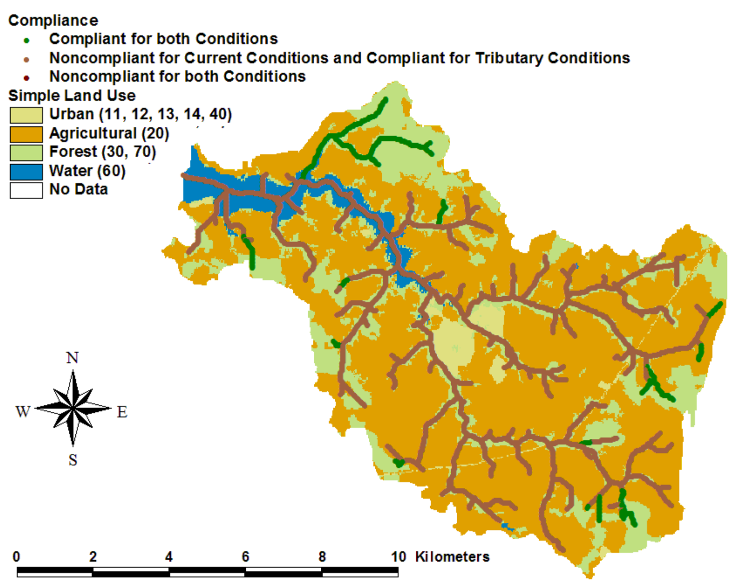


Figure A-4: Corsica River watershed (4) and outlet (473714.8, 157682.0).

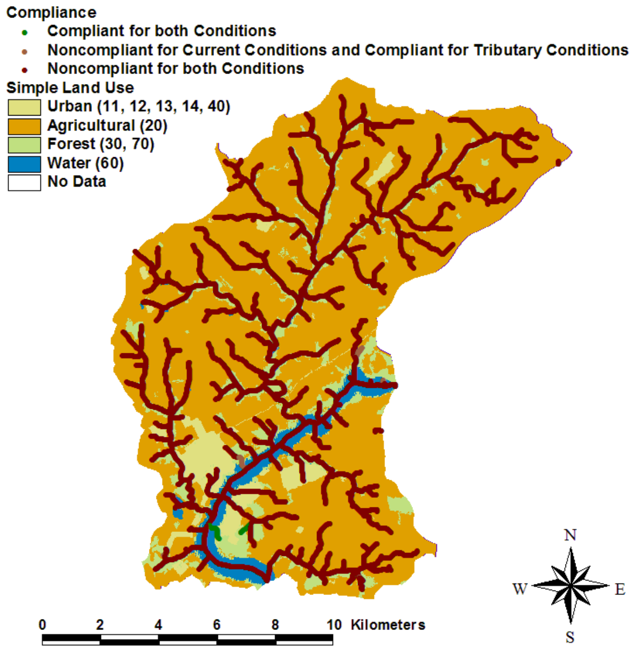


Figure A-5: Middle Chester River watershed (5) and outlet (482604.1, 168274.5).

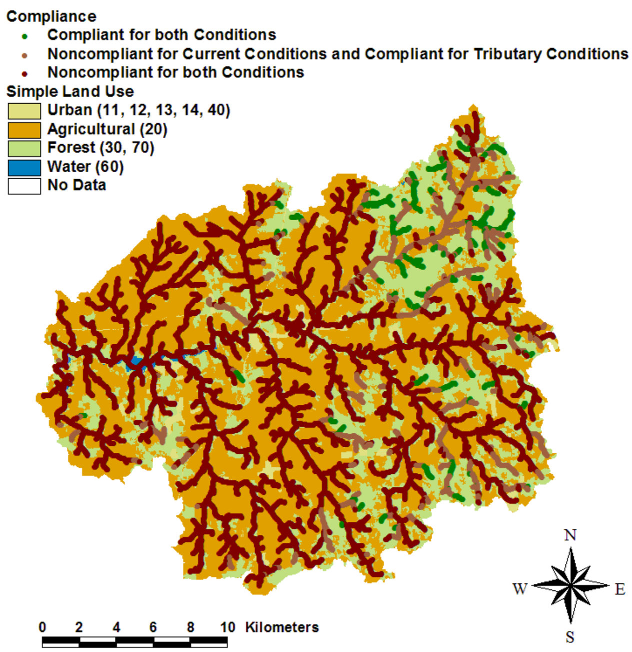


Figure A-6: Upper Chester River watershed (6) and outlet (486957.4, 174998.5).

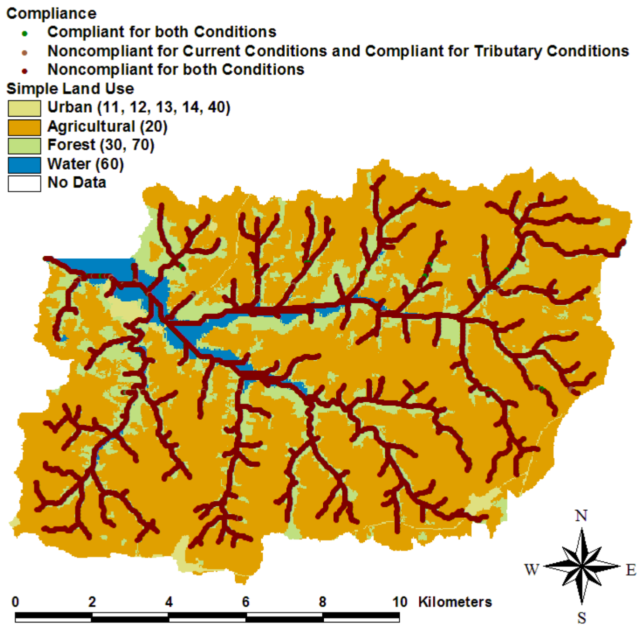


Figure A-7: Bohemia River watershed (7) and outlet (494125.8, 201416.8).

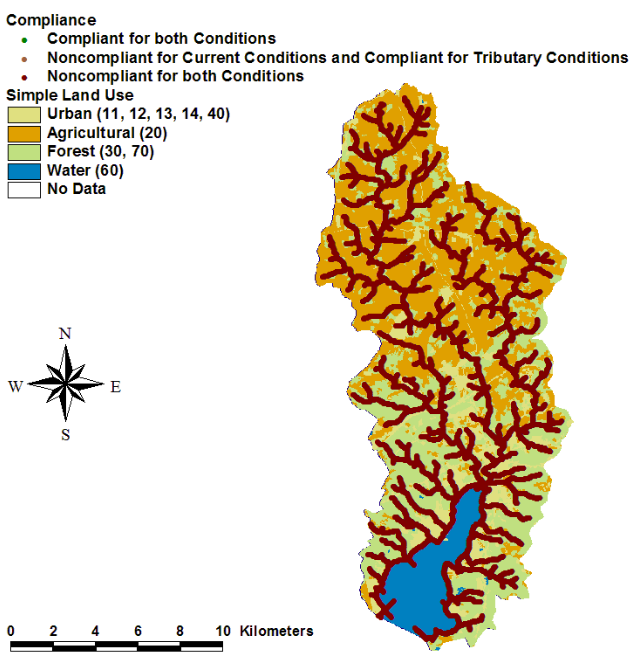


Figure A-8: Northeast River watershed (8) and outlet (487654.9, 207203.4).

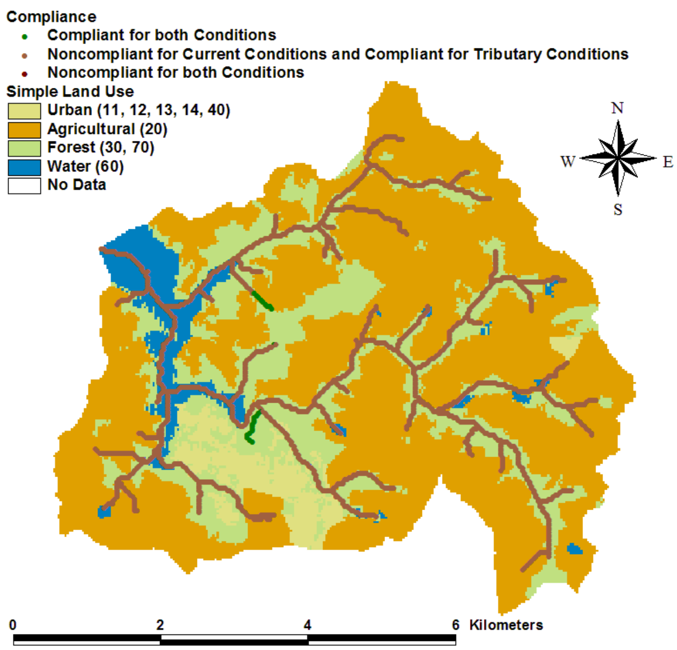


Figure A-9: Worton Creek watershed (9) and outlet (470666.6, 181046.5).

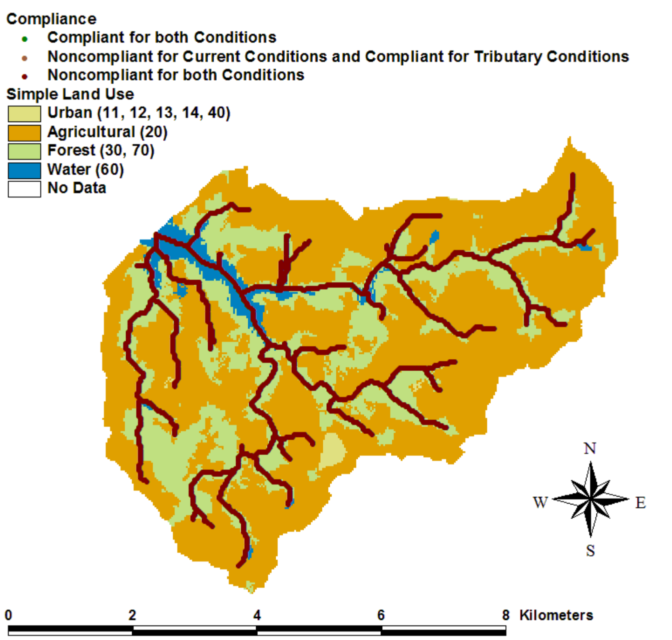


Figure A-10: Fairlee Creek watershed (10) and outlet (468716.6, 176456.5).

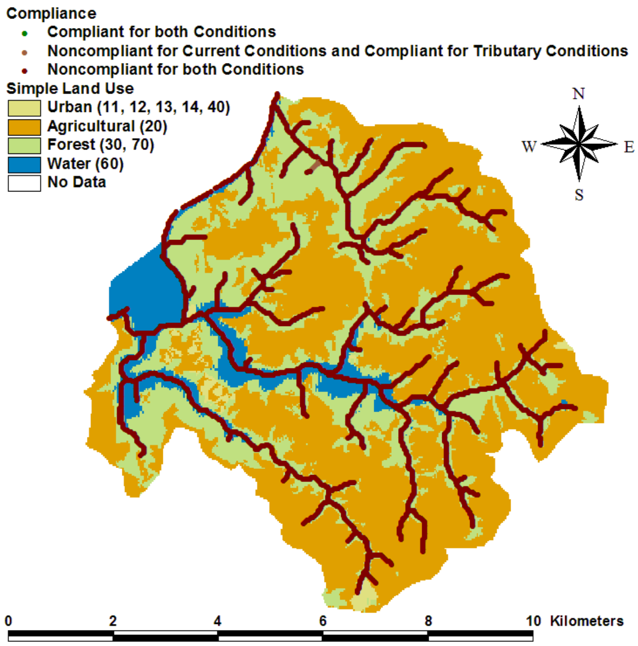


Figure A-11: Still Pond Creek watershed (11) and outlet (473336.6, 185412.8).

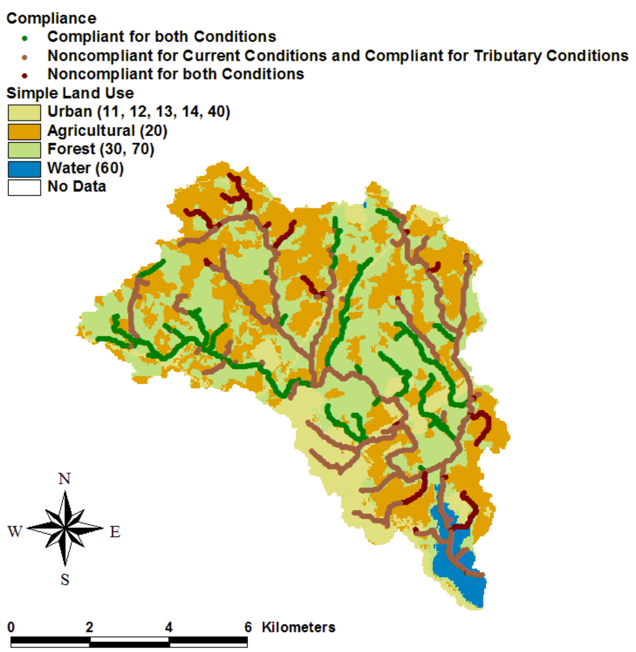


Figure A-12: Swan Creek watershed (12) and outlet (475778.4, 202529.7).

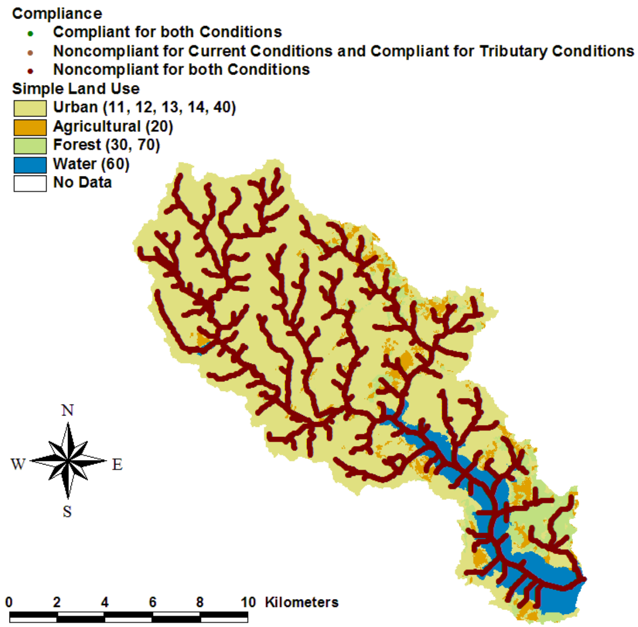


Figure A-13: Back River watershed (13) and outlet (451706.6, 175228.4).

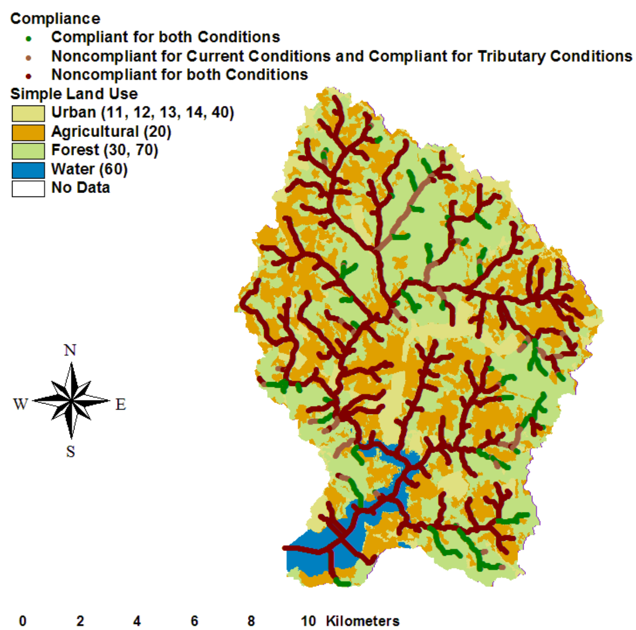


Figure A-14: Breton Bay watershed (14) and outlet (428119.8, 65217.1).

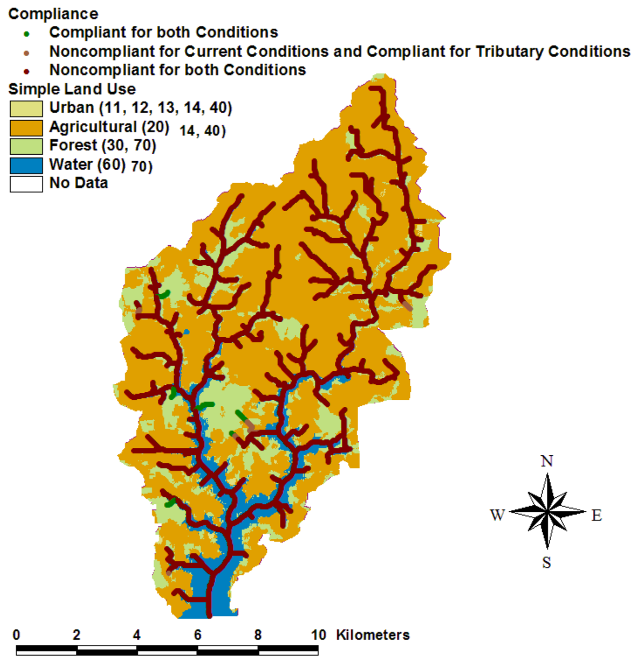


Figure A-15: Langford Creek watershed (15) and outlet (471230.8, 158680.7).

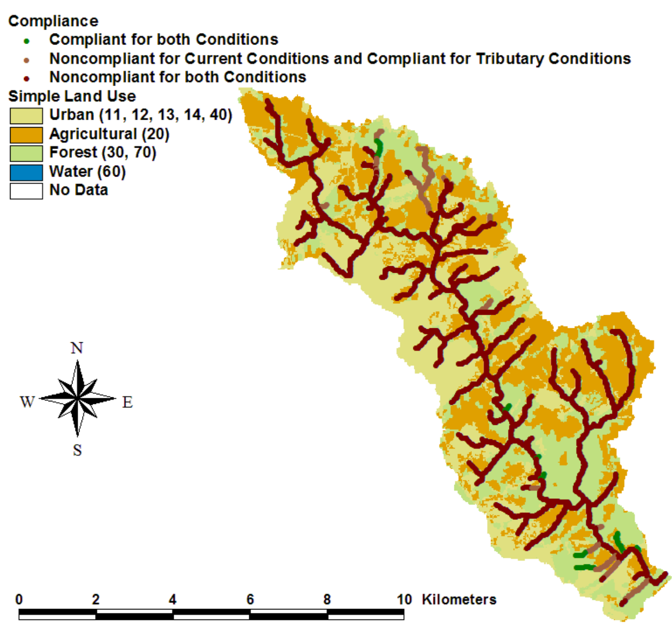


Figure A-16: Bynum Run watershed (16) and outlet (463642.7, 200558.5).

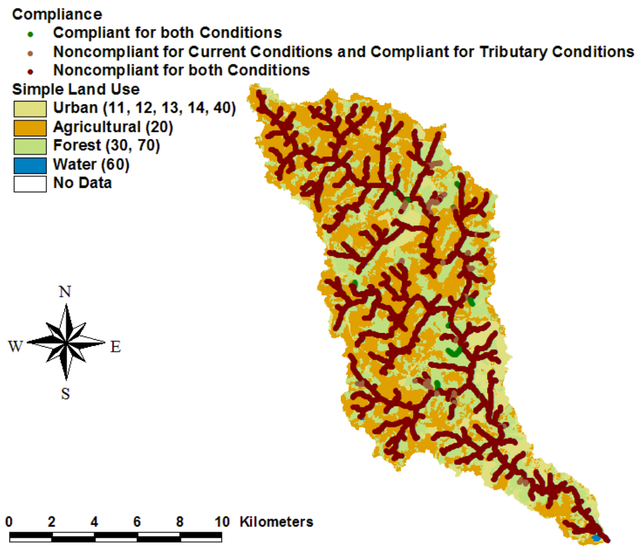


Figure A-17: Middle Patuxent River watershed (17) and outlet (414462.0, 163349.6).

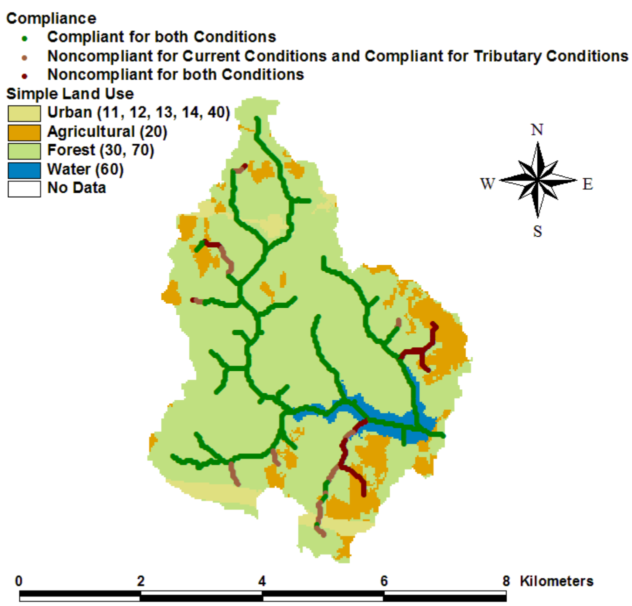


Figure A-18: Saint Mary's Lake watershed (18) and outlet (441061.0, 65051.84).

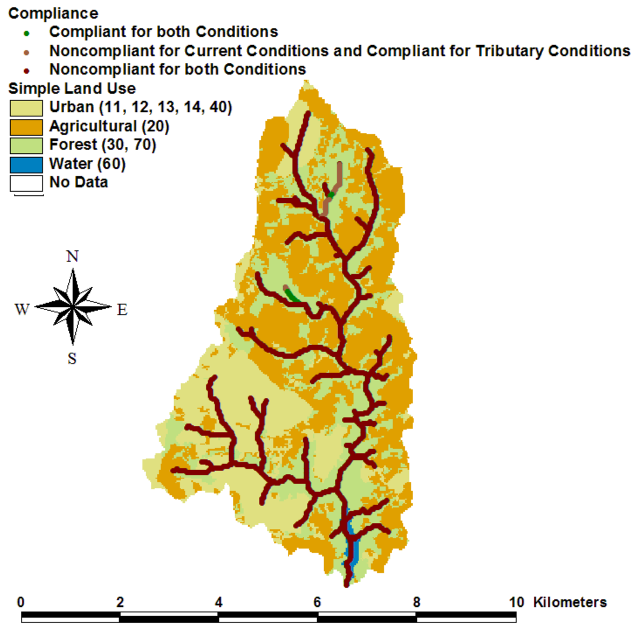


Figure A-19: Needwood Lake watershed (19) and outlet (388765.2, 160543.4).

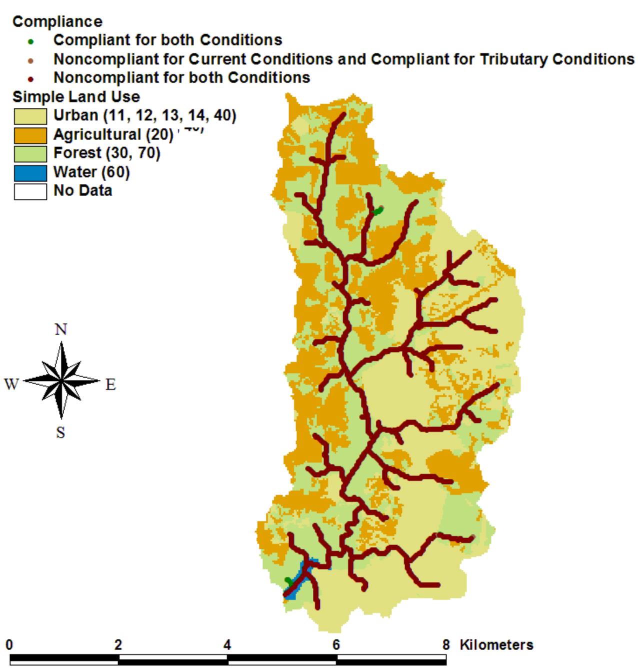


Figure A-20: Lake Bernard Frank watershed (20) and outlet (389875.0, 159463.0).

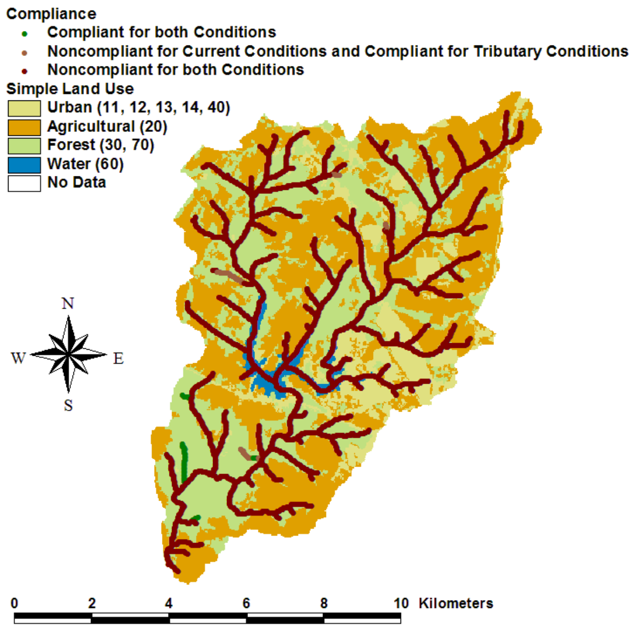


Figure A-21: Little Seneca Lake watershed (21) and outlet (370979.0, 164090.8).

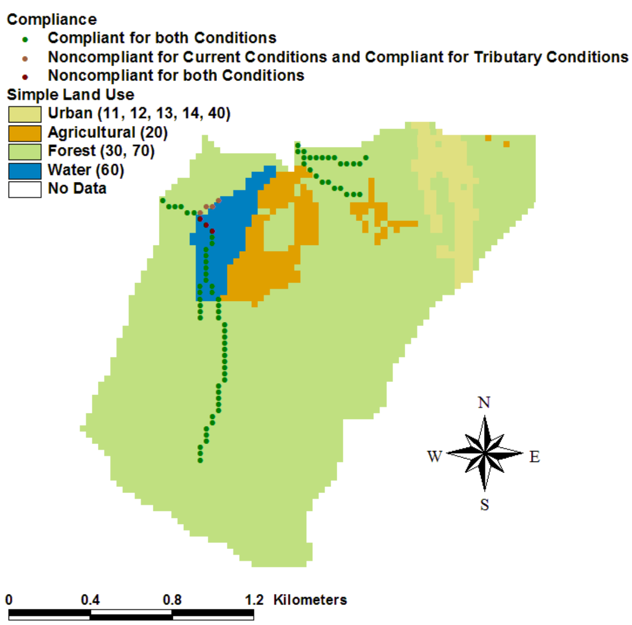


Figure A-22: Antietam Creek watershed (22) and outlet (346456.2, 208098.8).

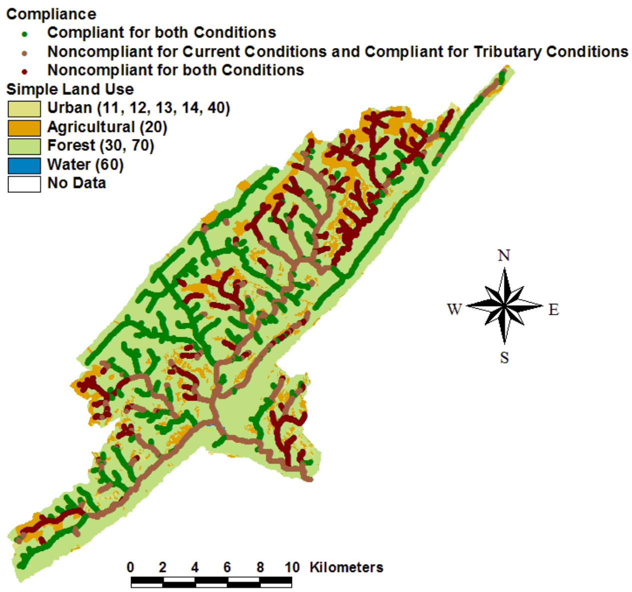


Figure A-23: Savage River watershed (23) and outlet (222083.7, 203370.0).

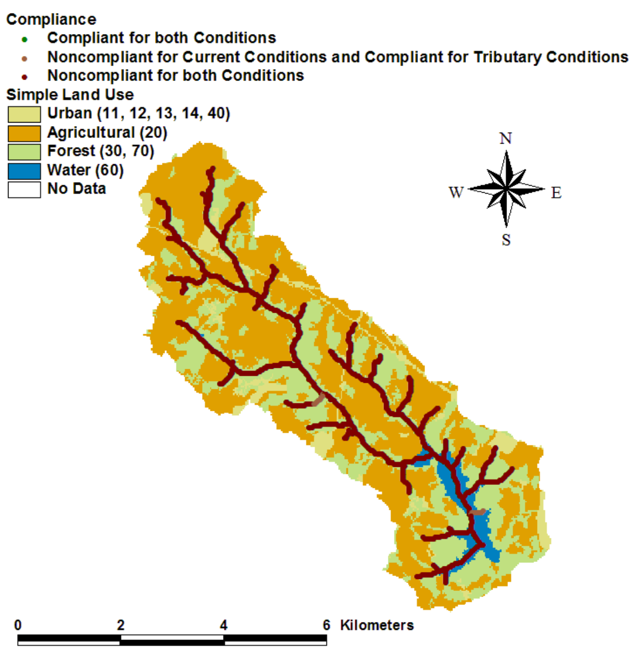


Figure A-24: Piney Run Reservoir watershed (24) and outlet (401801.0, 191356.0).

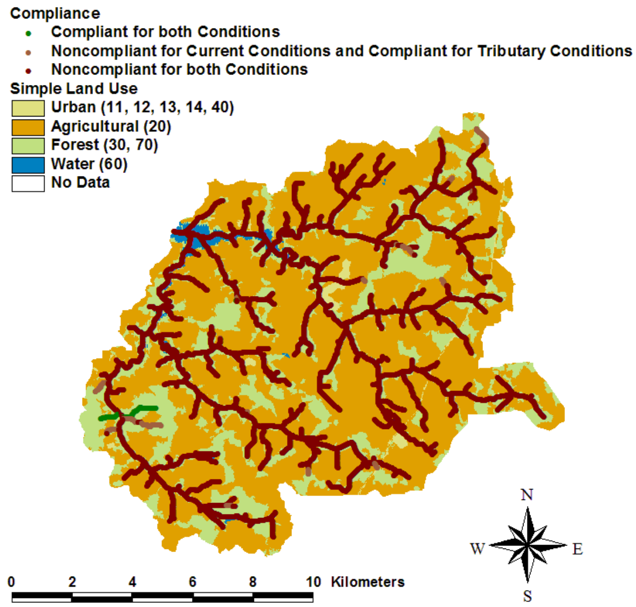


Figure A-25: Southeast Creek watershed (25) and outlet (482650.6, 166187.2).

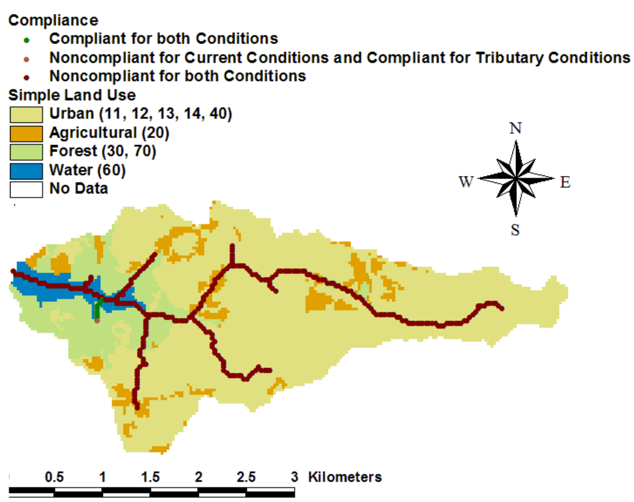


Figure A-26: Clopper Lake watershed (26) and outlet (377847.1, 163970.8).

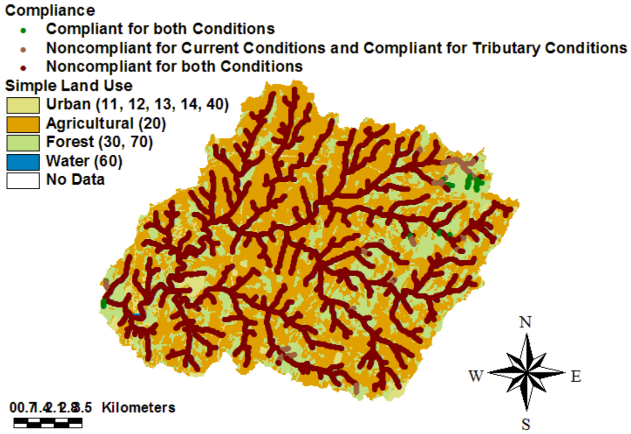


Figure A-27: Lake Linganore watershed (27) and outlet (371808.0, 194303.6).

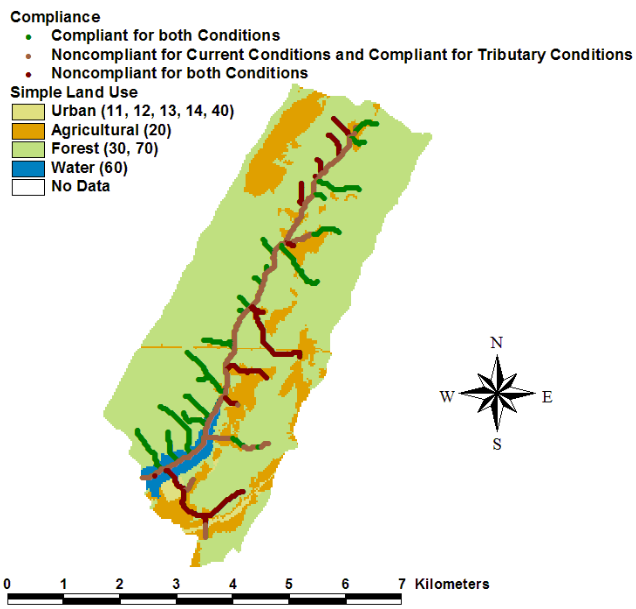


Figure A-28: Lake Habeeb watershed (28) and outlet (257887.9, 227266.3).

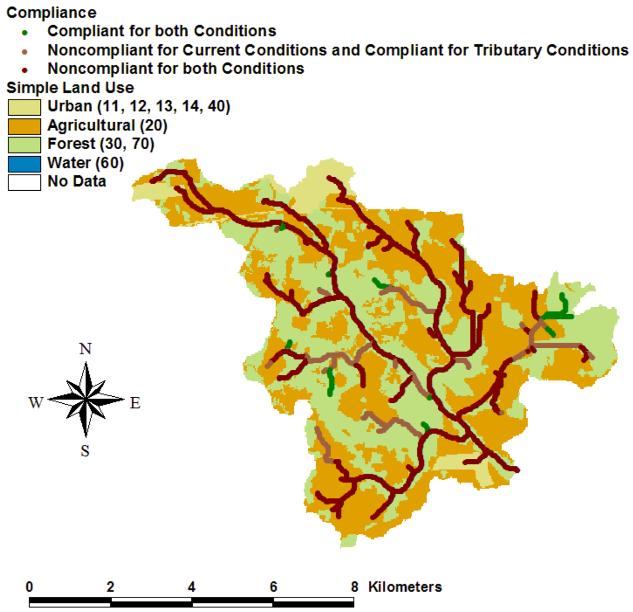


Figure A-29: Adkins Pond watershed (29) and outlet (544235.4, 73630.2).

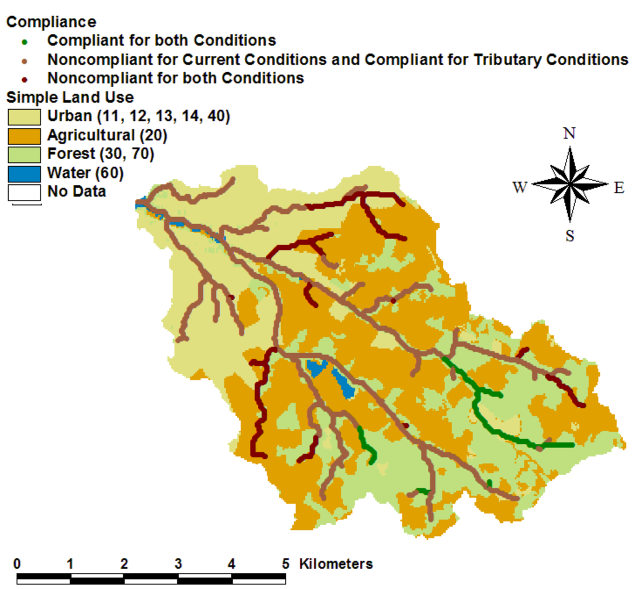


Figure A-30: Tony Tank Lake watershed (30) and outlet (519589.5, 76030.8).

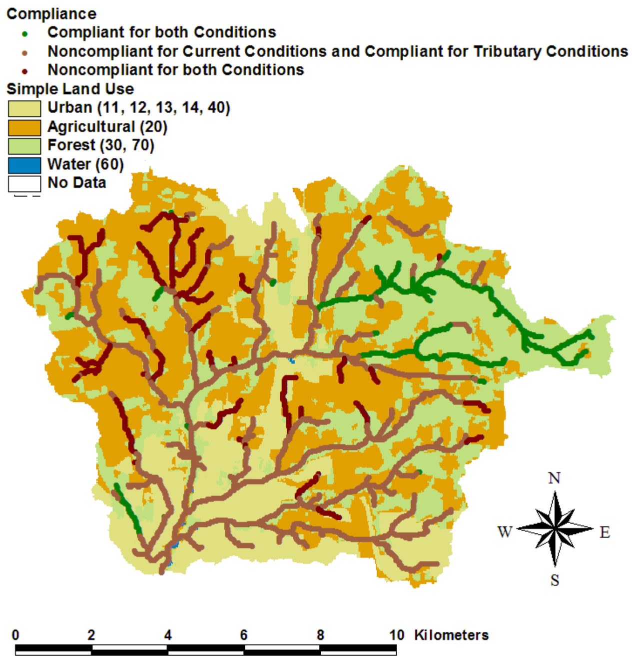


Figure A-31: Johnson Pond watershed (31) and outlet (522129.3, 79248.0).

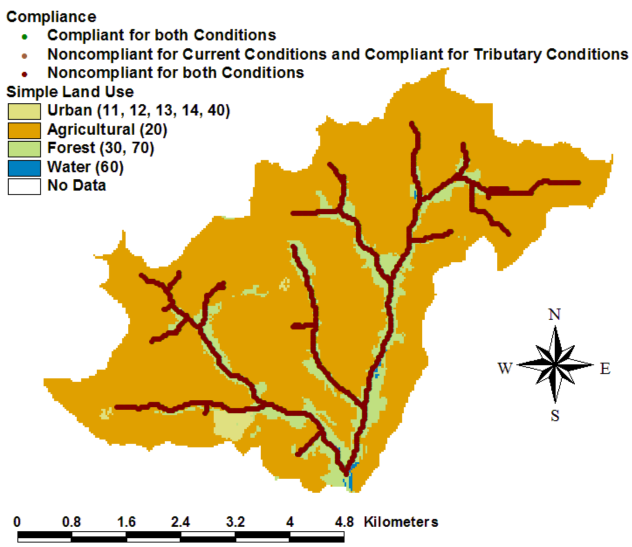


Figure A-32: Urieville Lake watershed (32) and outlet (484194.1, 179674.5).

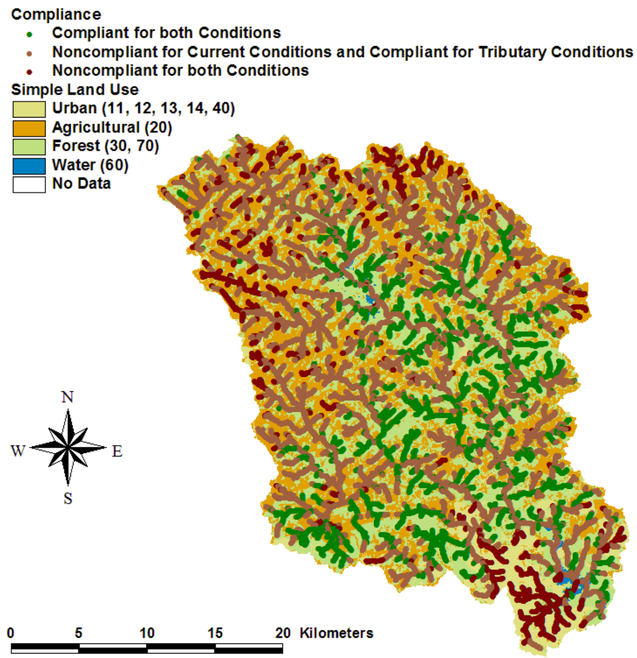


Figure A-33: Loch Raven Reservoir watershed (33) and outlet (439460.4, 195401.0).

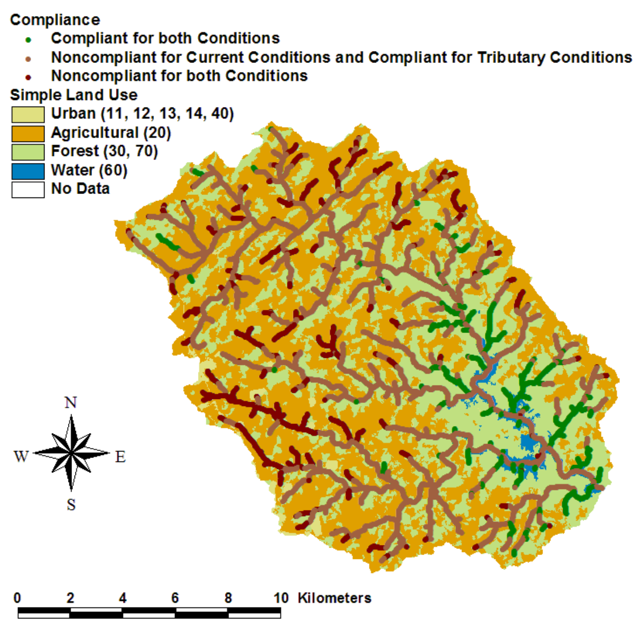


Figure A-34: Prettyboy Reservoir watershed (34) and outlet (425150.4, 216891.2).

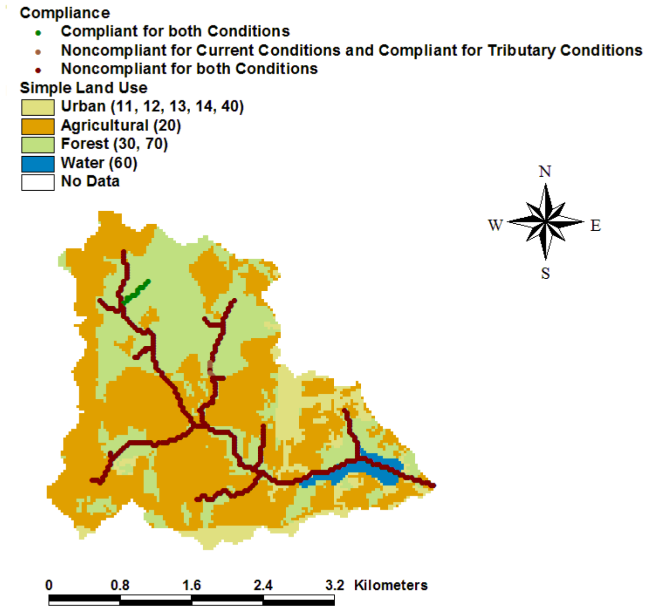


Figure A-35: Centennial Lake watershed (35) and outlet (413120.7, 174689.6).

A.2 Fitted Spherical Semivariograms for Selected Watersheds

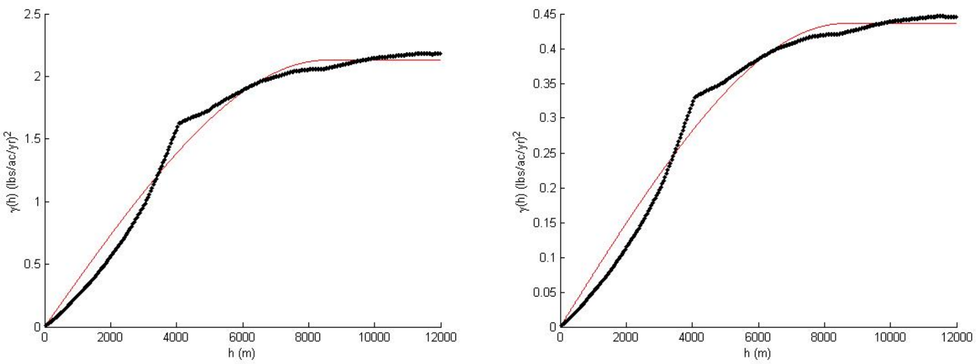


Figure A-36: Chicamicomico River watershed (3) spherical semivariograms for noncompliant Current conditions (Left) and noncompliant Tributary Strategy conditions (Right).

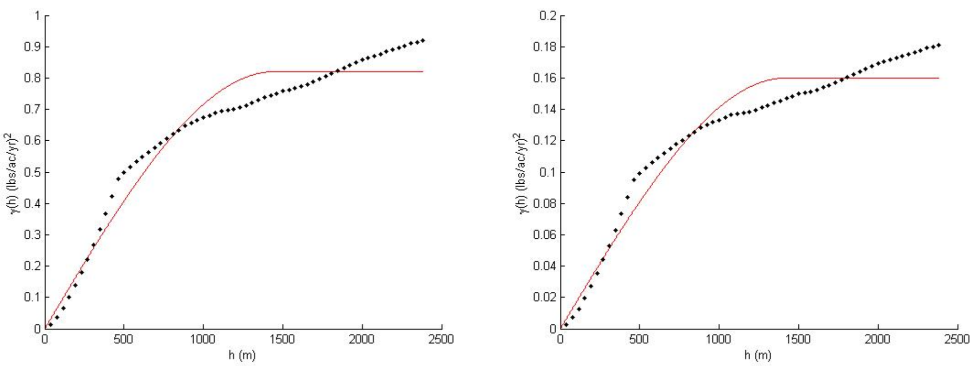


Figure A-37: Corsica River watershed (4) spherical semivariograms for noncompliant Current conditions (Left) and compliant Tributary Strategy conditions (Right).

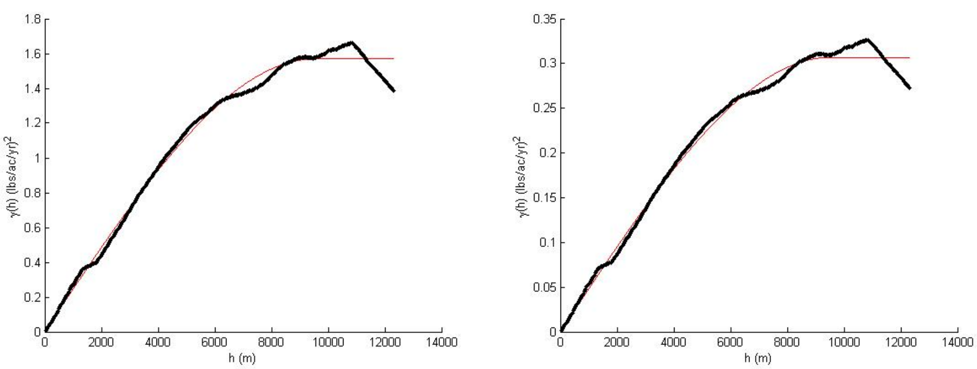


Figure A-38: Upper Chester River watershed (6) spherical semivariograms for noncompliant Current conditions (Left) and noncompliant Tributary Strategy conditions (Right).

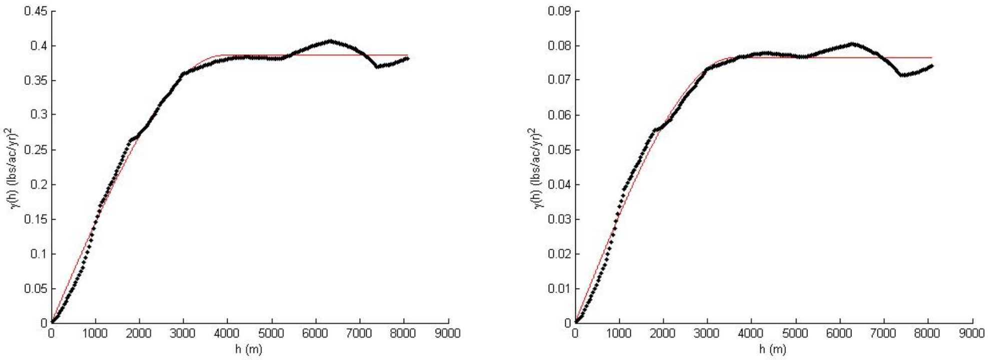


Figure A-39: Bohemia River watershed (7) spherical semivariograms for noncompliant Current conditions (Left) and noncompliant Tributary Strategy conditions (Right).

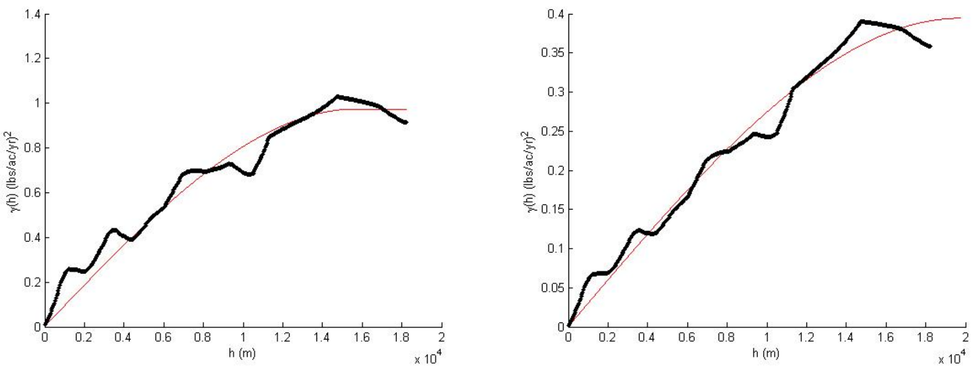


Figure A-40: Northeast River watershed (8) spherical semivariograms for noncompliant Current conditions (Left) and noncompliant Tributary Strategy conditions (Right).

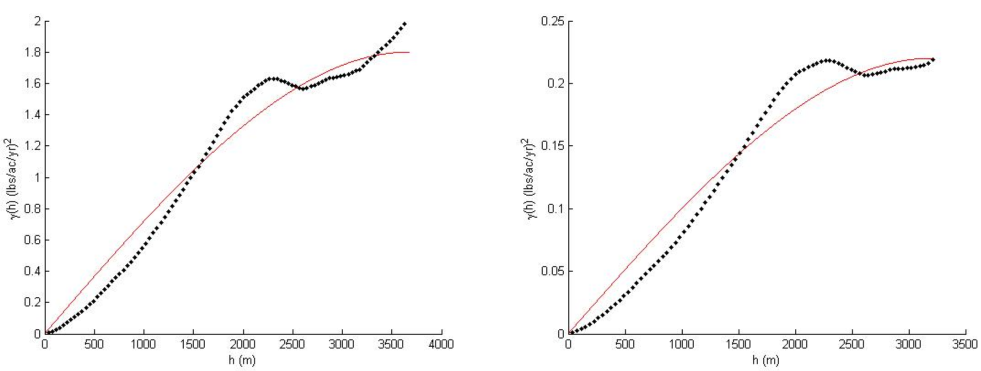
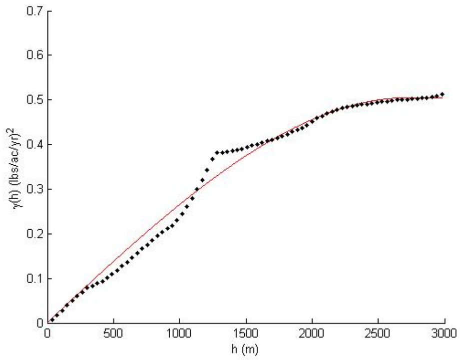


Figure A-41: Fairlee Creek watershed (10) spherical semivariograms for noncompliant Current conditions (Left) and noncompliant Tributary Strategy conditions (Right).



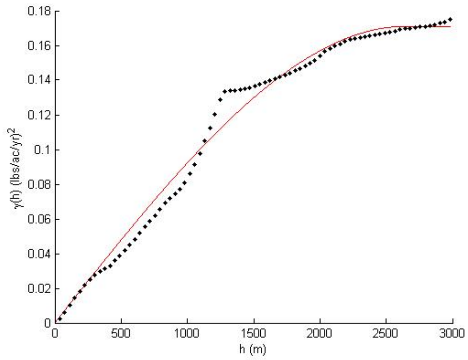
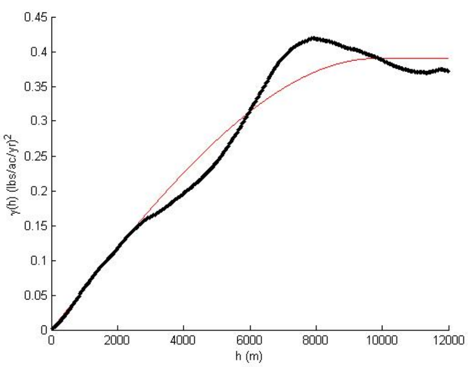


Figure A-42: Swan Creek watershed (12) spherical semivariograms for compliant Current conditions (Left) and compliant Tributary Strategy conditions (Right).



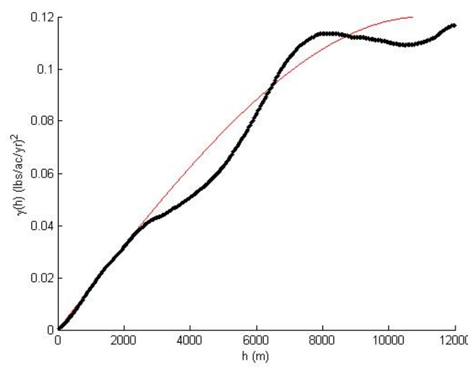
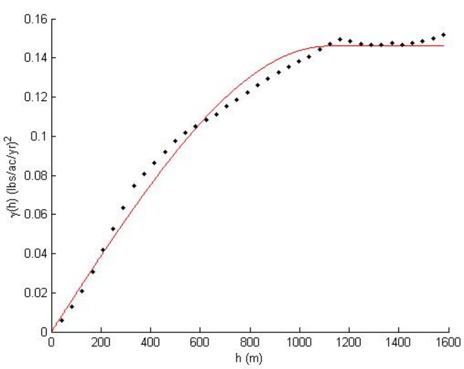


Figure A-43: Back River watershed (13) spherical semivariograms for noncompliant Current conditions (Left) and noncompliant Tributary Strategy conditions (Right).



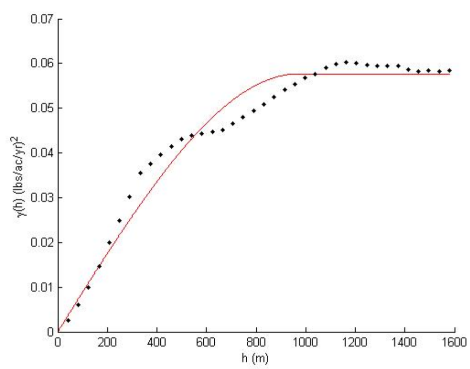


Figure A-44: Breton Bay watershed (14) spherical semivariograms for noncompliant Current conditions (Left) and noncompliant Tributary Strategy conditions (Right).

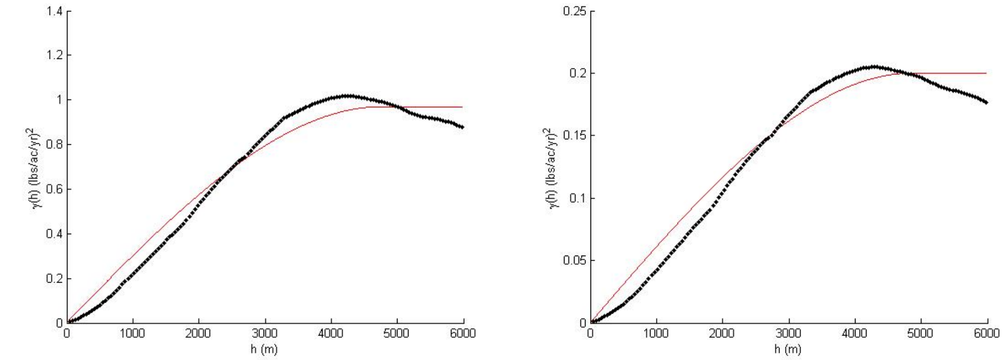


Figure A-45: Langford Creek watershed (15) spherical semivariograms for noncompliant Current conditions (Left) and noncompliant Tributary Strategy conditions (Right).

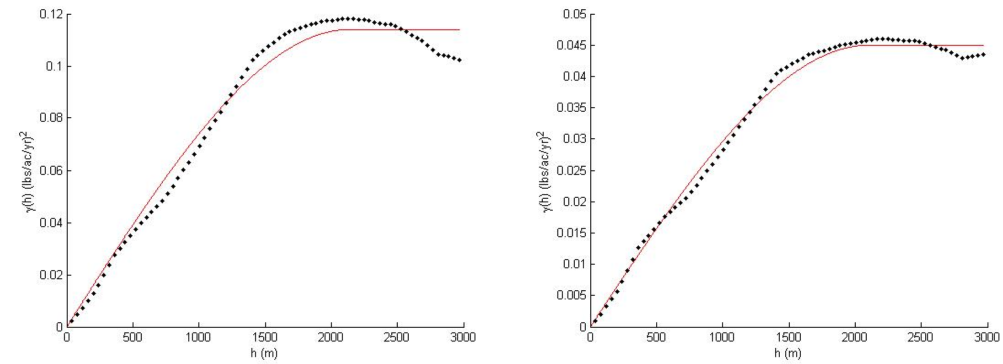


Figure A-46: Bynum Run watershed (16) spherical semivariograms for noncompliant Current conditions (Left) and noncompliant Tributary Strategy conditions (Right).

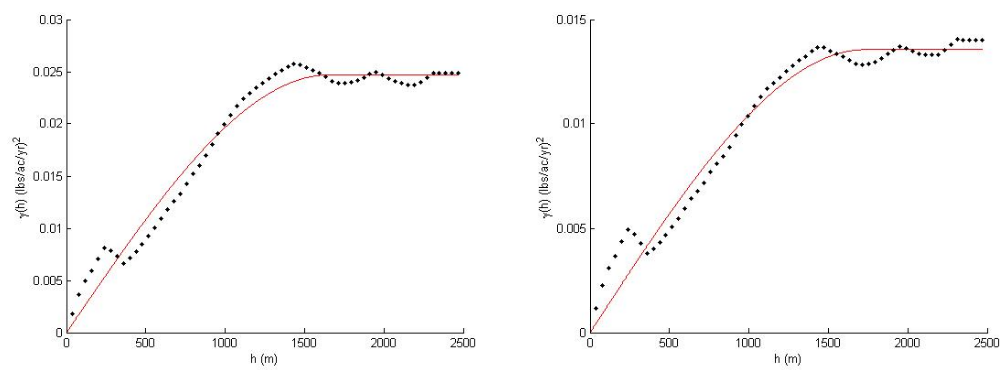


Figure A-47: Middle Patuxent River watershed (17) spherical semivariograms for noncompliant Current conditions (Left) and noncompliant Tributary Strategy conditions (Right).

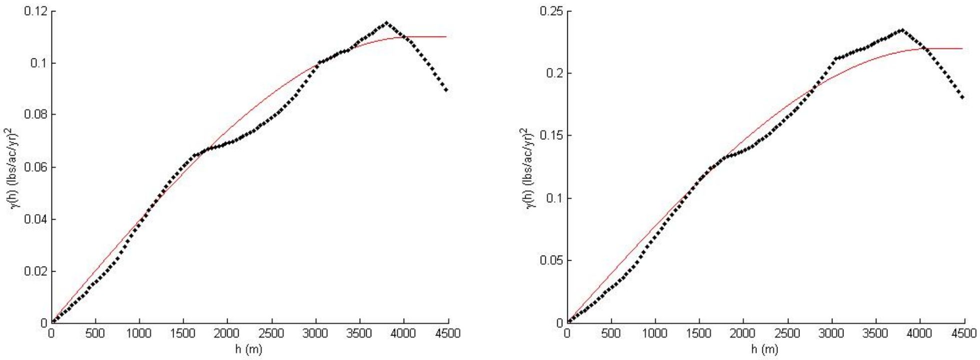


Figure A-48: Saint Mary's Lake watershed (18) spherical semivariograms for compliant Current conditions (Left) and compliant Tributary Strategy conditions (Right).

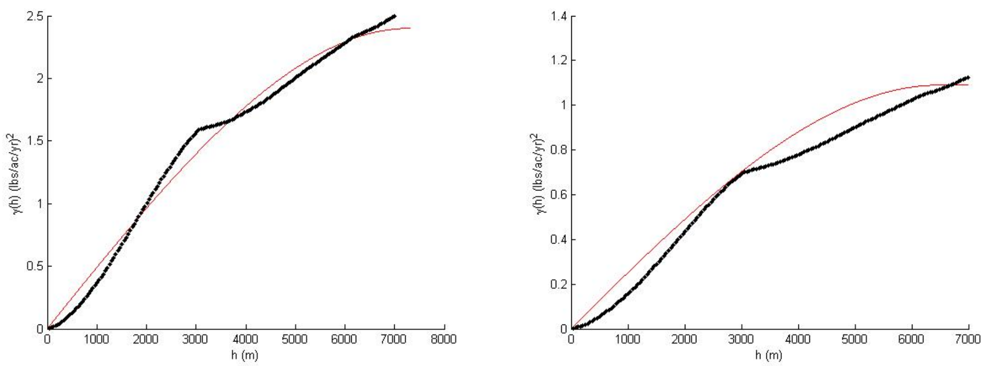


Figure A-49: Needwood Lake watershed (19) spherical semivariograms for noncompliant Current conditions (Left) and noncompliant Tributary Strategy conditions (Right).

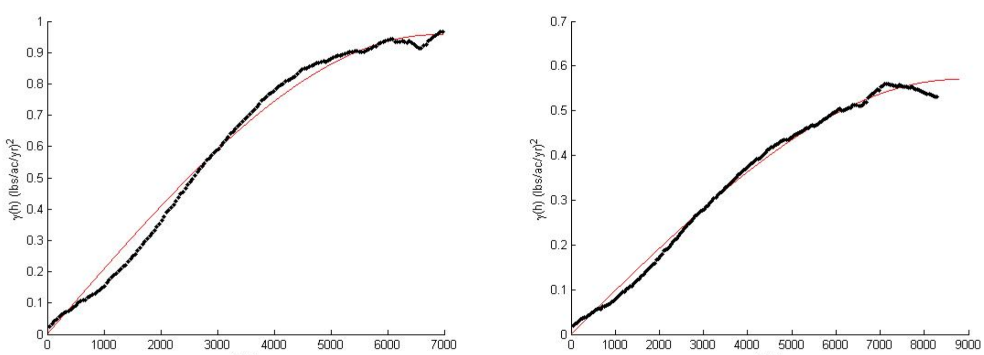


Figure A-50: Lake Bernard Frank watershed (20) spherical semivariograms for noncompliant Current conditions (Left) and noncompliant Tributary Strategy conditions (Right).

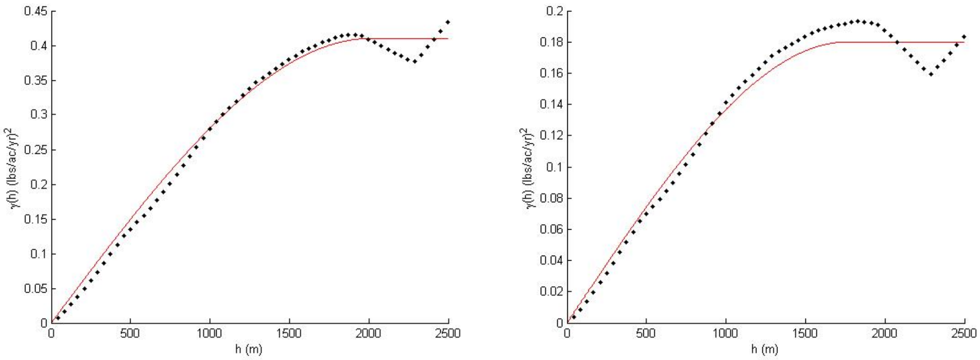


Figure A-51: Little Seneca Lake watershed (21) spherical semivariograms for noncompliant Current conditions (Left) and noncompliant Tributary Strategy conditions (Right).

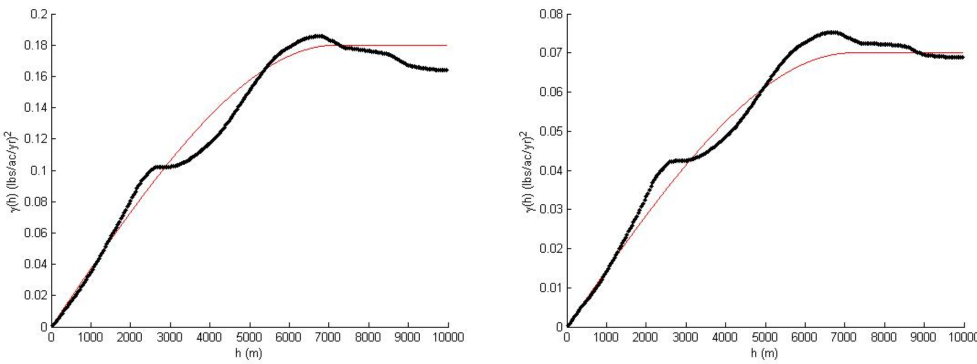


Figure A- 52: Savage River watershed (23) spherical semivariograms for compliant Current conditions (Left) and compliant Tributary Strategy conditions (Right).

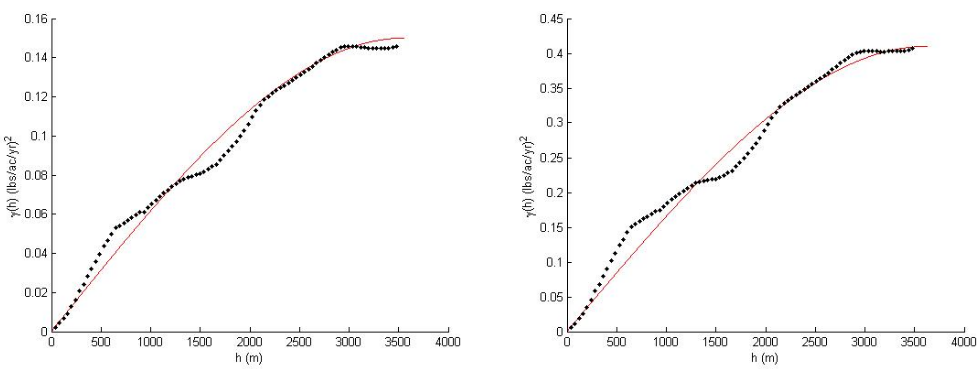


Figure A-53: Piney Run Reservoir watershed (24) spherical semivariograms for noncompliant Current conditions (Left) and noncompliant Tributary Strategy conditions (Right).

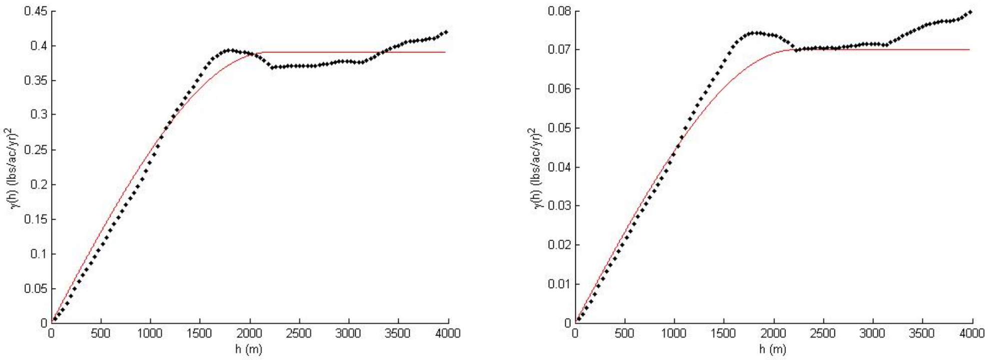


Figure A-54: Southeast Creek watershed (25) spherical semivariograms for noncompliant Current conditions (Left) and noncompliant Tributary Strategy conditions (Right).

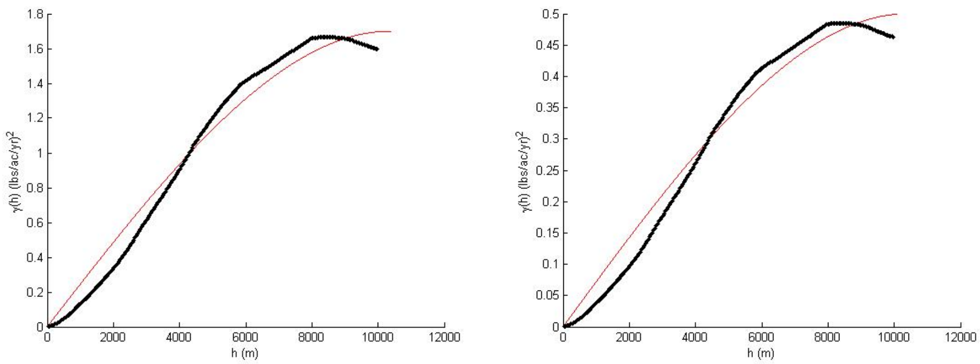


Figure A-55: Lake Linganore watershed (27) spherical semivariograms for noncompliant Current conditions (Left) and noncompliant Tributary Strategy conditions (Right).

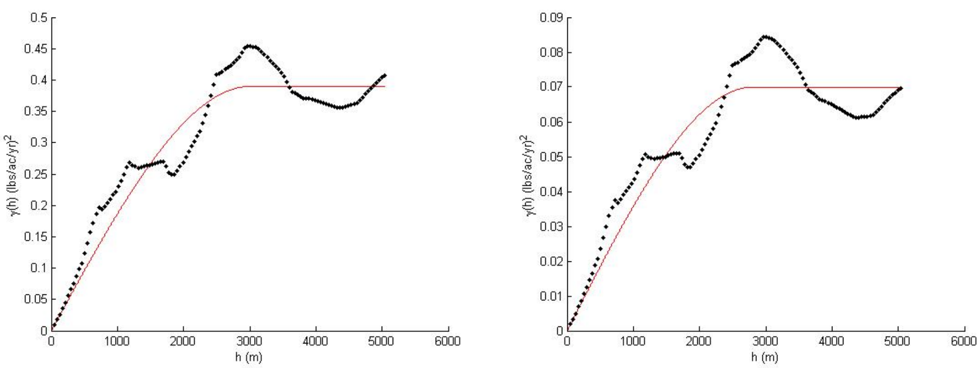


Figure A-56: Lake Habeeb watershed (28) spherical semivariograms for compliant Current conditions (Left) and compliant Tributary Strategy conditions (Right).

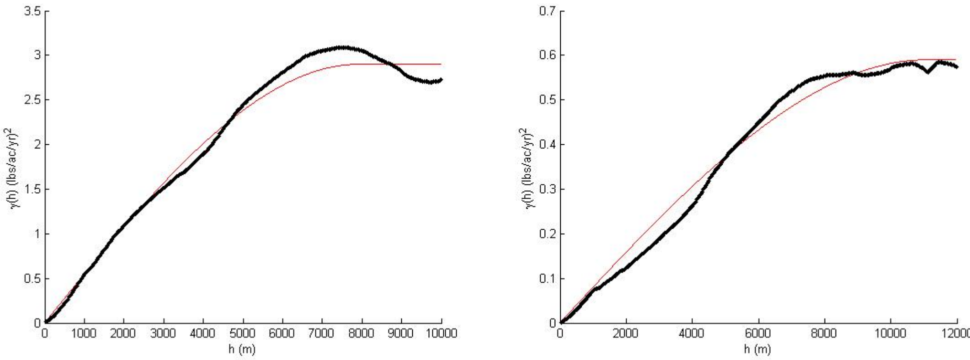


Figure A-57: Adkins Pond watershed (29) spherical semivariograms for noncompliant Current conditions (Left) and noncompliant Tributary Strategy conditions (Right).

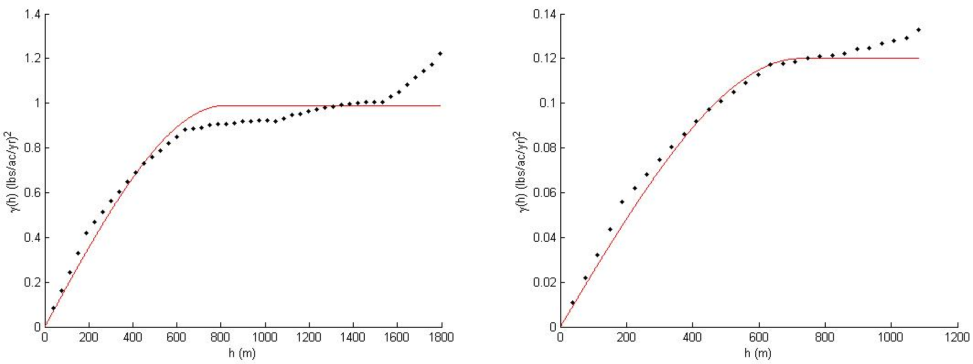


Figure A-58: Tony Tank Lake watershed (30) spherical semivariograms for compliant Current conditions (Left) and compliant Tributary Strategy conditions (Right).

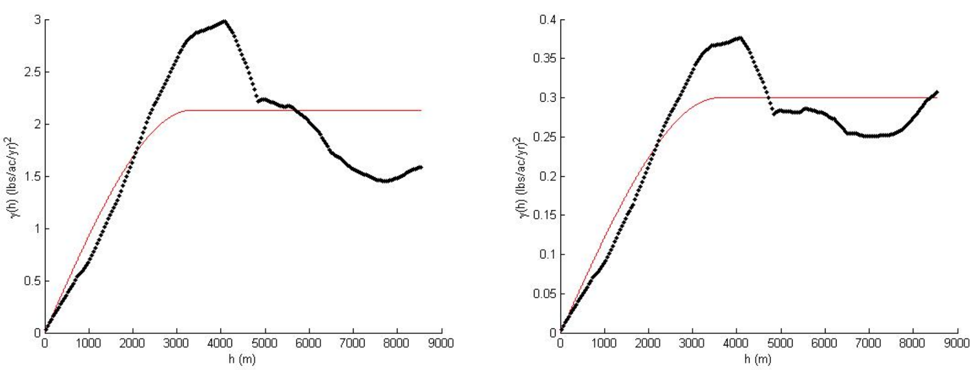


Figure A-59: Johnson Pond watershed (31) spherical semivariograms for noncompliant Current conditions (Left) and compliant Tributary Strategy conditions (Right).

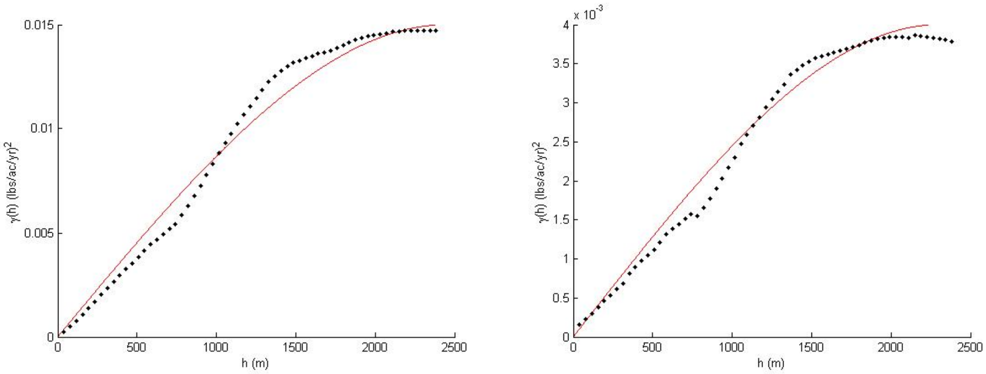


Figure A-60: Loch Raven Reservoir watershed (33) spherical semivariograms for noncompliant Current conditions (Left) and compliant Tributary Strategy conditions (Right).

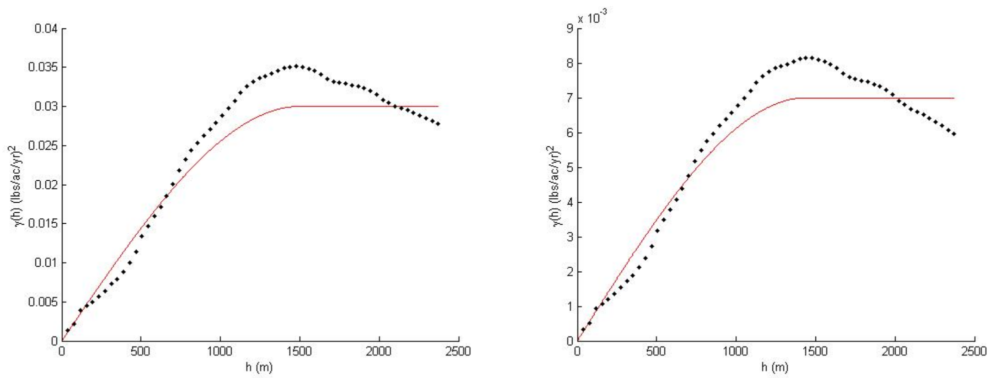


Figure A-61: Prettyboy Reservoir watershed (34) spherical semivariograms for noncompliant Current conditions (Left) and compliant Tributary Strategy conditions (Right).

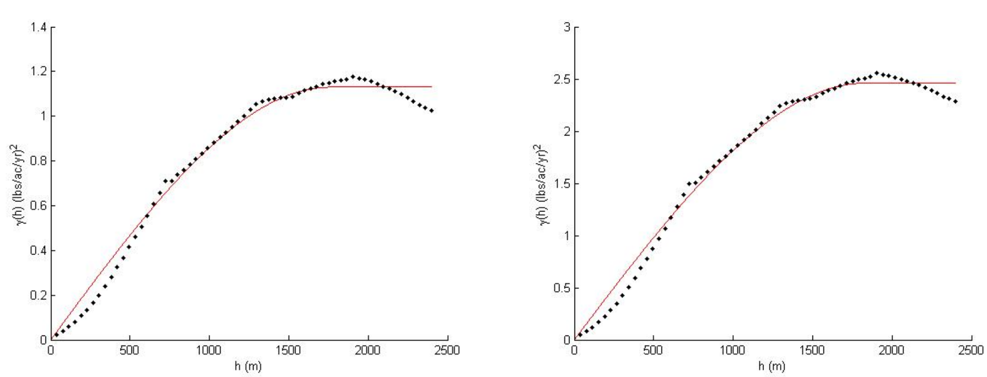


Figure A-62: Centennial Lake watershed (35) spherical semivariograms for noncompliant Current conditions (Left) and noncompliant Tributary Strategy conditions (Right).

A.3 ArcView Scripts

The following Avenue (ArcView GIS) computer scripts are included in subsequent sections:

1. Thesis.MasterScript_Part1 was used to access data layers from the view and send those data layers to other scripts.
2. Thesis.SetExtent_Part2 was used to restrict the area of interest for the view so that the entire view was not used in calculations.
3. Thesis.PercentAgriculture_Part3 was used to collect the percent high tillage, low tillage, pasture, hay, nonagricultural, and manure land use from the county segment table.
4. Thesis.LandUseFromLandCover_Part4 was used to convert land cover to land use.
5. Thesis.AccumulateAndAreaNormalizeLandUse_Part5 was used to accumulate values in a grid and divide those values by the drainage area accumulated to each cell in the grid.
6. Thesis.GetAllPoints_Part6 was used to create a table of every point in the watershed stream network.
7. Thesis.GetAllAreas_Part7 was used to identify all the area normalized land use areas and store those values in the stream network table.
8. Thesis.ExportCoeff_Part8 was used to create a text file that stored the loading rate statistics for the local state segment.
9. Thesis.SelectNeighbors_Part8_1 was used to identify the state segments adjacent to the state segment coincident with the watershed centroid.

10. Thesis.Watershedcenter_Part8_1_1 was used to identify the watershed centroid.
11. Thesis.CoefficientStats_Part8_2 was used to calculate the mean and standard deviation of each land use specific loading rate.
12. Analysis.Compliance was used to generate a shape file for the entire stream network that stores the status of each point as either always, sometimes, or never compliant with water quality standards.
13. Analysis.SelectReachTool was used to collect data along a stream length and store that data in a text file.

A.3.1 ArcView Script for Thesis.MasterScript_Part1

```
theView = av.GetActiveDoc
theflow priority = theview.findtheme("Flow priority Direction")
theaccum = theview.findtheme("Flow priority Acc.")
thestream = theview.findtheme("Inferred Streams")
stSN = SrcName.Make("$UMDGISM\cbpo\p4stsegstpm.shp")
	sttheme = Theme.Make(stSN)
	sttheme.SetVisible (True)
	theview.addtheme(sttheme)
theshed = theview.findtheme("Watershed").getgrid
	themask = theshed/theshed
therect = av.run("THESIS.SETEXTENT_PART2",{theview,themask})
thepag =
av.run("THESIS.PERCENTAGRICULTURE_PART3",{theview,themask,therect})
thelugrids = av.run("THESIS.LANDUSEFROMLANDCOVER_PART4",{theview,
themask, thepag})
theareanormaccumlu =
av.run("THESIS.ACCUMULATEANDAREANORMALIZELANDUSE_PART5",
{theflow priority, thelugrids, themask})

' Stores info in a FTable and creates a shape file
thepointftab = av.run("THESIS.GETALLPOINTS_PART6",{theview, theflow
priority, theaccum,theshed,thestream,theareanormaccumlu})
theareainfo = av.run("THESIS.GETALLAREAS_PART7",{theview, theflow
priority, theaccum,theshed,thestream,theareanormaccumlu})

'Stores info in a text file that can be imported and turned into an event theme
thecoefftxt = av.run("THESIS.EXPORTCOEFF_PART8",{sttheme, theshed, theflow
priority, therect})
```

A.3.2 ArcView Script for Thesis.SetExtent_Part2

'Script sets the analysis extent based on the watershed extent to make calculations more manageable.

```
theview = self.get(0)
themask = self.get(1)

aFileName = "c:\temp\temppoly.shp".AsFileName
theResult = themask.AsPolygonFTab(aFileName,FALSE,prj.makenull)
theshapefield = theResult.findfield("shape")
theshape = theresult.returnvalue(theshapefield,0)
therect = theshape.returnextent

therect = therect.expandby(themask.getcellsize)

ae = theView.GetExtension(AnalysisEnvironment)
ae.SetExtent(#ANALYSISENV_VALUE, therect)
ae.SetCellSize(#ANALYSISENV_VALUE, themask.getcellsize)
ae.Activate

return therect
```

A.3.3 ArcView Script for Thesis.PercentAgriculture_Part3

```
theview = self.get(0)
themask = self.get(1)
therect = self.get(2)

coSN = SrcName.Make("$UMDGISM\cbpo\p4cosegstpm.shp")
coFT = FTab.Make(coSN)
fcoseg = coFT.findfield("Coseg")
fstateseg = coFT.findfield("Stateseg1")

'Makes a grid where each pixel is assigned a coseg number.
cogrid = grid.MakeFromFTab (coFT, prj.makenull, fcoseg,
{themask.getcellsize,therect})
coVT = cogrid.getVTab

'Finds the field containing the number of pixels for each unique coseg number
fval = coVT.findfield("Value")

'Finds the field names for percent land use
coVT.join(fval,coFT,fcoseg)
phi = coVT.findfield("Phi_till")
plo = coVT.findfield("Plo_till")
ppas = coVT.findfield("Ppasture")
phay = coVT.findfield("Phay")
pmix = coVT.findfield("Pnonag")
pman = coVT.findfield("Pmanure")
thefields = {phi, plo, ppas, phay, pmix, pman}

'Creates a list of grids containing percent land use by coseg number.
thepaggrid = {}
for each j in 1..thefields.count
        tempgrid = 0.asgrid
        for each i in 1..coVT.getnumrecords
                thepag = coVT.returnvalue(thefields.get(j-1), i-1)
                theval = coVT.returnvalue(fval, i-1)
                tempgrid = thepag.asgrid * (cogrid = theval.asgrid) + tempgrid
        end
        thepaggrid.add(tempgrid)
end

return thepaggrid
```

A.3.4 ArcView Script for Thesis.LandUseFromLandCover_Part4

```
theview = self.get(0)
themask = self.get(1)
thepag = self.get(2)

thefactor = 0.222394843.asgrid        'convert 900 m^2 pixel to acres

SrcN = grid.makesrcname ("$UMDGISM\cbpo\p4lcstpm")
lcgrid = grid.make(SrcN)
lu11 = lcgrid = 11
lu12 = lcgrid = 12
lu13 = lcgrid = 13
lu14 = lcgrid = 14
lu20 = lcgrid = 20
lu30 = lcgrid = 30
lu40 = lcgrid = 40
lu60 = lcgrid = 60
lu70 = lcgrid = 70

thephi = thepag.get(0)
theplo = thepag.get(1)
thephay = thepag.get(2)
theppas = thepag.get(3)
thepmix = thepag.get(4)
thepman = thepag.get(5)

thefor = (lu30 + lu70) * thefactor
theiurb = ((0.85.asgrid * lu11) + (0.4.asgrid * lu12) + (0.1.asgrid * lu13) + (0.1.asgrid
* lu14) + (0.4.asgrid * lu40)) * thefactor   ' converts 30m pixels to acres
thepurb = ((0.15.asgrid * lu11) + (0.6.asgrid * lu12) + (0.9.asgrid * lu13) +
(0.9.asgrid * lu14) + (0.6.asgrid * lu40)) * thefactor   ' converts 30m pixels to acres
thewater = lu60 * thefactor
thehi = lu20 * thephi * thefactor
thelo = lu20 * theplo * thefactor
thehay = lu20 * thephay * thefactor
thepas = lu20 * theppas * thefactor
themix = lu20 * thepmix * thefactor
theman = lu20 * thepman * thefactor
thelugrids = {thehi, thelo, thepas, thehay, themix, theman, thepurb, theiurb, thewater,
thefor}

return thelugrids
```

A.3.5 ArcView Script for Thesis.AccumulateAndAreaNormalizeLandUse_Part5

```
theflow priority = self.get(0)
thelugrids = self.get(1)
theflow prioritygrid = theflow priority.getgrid
thefactor = 0.222394843.asgrid

thearea = (theflow prioritygrid.flow priorityaccumulation(NIL) + 1.asGrid)*thefactor

thefinallugrids = {}
for each i in 1..10
        temp = thelugrids.get(i-1)
        accumtemp = theflow prioritygrid.flow priorityaccumulation(temp) + temp
        normaccumtemp = accumtemp/thearea
        thefinallugrids.add(normaccumtemp)
end

return thefinallugrids
```

A.3.6 ArcView Script for Thesis.GetAllPoints_Part6

```
theview = self.get(0)
dirgrid = self.get(1).getgrid
areagrid = self.get(2).getgrid
shedgrid = self.get(3)
streamgrid = self.get(4).getgrid

dirfile = "c:\alfonso\alfdir.txt"
streamfile = "c:\alfonso\stream.txt"
outfile = "c:\alfonso\hope.txt"

mask = (streamgrid / streamgrid) * (shedgrid / shedgrid)
lookUptab = av.finddoc("dirlookup.txt").getvtab
LookUpField = LookUpTab.FindField("Arcview Direction")

'  Convert flow priority direction grid values to 1-8
dirgridav = mask * dirgrid
dirTab = dirgridav.GetVTab
dirGridField = dirTab.FindField("Value")
dirTab.Join(dirGridField, LookupTab, LookUpField)
dirgrid = dirgridav.Lookup("Moglen direction")
dirTab.UnJoinAll

' Export files to pass to FORTRAN code
if (File.Exists(dirfile.AsFilename)) then
        File.Delete(dirfile.AsFilename)
end
dirgrid.SaveAsASCII (dirfile.AsFileName)

if (File.Exists(streamfile.AsFilename)) then
        File.Delete(streamfile.AsFilename)
end
streamgrid.SaveAsASCII (streamfile.AsFileName)

"c:\alfonso".asfilename.setcwd
System.ExecuteSynchronous ("c:\alfonso\kml")'.exe > c:\alfonso\hope.txt")
outFN = FileName.Make("c:\alfonso\hope.txt")
thetab = VTab.Make(outFN, FALSE, FALSE)

x1field = thetab.findfield("x1")
y1field = thetab.findfield("y1")

myfile = "C:\thesisoutput\areatable.shp".asFileName
a = FTab.MakeNew (myfile, point)
theshapefield = a.findfield("shape")
```

```
idfield = field.make("ID",#field_short,6,0)
hifield = field.make("A_hi",#field_decimal,10,6)
lofield = field.make("A_lo",#field_decimal,10,6)
pafield = field.make("A_pa",#field_decimal,10,6)
hafield = field.make("A_ha",#field_decimal,10,6)
mxfield = field.make("A_mx",#field_decimal,10,6)
mafield = field.make("A_ma",#field_decimal,10,6)
pufield = field.make("A_pu",#field_decimal,10,6)
iufield = field.make("A_iu",#field_decimal,10,6)
atfield = field.make("A_at",#field_decimal,10,6)
frfield = field.make("A_fr",#field_decimal,10,6)
lengthfield = field.make("Pixel_L",#field_decimal,10,6)
a.addfields({idfield, hifield,lofield, pafield, hafield, mxfield, mafield, pufield, iufield,
atfield, frfield, lengthfield})

n = thetab.getnumrecords
for each i in 1..n
        x1 = thetab.returnvalue(x1field, i - 1).asnumber
        y1 = thetab.returnvalue(y1field, i - 1).asnumber
        thepoint = Point.Make(x1, y1)
        theflow prioritynum = (dirgrid).cellvalue(thepoint, Prj.MakeNull)
        if ((theflow prioritynum = 1) or (theflow prioritynum = 4) or (theflow
prioritynum = 16) or (theflow prioritynum = 64))      then
                lengthval = 30
        else
                lengthval = 42.4264069
        end
        newrec = a.addrecord
        a.setvalue(theshapefield, newrec, thepoint)
        a.setvalue(idfield, newrec, i)
        a.setvalue(lengthfield, newrec, lengthval)
end
a.seteditable (FALSE)

at = FTheme.Make(a)
at.setname("Points")
at.setvisible(TRUE)
theview.addtheme(at)

return a
```

A.3.7 ArcView Script for Thesis.GetAllAreas_Part7

```
theview = self.get(0)
dirgrid = self.get(1).getgrid
areagrid = self.get(2).getgrid
shedgrid = self.get(3)
streamgrid = self.get(4).getgrid
theareanormaccumlu = self.get(5)

pntSN = SrcName.Make("C:\thesisoutput\areatable.shp")
if (pntSN <> nil) then
        a = ftab.Make(pntSN)
        theshapefield = a.findfield("shape")
        idfield = a.findfield("ID")
        hifield = a.findfield("A_hi")
        lofield = a.findfield("A_lo")
        pafield = a.findfield("A_pa")
        hafield = a.findfield("A_ha")
        mxfield = a.findfield("A_mx")
        mafield = a.findfield("A_ma")
        pufield = a.findfield("A_pu")
        iufield = a.findfield("A_iu")
        atfield = a.findfield("A_at")
        frfield = a.findfield("A_fr")
        lengthfield = a.findfield("Pixel_L")

        n = a.getnumrecords
        m = 1 'edit here if script breaks
        for each i in m..n
                thepoint = a.returnvalue(theshapefield,i-1)
                a.seteditable (TRUE)
                newrec = i-1

                a.seteditable (TRUE)
        a.setvalue(hifield,newrec,(theareanormaccumlu.get(0)).cellvalue(thepoint,
                prj.makenull))
                a.seteditable (FALSE)

                a.seteditable (TRUE)
        a.setvalue(lofield,newrec,(theareanormaccumlu.get(1)).cellvalue(thepoint,
                prj.makenull))
                a.seteditable (FALSE)
                a.seteditable (TRUE)
        a.setvalue(pafield,newrec,(theareanormaccumlu.get(2)).cellvalue(thepoint,
                prj.makenull))
                a.seteditable (FALSE)
```

```
            a.seteditable (TRUE)
        a.setvalue(hafield,newrec,(theareanormaccumlu.get(3)).cellvalue(thepoint,
            prj.makenull))
            a.seteditable (FALSE)

            a.seteditable (TRUE)
        a.setvalue(mxfield,newrec,(theareanormaccumlu.get(4)).cellvalue(thepoint,
            prj.makenull))
            a.seteditable (FALSE)

            a.seteditable (TRUE)
        a.setvalue(mafield,newrec,(theareanormaccumlu.get(5)).cellvalue(thepoint,
            prj.makenull))
            a.seteditable (FALSE)

            a.seteditable (TRUE)
        a.setvalue(pufield,newrec,(theareanormaccumlu.get(6)).cellvalue(thepoint,
            prj.makenull))
            a.seteditable (FALSE)

            a.seteditable (TRUE)
        a.setvalue(iufield,newrec,(theareanormaccumlu.get(7)).cellvalue(thepoint,
            prj.makenull))
            a.seteditable (FALSE)

            a.seteditable (TRUE)
        a.setvalue(atfield,newrec,(theareanormaccumlu.get(8)).cellvalue(thepoint,
            prj.makenull))
            a.seteditable (FALSE)

            a.seteditable (TRUE)
        a.setvalue(frfield,newrec,(theareanormaccumlu.get(9)).cellvalue(thepoint,
            prj.makenull))
            a.seteditable (FALSE)
        end
else
        msgbox.info("Missing C:\thesisoutput\areatable.shp","Break At
        THESIS.GETALLAREAS")
end

return a
```

A.3.8 ArcView Script for Thesis.ExportCoeff_Part8

```
sttheme = self.get(0)
theshed = self.get(1)
themask = theshed/theshed
theflow priority = self.get(2)
therect = self.get(3)
thenutrientlist = {"Nitrogen","Phosphorus","Sediment"}
thefilenamelist = {"C:\thesisoutput\CCoeff","C:\thesisoutput\TCoeff"}
theloadingfilepathlist = {"$UMDGISM\cbpo\", "$UMDGISM\cbpo\tribstrategies\"}

strings = {"hi","lo","pa","ha","mx","ma","pu","iu","at","fr"}

neighborslist =
av.run("THESIS.SELECTNEIGHBORS_PART8_1",{theshed,sttheme})
	neighborstab = neighborslist.get(1)
	centerpolygonrecord = neighborslist.get(0)

recnum = 0
for each i in 1..thefilenamelist.count
	theloadingfilepath = theloadingfilepathlist.get(i-1)
	thefilename = thefilenamelist.get(i-1)
	myfile = thefilename.asFileName
	a = VTab.MakeNew(myfile, dBASE)
	theidfield = field.make("ID",#field_short,6,0)
	a.addfields({theidfield})
	for each j in strings
		newfield = field.make("C_"+j,#field_decimal,10,6)
		a.addfields({newfield})
	end
	for each j in strings
		newfield = field.make("Std_"+j,#field_decimal,10,6)
		a.addfields({newfield})
	end
	for each j in 1..thenutrientlist.count
		therec = a.addrecord
		a.setvalue(theidfield, therec, j)

		thenutrient = thenutrientlist.get(j-1)
		thecoeff = av.run("THESIS.COEFFICIENTSTATS_PART8_2",
		{thenutrient,neighborstab,sttheme,centerpolygonrecord,
		theloadingfilepath})
			thevallist = thecoeff.get(0)
			thestdevlist = thecoeff.get(1)
		for each k in 1..strings.count
			thecfield = a.findfield("C_"+strings.get(k-1))
```

```
                thestdfield = a.findfield("Std_"+strings.get(k-1))
                theval = thevallist.get(k-1)
                thestdev = thestdevlist.get(k-1)
                a.setvalue(thecfield,therec,theval)
                a.setvalue(thestdfield,therec,thestdev)
            end
        end
        a.export(thefilename.asfilename, DText, FALSE)
end
```

A.3.8.1 ArcView Script for Thesis.SelectNeighbors_Part8_1

```
'Script selects the polygon underneath watershed center point and selects its
neighboring polygons.

shedgrid = self.get(0) 'watershed grid
polygontheme = self.get(1) 'stsegment theme
polygontable = polygontheme.getftab

shapefield = polygontable.findfield("Shape")
shedcenterpoint =
av.run("THESIS.WATERSHEDCENTER_PART8_1_1",{shedgrid}) 'returns a point
thepolygonlist = polygontheme.findbypoint(shedcenterpoint)
thepolygonshape = polygontable.returnvalue(shapefield, thepolygonlist.get(0))
polygontable.selectbypolygon(thepolygonshape, #VTAB_SELTYPE_OR )

return {thepolygonlist.get(0), polygontable}
```

A.3.8.2 ArcView Script for Thesis.WatershedCenter_Part8_1_1

```
'Script converts a watershed grid to a polygon, unions all orphaned polygons and fins
the center point.
shedgrid = self.get(0)
tempfile = "c:\temp\plytemp.shp".asfilename
polygontemp = shedgrid.aspolygonftab(tempfile,FALSE,Prj.MakeNull)
shedshapefield = polygontemp.findfield("shape")
n = polygontemp.getnumrecords
shedpolygon = polygontemp.returnvalue(shedshapefield, 0)
if (n > 1) then
	for each i in 2..n
		tempshape = polygontemp.returnvalue(shedshapefield, i - 1)
		shedpolygon = shedpolygon.returnunion(tempshape)
	end
end

shedcenterpoint = shedpolygon.returncenter

return shedcenterpoint
```

A.3.8.3 ArcView Script for Thesis.CoefficientsStats_Part8_2

```
i = self.get(0) 'nutrient
thetable = self.get(1) 'neighborstab
sttheme = self.get(2)
centerpolygonrecord = self.get(3)
thefilepath = self.get(4)

'Define Coefficient Text File
if (i = "nitrogen") then
	thejoinfile = "p4nitcoeff.txt"
elseif (i = "phosphorus") then
	thejoinfile = "p4phoscoeff.txt"
elseif (i = "sediment") then
	thejoinfile = "p4sedcoeff.txt"
end

'Join coefficient text file with neighbors' table
theTable.UnjoinAll
fnseg = theTable.findfield("Stateseg1")
cFN = FileName.Make(thefilepath + thejoinfile)
coefftab = VTab.Make(cFN, FALSE, FALSE)
fcseg = coefftab.findfield("segment")
theTable.join(fnseg, coefftab, fcseg)

'Get statistics on coefficients
thevallist = {}
'themeanlist = {}
thestddevlist = {}

fieldlist = {"hi_till","lo_till","pasture","hay","mix_open","manure","p_urb",
"i_urb","at_dep","forest"}

for each label in fieldlist
	thefield = thetable.findfield(label)
	coeffval = theTable.returnvalue(thefield, centerpolygonrecord)

	if ( thetable.getselection.count = 0 ) then
		msgbox.info("Script has been exited because zero fields were
		selected","Error")
		break
	else
		theset = thetable.getselection
	end

	thesum = 0
```

```
        thecount = 0
        for each rec in theset
                thevalue = thetable.returnvaluenumber( thefield, rec )
                if ( not ( thevalue.isnull ) ) then
                        thesum = thevalue + thesum
                        thecount = thecount + 1
                end
        end

        themean = thesum / thecount

        thesumsqdev = 0
        for each rec in theset
                thevalue = thetable.returnvaluenumber( thefield, rec )
                if ( not ( theValue.IsNull ) ) then
                        thesqdev = ( thevalue - themean ) * ( thevalue - themean )
                        thesumsqdev = thesqdev + thesumsqdev
                end
        end

        if (thecount > 1) then
                thevariance = thesumsqdev / (thecount - 1)
                thestddev = thevariance.Sqrt
        else
                thevariance = 0
                thestddev = 0
        end

        thevallist.add(coeffval)
        ' themeanlist.add(themean)
        thestddevlist.add(thestddev)

end

return {thevallist, thestddevlist}
'return {thevallist, themeanlist,thestddevlist}
```

A.3.9 ArcView Script for Analysis.Compliance

```
theView = av.GetActiveDoc
labels = { "Trib Output File Name", "Current Output File Name", "Folder
Name","New File Name"}
defaults = { "ttnloadsredo2.txt", "ctnloadsredo2.txt", "foldername","compliance.shp"}
inputlist = MsgBox.MultiInput( "Enter Output File Info", "", labels, defaults )
Tfilepath = inputlist.get(0)
Cfilepath = inputlist.get(1)
foldername = inputlist.get(2)
f = inputlist.get(3)

atheme = theview.findtheme("areatable.shp")

pntstable = atheme.getftab
pntsfield = pntstable.findfield("Shape")

Tfile = FileName.Make("C:\thesisoutput\" + foldername + "\" + Tfilepath)
Cfile = FileName.Make("C:\thesisoutput\" + foldername + "\" + Cfilepath)
Tvtab = VTab.Make(Tfile, FALSE, FALSE)
Cvtab = VTab.Make(Cfile, FALSE, FALSE)
idfield = Tvtab.findfield("ID")
Tfield = Tvtab.findfield("ProbExceed")
Cfield = Cvtab.findfield("ProbExceed")

newtable = ftab.makenew(("c:\thesisoutput\" + foldername + "\" +
f).asfilename,point)
shapefield = newtable.findfield("Shape")
newidfield = field.make("Id",#field_short,6,0)
rfield = field.make("Ratio",#field_decimal,10,6)
dfield = field.make("Difference",#field_decimal,10,6)
drfield = field.make("Diff_Ratio",#field_decimal,10,6)
sfield = field.make("Status",#field_short,6,0)

newtable.addfields({newidfield,rfield,dfield,drfield,sfield})

for each i in 1..Tvtab.getnumrecords
	pnt = pntstable.returnvalue(pntsfield, i-1)
	IDvalue = Tvtab.returnvalue(idfield, i-1)
	 Tvalue = Tvtab.returnvalue(Tfield, i-1).asnumber
	Cvalue = Cvtab.returnvalue(Cfield, i-1).asnumber
	Ratio = Tvalue/Cvalue
	Diff = Tvalue-Cvalue
	Diff_Ratio = (Tvalue-Cvalue)/Cvalue
	' status = 1 (always) 2 (sometimes) 3 (never)
	if (cvalue > 0.1) then
```

```
                if (Tvalue > 0.1) then
                        status = 3 'never
                elseif (Tvalue < 0.1) then
                        status = 2 'sometimes
                else
                        status = 0 'unknown
                end
        elseif (cvalue < 0.1) then
                status = 1 'always
        else
                status = 0 'unknown
        end

        therec = newtable.addrecord
        newtable.setvalue(shapefield,i-1,pnt)
        newtable.setvalue(newidfield,i-1,IDvalue)
        newtable.setvalue(rfield,i-1,Ratio)
        newtable.setvalue(dfield,i-1,Diff)
        newtable.setvalue(drfield,i-1,Diff_Ratio)
        newtable.setvalue(sfield,i-1,status)

end

a = FTheme.Make(newtable)
a.setname("Ratio Output")
theview.addtheme(a)
```

A.3.10 ArcView Script for Analysis.SelectReachTool

```
'Modified from RaindropTool script

av.UseWaitCursor
theView = av.GetActiveDoc

' get flow dir from extension preferences
HydroExt = Extension.Find("CE301Hydro")

if (hydroExt = NIL) then
	 MsgBox.Error("Cannot find extension!","Rain Drop Tool")
	return NIL
end
flowDirGThemeName = hydroExt.GetPreferences.Get("Flow Property")
theFlowDirGTheme = theView.FindTheme(flowDirGThemeName)
if (theFlowDirGTheme = NIL) then
	MsgBox.Error("Cannot find flow direction theme in view!","Rain Drop
	Tool")
	return NIL
end
theDisplay = theView.GetDisplay
theFlowDirGrid = theFlowDirGTheme.GetGrid
theGridTheme = theView.GetActiveThemes.Get(0)
p = theDisplay.ReturnUserPoint

mypoly = ((theGridTheme.GetGrid)).ReturnCostPath(theFlowDirGrid, p)
mypoints = mypoly.AsMultiPoint

'theftab = theview.findtheme("ttnloads.shp").getftab
'tf = TextFile.Make( "C:\thesisoutput\LoadFiles\datasemi_tn.txt".AsFileName,
#FILE_PERM_WRITE)
theftab = theview.findtheme("ctnloads.shp").getftab
tf = TextFile.Make( "C:\thesisoutput\LoadFiles\datasemi_cn.txt".AsFileName,
#FILE_PERM_WRITE)
thefield = theftab.findfield("mean")
theidfield = theftab.findfield("id")
thepixelfield = theftab.findfield("Pixel_l")

mystring = "ID,XCOORD,YCOORD,DIST,VAL,INT" + NL
for each i in 1..(mypoints.aslist).count
	temppoint = (mypoints.aslist).get(i-1)
	tempdistance = (p.AsMultiPoint).Distance(temppoint) 'distance from user
	point
	theftab.SelectByPoint(temppoint,15, #VTAB_SELTYPE_NEW)
```

```
    for each rec in theftab.GetSelection
        thevalue = theftab.ReturnValueString(theField,rec)
        theid = theftab.ReturnValueString(theidfield, rec)
        thepixel = theftab.ReturnValuestring(thepixelfield, rec)
        mystring = mystring + theid.asstring + "," + (temppoint.getx).asstring
        + "," + (temppoint.gety).asstring + ","+ tempdistance.asstring + "," +
        thevalue.asstring + "," + thepixel.asstring + NL
    end
end
tf.Write(mystring.asstring,500000)
```

A.4 MATLAB Code

The following MATLAB computer codes are included in subsequent sections:

1. AutomatedNitrogenDistribution.m was used to import data from ArcView GIS generated text files and use that data to calculate a load distribution for every stream segment in a specified watershed.
2. Semivariogram.m was used import data from ArcView GIS generated text files and calculate the semivariogram for a specified stream length.

A.4.1 MATLAB Code for NitrogenDistribution.m

```
close all
clear all
clc

% Define watershed Id here
s = 1 % selects watershed information by id

% Define input file path here
for condition = 1:1:2
        fileinputarea = 'C:\thesisoutput\ areatable.txt';
        if condition == 1
                fileinputcoeff = 'C:\thesisoutput\ ccoeff.txt';
                fileoutput ='C:\thesisoutput\ctnloads.txt';
        end
        if condition == 2
                fileinputcoeff = 'C:\thesisoutput \tcoeff.txt';
                fileoutput = 'C:\thesisoutput\ ttnloads.txt';
        end
        fida = fopen(fileinputarea, 'r');
        fidc = fopen(fileinputcoeff, 'r');
        file = fopen(fileoutput,'w');

        atable = textscan(fida, '%f %f %f %f %f %f %f %f %f %f %f %f',
        'headerlines', 1,'delimiter', ',');
        id = atable{1};
        n = length(id);

        ctable = textscan(fidc, '%f %f %f %f %f %f %f %f %f %f %f %f %f %f %f
        %f %f %f %f %f %f', 'headerlines', 1,'delimiter', ',');

        % Define nutrient here (1 = TN, 2 = TP, 3 = TS)
        nutrient = 1

        % Define watershed specific criteria here
        critvals =[7.7,5.1,6,10.7,6,4.9,4.8,1.6,9.4,1.5,2.3,7.6,0.7,3.4,4.8,4.8,4.8,4.8,
        4.8,4.8,4.8,4.8,4.8,4.8,4.8,4.8,4.8,4.8,4.8,7.7,7.7,6,4.8,4.8,4.8];
        crit = critvals(s) %TN

        coeffci = [];
        stdci = [];
        for i = 2:1:11
                coefflist = ctable{i};
                coeff = coefflist(nutrient,1);
```

```
            k = i + 10;
            stdevlist = ctable{k};
            stdev = stdevlist(nutrient,1);

            x1 = coeff*ones(size(id));
            x2 = stdev*ones(size(id));
            coeffci = cat(2,coeffci,x1);
            stdci = cat(2,stdci,x2);
        end

        probexceedance = [];
        variancesum = zeros(size(id));
        meansum = zeros(size(id));
        load_total = zeros(n,1);
        for i = 2:1:11
            arealist = atable{i}; % selects a land use area list i
            meanpart = arealist.*coeffci(:,i-1);
            meansum = meansum + meanpart;
            stdpart = arealist.*stdci(:,i-1);
            variancesum = variancesum + stdpart.^2;
        end
        stdsum = variancesum.^(1/2);

        specs = [crit, inf];
        for i = 1:1:length(id)
            mu = meansum(i);
            sigma = stdsum(i);
            prob_exceedance = probfunc(specs,mu,sigma);
            if (isnan(prob_exceedance) == 1)
                prob_exceedance =
                probfunc(specs,0.0000000000001,0.0000000000001);
            end
            probexceedance = cat(1,probexceedance,prob_exceedance);
        end

        update = [];
        update = cat(1, update, id');
        update = cat(1, update, meansum');
        update = cat(1, update, stdsum');
        update = cat(1, update, probexceedance');

        % File Output Info
        fprintf(file,'"ID","Mean","Sigma","ProbExceed" \r\n');
        fprintf(file,'%6.0f, %f, %f, %f \r\n',update);
        close all
    end
```

A.4.2 MATLAB Code for Semivariogram.m

```
close all
clear all
clc

% Define file paths here
fileinput = 'C:\thesisoutput\datasemi.txt'
fileoutput = 'C:\thesisoutput\semic.txt'
fid = fopen(fileinput, 'r');
file = fopen(fileoutput,'w');

hold on

table = textscan(fid, '%f %f %f %f %f %f', 'headerlines', 1,'delimiter', ',');
id = table{1};
dist = table{4};
val = table{5};
n = length(id);
testint = table{6};
tlength = sum(table{6});
avint = mean(table{6})
minpairs = 30
maxlength = tlength/2

myint = mean(testint)

count = 0;
skipped = 0;
separation = 0;
semivariogram = [];
averrors = [];
for i = 1:1:(n-1)
        a = 0;
        b = 1 + count;
        numerator = 0;
        temp = 0;
        temp2 = 0;
        separation = separation + myint;
        for j = 1:1:(n-b)
                calc = (val(j+a)-val(j+b))^2;
                temp = temp + calc;
                numerator = numerator + 1;
        end
        if separation <= maxlength
                if numerator >= minpairs
```

```
            test = 0.5*temp/(numerator);
            semivariogram = cat(1,semivariogram,[separation,test]);
            averrors = cat(1,averrors,[separation,temp2/numerator,
            abs(separation-temp2/numerator)]);
        end
    end
    count = count + 1;
end

figure
plot(semivariogram(:,1), semivariogram(:,2),'.g')
ylabel('\gamma(h) (lbs/ac/yr)^2')
xlabel('h (m)')

update = [];
update = cat(1, update, semivariogram(:,1)');
update = cat(1, update, semivariogram(:,2)');

% File Output Info
fprintf(file,'%f, %f \r\n',update);
fclose(file);
```

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