THESIS

QUANTIFICATION OF NUTRIENT LOADS IN URBAN STORMWATER ACROSS COLORADO MUNICIPAL AREAS

Submitted by

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ABSTRACT

QUANTIFICATION OF NUTRIENT LOADS IN URBAN STORMWATER ACROSS COLORADO MUNICIPAL AREAS

As nutrient pollution becomes a growing problem across the world, it becomes increasingly important to be able to quantify the amount of nutrients each of the different sources contributes. Understanding the quantity of nutrients each source is providing makes it possible to understand where and how to address nutrient pollution effectively. Increases in urbanization have resulted in the degradation of water quality specifically from urban stormwater. Due to regulations that have been adopted to address this problem, stormwater Best Management Practices (BMPs) have been implemented to provide water quality treatment and runoff reduction. Since these BMPs are altering the quality and quantity of urban stormwater they need to be included in modeling the urban watershed. As a first approach, a simple framework for which an order of magnitude estimate of nutrient loads from stormwater could be determined was developed. The effects of BMPs were incorporated into the framework as well as a method for estimating the current amount of drainage area being treated by BMPs.

The provided approach contains a simple model which can rapidly estimate nutrient loads from urban stormwater in any given watershed or area of interest using the most recently available national datasets. A simple approach was chosen because it is easy to understand regardless of a user's background in modeling. All of the inputs for the method are available through national datasets, allowing the approach to be applied anywhere within the United States. The proposed method of estimating nutrient loads was evaluated by comparing predicted event loads to observed event loads from two different study sites within Fort Collins, CO. From

this analysis it was determined that the proposed approach would only be applicable for estimating the order of magnitude of nutrient loads. A Monte Carlo simulation discovered large bands of uncertainty surrounding the prediction. However, a Bayesian statistical analysis found that the uncertainty bands around the estimate could be substantially reduced by using observed data within an area of interest. Overall the proposed approach should be used for planning level purposes where order of magnitude estimates are appropriate.

In order to consider BMPs into the method it was necessary to know how much drainage area was currently being treated by BMPs. An approach was developed that compared changes in land use as measured by National Land Cover Database (NLCD) products to provide a measurement of the estimated treatment drainage area provided by stormwater BMPs. This approach was evaluated in Fort Collins, CO and was found to be able to effectively predict a range of BMP implementation which captured the actual amount of BMP implementation for Fort Collins as a whole as well as for 11 of the 12 sub-basins within Fort Collins.

Further research should include evaluating the proposed approach for load estimation in other urban watersheds of varying sizes utilizing different structural BMPs and green infrastructure. This would require a watershed to have readily available data regarding the nutrient load being exported by urban sources within the watershed. Further research should also include conducting the BMP treatment area estimation approach in other urban watersheds to determine whether the method is applicable in other regions and municipalities other than Fort Collins.

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Soli Deo Gloria.

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CHAPTER 1: INTRODUCTION

Over the past several decades a new threat has risen to our natural environment, nutrient pollution. Nutrient pollution in the form of nitrogen and phosphorus has increased around the world and is evident in surface water bodies across the United States (Carpenter et al. 1998). When nutrients reach high enough levels in watersheds they can cause eutrophication, acidification, polluted drinking water, increased water treatment costs, fish kills, and poisoned ecosystems (Novotny 2011; USEPA 2016b; Worrell et al. 2001). There are several sources contributing to nutrient pollution such as agriculture, stormwater, wastewater, and atmospheric deposition (USEPA 2016b). In order to properly address the problem of nutrient pollution, it is necessary to understand how each source is contributing to the total amount of nutrient loads being received by a water body. The source of interest for this study is stormwater. As a source of nutrient pollution, it is necessary to develop a model that can simply and rapidly predict the nutrient load at different spatial scales from urban stormwater.

1.1: Background of Urban Stormwater

Over the past several decades many countries in the world have been altering land use by taking undeveloped non-urban areas and developing them. Population shifts have resulted in the percent of population living in urban areas to increase from 40 percent in 1900 to more than 80 percent in 2010 (USEPA 2011). This has corresponded to a 59% increase in the amount of urban area from 1982 to 2012 (USDA 2015). Urbanization increases the amount of impervious area, which increases the volume of runoff, increases peak runoff rates, as well as increases the flow velocity (Hall and Ellis 1985). **Figure 1.1,** from Hall and Ellis displays a flow chart depicting the changes to the urban hydrology as a result of urbanization.

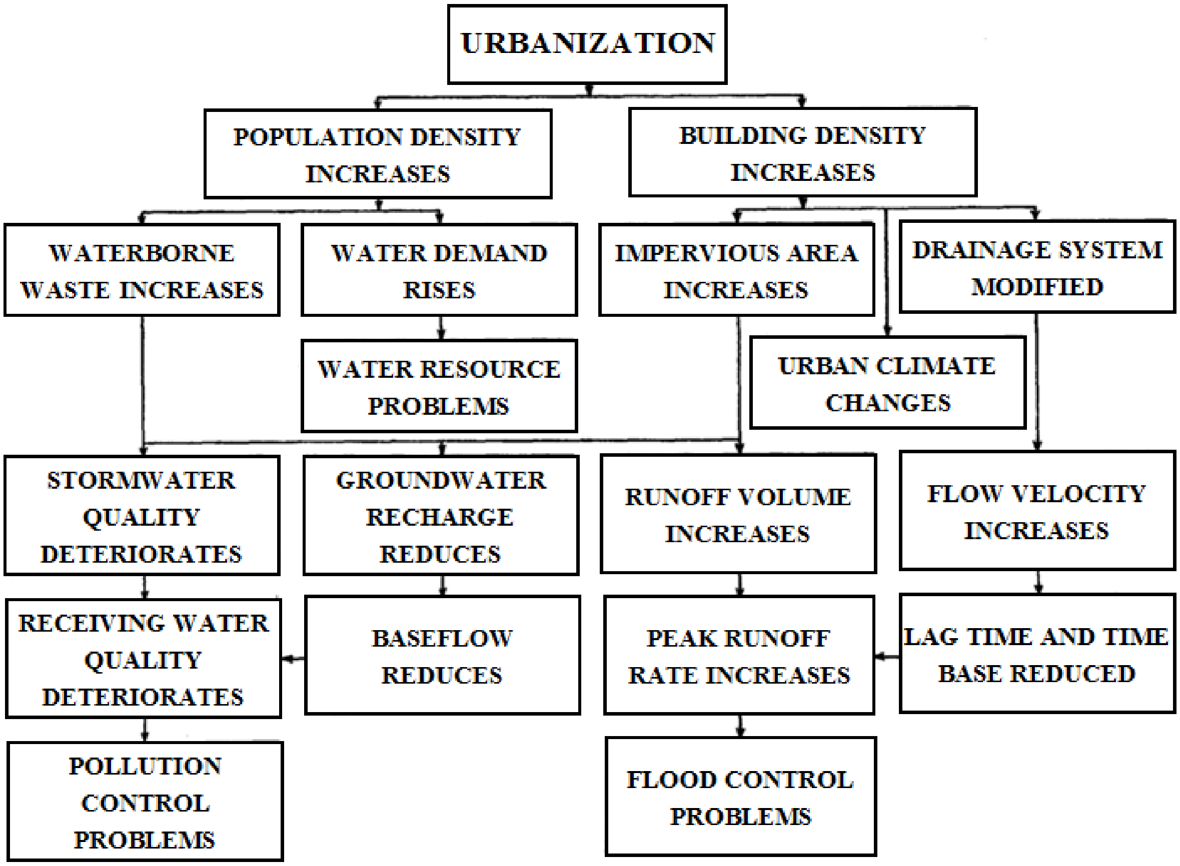

Figure 1.1: The effects of urbanization on hydrological processes (Hall and Ellis 1985)

Increases in urbanization have also resulted in the degradation of water quality. After becoming aware of the strain that urban areas can place on water quality, particularly in surface water, the United States began to pass laws and regulations requiring that this problem be addressed. One element highlighted in newer regulations has been the protection of the nation's water bodies from urban stormwater. According to Novotny (2011), urbanization results in an increase of flooding, increase in diffuse pollution , and the deterioration of the habitat of urban streams. The National Urban Runoff Program (NURP) found that urban areas also result in an increase in pollution loads that can be harmful to receiving water bodies (USEPA 1983). The U.S. Geological Survey (1999) found that urban streams have higher frequencies of occurrence of harmful pollutants such as DDT, complex mixtures of pesticides, and elevated phosphorus levels. Due to the hydrologic changes as a result of urbanization and the additional water quality concerns, urban stormwater is one of the more complicated sources to quantify (Davidson et al. 2010; Grimm et al. 2008).

1.2: Regulations

As urbanization increased and the U.S. government became aware of the harmful effects, it began to pass laws and regulations to address these effects. The first law defending the nation's water was the Federal Water Pollution Control Act, enacted in 1948, but was reorganized and expanded in 1972 into what is commonly known as the Clean Water Act. The main objective of the Clean Water Act is to restore and maintain the chemical, physical, and biological integrity of the Nation's waters. In order to achieve this, the National Pollutant Discharge Elimination System (NPDES) permit program was established by Section 402 of the Clean Water Act. The NPDES permit program was established in order to control the discharge of pollutants from point source discharges.

In the Water Quality Act of 1987, Congress directed the EPA to begin controlling stormwater discharges resulting in an expansion of NPDES permits to include urban stormwater as point source in municipal separate storm sewer systems (MS4s) (USEPA 2000a). MS4s are any conveyance or system of conveyances that are owned or operated by a state or local government entity and are designed for collecting and conveying stormwater and are not part of a publicly owned treatment work or combined sewer. MS4 permits controlling urban stormwater were issued through the Stormwater Phase I Final Rule, in 1990, and the Stormwater Phase II Final Rule in 1999. Stormwater Phase I and Phase II Final Rules require MS4s to provide water quality treatment to the Maximum Extent Practical (USEPA 2000a; b). They also require that structural best management practices (BMPs) be built and maintained in any newly developed or redeveloped areas. Including BMPs has caused urban hydrology to become even more complex as BMPs have the capabilities to affect both the quantity and quality of urban stormwater (Ahiablame et al. 2012; Dietz 2007; Leisenring et al. 2014; Poresky et al. 2011)

1.3: Modeling Urban Stormwater

Even though urban stormwater may be difficult to calculate as a result of urbanization and implementation of BMPs, it is necessary for urban stormwater loads to be quantified. There are several models that are currently available for computing surface water runoff, and by extension of pollutant concentrations, nutrient loads for urban stormwater. Some of these models are very complex such as SWMM (Rossman 2015), and some can be very basic like the curve number method. Other complex models available for computing urban stormwater loads include the Hydrological Simulation Program (HSP-F), Distributed routing rainfall-runoff model (DR3M-QUAL), and Storage, Treatment, Overflow, Runoff Model (STORM) (Alley and Smith 1982; Bicknell et al. 1997; HEC 1977). Each of these models have the capabilities to quantify urban stormwater runoff from largely impervious land and account for stormwater being quickly conveyed out of urban areas without providing opportunities for natural processes such as infiltrations to occur.

As studies cited earlier have shown, BMPs affect both the quantity and quality of urban stormwater runoff, and therefore, when they are present, should be included in the modeling of urban stormwater. Some of the models, such as SWMM, allow for the inclusion of structural BMPs. In most cases, if structural BMPs are wished to be simulated it is required that the modeler have a detailed knowledge of where and how each practice is being implemented. None of these models attempt to predict where BMPs are currently in use. Also most stormwater models require multiple inputs and can become burdensome to users who are looking for a simple estimation of nutrient loads. Sometimes even simpler methods like the curve number method or USGS regression equations (Driver and Tasker 1988) can be difficult to collect all of the necessary inputs.

The Simple Method (Schueler 1987) was used in this research for driving the model to calculate nutrient loads. The Simple Method estimates pollutant loads based on drainage area, impervious cover, and the median event mean pollutant concentrations. Pollutant load estimates are the product of estimated runoff volume and pollutant concentrations (Martin et al. 2015). The Simple Method is shown in **Equation 1.1**.

$$L = 0.226 * P * Pr * Rv * A * C \qquad \textbf{Equation 1.1}$$

Where: L = Pollutant load (lbs), P = Precipitation (in), Pr = Fraction of precipitation that produces runoff, Rv = Runoff Volume Coefficient, A = Drainage area (acres), C = Pollutant concentration (mg/L) and 0.226 represents the unit conversion. P, Pr, Rv, and A represent the stormwater volume as predicted by the Simple Method. Multiplying the stormwater volume by the pollutant concentration allows for the calculation of the nutrient load from urban stormwater.

The Simple Method has been used in several stormwater manuals such as New York, Minnesota, New Hampshire, North Carolina, Newton Kansas, and the Chesapeake Bay (CSN) 2011; City of Newton 2016; (MPCA) 2015; (NHDES) 2008; (NYSDEC) 2008; (NCDENR) 2009). The Simple Method provides approximations of nutrient loads in stormwater for TMDL analysis, understanding necessary nutrient reductions, or determining target areas for stormwater treatment through best management practices. Due to the simplicity, the Simple Method is a very transparent method that allows users to understand what each input for the method means. When users understand what the inputs mean it helps avoid the feeling of a black box model that can arise in sophisticated modeling methods. The Simple Method was also chosen due to the readily available inputs provided by national datasets. By using national datasets, there is a consistency with the collection of inputs and its availability across the United States.

The Simple Method has limitations incorporated with it. The Simple Method's inputs do not allow the capture of the complexity that is present in most hydrologic systems such as differences in rainfall regime across different climates. For this reason, its main use is for assessing and comparing the relative stormwater pollutant load, and though it may come close to the true value, it ultimately should only be used when desiring to calculate the relative magnitude of the load (SMRC, 2014). Also, the Simple Method does not provide any information for the conveyance of runoff, peak of runoff, or have the ability to monitor any hydrologic responses within an event, but can only estimate the final volume and load after the event. Finally, the Simple Method also does not include baseflow, which comes into effect when considering larger watersheds. Since the goal of this method was to quantify the stormwater runoff nutrient load, baseflow was not a consideration, but in order to correctly budget the watershed load, baseflow should be included in some analysis. Baseflows would have a larger role if structural BMPs were installed providing more infiltration, ultimately resulting in more groundwater flow.

1.4: Objectives

The overall goal of this study was to determine a methodology that could be easily understood by users with limited modeling experience for quantifying nutrient loads from urban stormwater at the watershed scale. Objectives of the study included: 1) select a model that is simple and can rapidly estimate a load for any given watershed across the United States using national datasets; 2) evaluate the selected model using observed nutrient load data from a watershed; 3) quantify and reduce the uncertainty within a load estimate; 4) develop a novel approach for estimating the amount of drainage area being treated by structural BMPs currently present in a given area of interest; and 5) evaluate the developed approach using known locations of BMP drainage areas within a municipality.

As discussed above, the Simple Method was chosen as the driving model for estimating nutrient loads. Since the Simple Method did not contain any way to include BMPs into the analysis, it was modified to provide this function. In order to evaluate the appropriateness of the Simple Method and the modifications, estimated loads were compared to observed loads in two study sites in Fort Collins. After estimated loads were compared to observed loads, uncertainty bands were created using a Monte Carlo simulation. Since large amounts of uncertainty were observed for each estimated event load, a Bayesian statistical method was employed to reduce the uncertainty using observed event loads.

Finally, as a part of the modifications to the Simple Method to account for structural BMPs, it was necessary to develop an approach for estimating the amount of drainage area being treated by structural BMPs. This approach investigated using National Land Cover Database (NLCD) layers to predict areas of new urban development and redevelopment which, by regulations, should also represent areas being treated by water quality BMPs. The developed approach was evaluated by comparing areas estimated to be treated by BMPs with known BMP drainage areas provided for Fort Collins, CO.

CHAPTER 2: QUANTIFICATION OF NUTRIENT LOADS IN URBAN AREAS USING THE SIMPLE METHOD WITH NATIONAL DATASETS

2.1: Introduction

As a result of an increase in fertilizer use and urbanization, nutrient pollution has become a problem for many people around the world. Nutrient pollution has caused eutrophication, acidification, polluted drinking water, increased water treatment costs, fish kills, and poisoned ecosystems. There are several sources contributing to nutrient pollution such as agriculture, stormwater, wastewater, and atmospheric deposition. In order to properly address the problem of nutrient pollution, it is necessary to understand how each source is contributing to total amount of nutrient loads being received by a water body. The source of interest for this study is stormwater. As a source of nutrient pollution, it is necessary to develop a model that can simply and rapidly predict the nutrient load at different spatial scales from the urban environment.

2.1.1: Background

Nutrient pollution in the form of nitrogen and phosphorus has increased around the world and is evident in surface water bodies across the United States (Carpenter et al. 1998). Prime examples of the negative impacts that result from an excess of nutrients in water bodies are seen in the dead zone at the Mississippi delta and the Chesapeake Bay (Chesapeake Bay Foundation 2016; USEPA 2016a). Nutrients come from multiple sources such as the atmosphere, agricultural, stormwater, wastewater, and background loads present in the stream(USEPA 2016b). When these nutrients reach high enough levels in watersheds they can cause eutrophication, acidification, polluted drinking water, increased water treatment costs, fish kills, and poisoned ecosystems (Novotny 2011; USEPA 2016b; Worrell et al. 2001).

Since there are several sources which contribute to nutrient pollution within a watershed (Howarth et al. 2002), each source should be quantified in order to identify which contribute the largest portion of nutrients and should be targeted for nutrient reductions. One of the more complicated sources to quantify is urban stormwater (Davidson et al. 2010; Grimm et al. 2008). According to Novotny (2011), urbanization results in an increase of flooding, increase in diffuse pollution , and the deterioration of the habitat of urban streams. The National Urban Runoff Program (NURP) found that urban areas also result in an increase in pollution loads that can be harmful to receiving water bodies (USEPA 1983). The U.S. Geological Survey (1999) found that urban streams have higher frequencies of occurrence of harmful pollutants such as DDT, complex mixtures of pesticides, and elevated phosphorus levels.   However, even though urban stormwater may be complicated to calculate due to the changes as a result of urbanization, it is necessary for urban stormwater loads to be quantified.

2.1.2: Urban Stormwater Model

There are several models that are currently available for computing surface water nutrient loads for urban stormwater. Some of these models are very complex such as SWMM (Rossman 2015), and some can be very basic like the curve number method. Other models available for computing urban stormwater loads include the Hydrological Simulation Program (HSP-F), Distributed routing rainfall-runoff model (DR3M-QUAL), and Storage, Treatment, Overflow, Runoff Model (STORM) (Alley and Smith 1982; Bicknell et al. 1997; Hydrologic Engineering Center (HEC) 1977). Each of these models have the capabilities to quantify urban stormwater loads from largely impervious land and account for stormwater being quickly conveyed out of urban areas without providing opportunities for natural processes such as infiltrations to occur.

Although each of these models accomplish similar goals, they each are different (Obropta and Kardos 2007). Understanding these differences requires an in-depth knowledge of urban stormwater phenomena and how different systems attempt to model these phenomena. Each model requires multiple inputs and becomes burdensome to users who are looking for a simple estimation of nutrient loads. Sometimes even methods like curve number or USGS regression equations (Driver and Tasker 1988) can be difficult to collect all of the necessary inputs.

The adopted approach for this research was driven by the Simple Method (Schueler 1987). Pollutant loads are estimated using the Simple Method as the product of estimated runoff volume and pollutant concentrations (Martin et al. 2015). Loads are calculated based on drainage area, precipitation, impervious cover, and median event mean pollutant concentrations. The Simple Method is shown in **Equation 2.1**.

$$L = 0.226 * P * Pr * Rv * A * C \qquad \textbf{Equation 2.1}$$

Where: L = Pollutant load (lbs), P = Precipitation (in), Pr = Fraction of precipitation that produces runoff, Rv = Runoff Volume Coefficient, A = Drainage area (acres), C = Pollutant concentration (mg/L) and 0.226 represents the unit conversion. The Rv coefficient is calculated using a linear regression of percent imperviousness, I, of the watershed. P, Pr, Rv and A represent the stormwater volume predicted by the Simple Method, and multiplying by the pollutant concentration calculates the stormwater nutrient load.

Several stormwater manuals have included the Simple Method or a similar version for planning purposes such as New York, Minnesota, New Hampshire, North Carolina, Newton Kansas, and the Chesapeake Bay (CSN) 2011; City of Newton 2016; (MPCA) 2015; (NHDES) 2008; (NYSDEC) 2008; (NCDENR) 2009). Using an approach like the Simple Method, approximations of nutrient loads in stormwater could be easily determined for TMDL analysis, understanding necessary nutrient reductions, or determining target areas for stormwater treatment through best management practices.

The Simple Method is a transparent method that allows users to understand what each input for the method represents and avoids the feeling of a black box model that arises in sophisticated modeling methods. The Simple Method was also chosen due to the readily available inputs provided by national datasets. By using national datasets, there is consistency in inputs and their availability across the United States. The Simple Method does have limitations associated with it. The Simple Method's few inputs are not able to account for complex rainfall regimes. Also, the Simple Method is meant for annual load estimation and smaller time scales include additional uncertainty. Finally, the Simple Method does not include baseflow, which can become a significant source in large areas of interest.

2.1.3: Objectives

For this study, the goal was to determine a methodology that could be easily understood by users with limited modeling experience for quantifying nutrient loads from urban stormwater at various scales using national datasets. The goal of this study was accomplished through three objectives. The first objective selected an approach for quantifying nutrient loads from urban stormwater. The approach involved using the Simple Method as proposed by (Schueler 1987). The Simple Method was first used to quantify nutrient loads from stormwater without including treatment from Best Management Practices (BMPs). The Simple Method was then adapted to account for the changes in quantity and quality of stormwater due to BMP implementation. The second objective evaluated each use of the Simple Method by comparing observed nutrient loads at the inflow and outflow of two wetland detention basins in Fort Collins. The third objective calculated the uncertainty of the proposed approach and attempted to reduce this uncertainty.

2.2: Methods

The following section contains the methods used for accomplishing the three objectives as set forth in the introduction. The selected model for providing load estimates was the Simple Method which was evaluated using observed loads for two different study areas within Fort Collins, CO. After the method was evaluated uncertainty bands were estimated using a Monte Carlo simulation. After observing large amounts of uncertainty, a Bayesian statistical analysis was investigated for reducing the uncertainty.

2.2.1: The Simple Method

The adopted approach was driven by the Simple Method. The Simple Method calculates a load by estimating the amount of runoff volume and multiplying by a pollutant concentration. There are multiple inputs for the Simple Method including precipitation, fraction of precipitation that produces runoff, runoff volume coefficient, drainage area, and pollutant concentration. Each of the inputs for the Simple Method is described in more detail below. The Simple Method is capable of calculating both annual and event based loads, however, it works best for calculating annual loads. When calculating event based loads there are larger amounts of uncertainty associated with the estimate.

The Simple Method is applied to a selected study area through GIS based processes using raster analysis. National databases provide the inputs for the analysis at a 30-m raster cell resolution. Using a raster analysis accounts for changes within watersheds that could occur through changes in space and doesn't require users to use a lumped average for each input across the entire watershed but can account for how each input changes throughout the watershed. Each 30-m raster cell was treated as if it was its own watershed requiring the Simple Method to be conducted for each 30-m raster cell and then summed up across the entire study area.

Conducting the analysis in this fashion allows for the different inputs to interact with one another i.e. if one cell has high concentration, but low imperviousness, the resulting load includes both effects. Since the analysis was conducted for each cell using raster operations it was necessary to apply the approach through a GIS platform. Using a GIS platform allows the Simple Method to be applied at a 30-m resolution and then the total load of each cell is aggregated across an entire area of interest providing a total load estimate.

The largest assumption that is made by applying the Simple Method to each 30-m cell and then summing up each cell to create a total is that the load produced by a cell will eventually discharge into the watershed. Meaning that the interaction between cells is not accounted for, particularly in the case where a cell with large amounts of imperviousness, which produces a lot of runoff, discharges the nutrient load to a cell with large amounts of perviousness, which does not produce a lot of runoff. In this scenario, the pervious cell may have the capacity to infiltrate and reduce the load from the connected impervious cell thus reducing the total load. Interactions such as these, however, do not result in larger loads being produced by a watershed but smaller loads. And since the method does not factor in the possibility of impervious to pervious run on, a more conservative estimate is produced. The interaction between cells where impervious runoff is infiltrated by pervious regions is one of the reasons that the runoff volume coefficient in the method has as much uncertainty as presented later in this study.

2.2.2: Collecting Inputs for the Simple Method

Once it is understood how the Simple Method is deployed for this approach, it is necessary to collect the inputs for the method. The first input needed is precipitation, which is the main driver for estimating the amount of runoff. Precipitation values were obtained from the PRISM Climate Group. PRISM (Parameter-elevation regressions on independent slopes model) is a climate analysis system which uses point data, digital elevation models, and other spatial datasets to generate gridded estimates of annual, monthly, and daily climate parameters (Daly et al. 1997). PRISM is a national dataset providing temperature and precipitation data for daily, monthly, and annual time intervals. PRISM also produces normals for precipitation which are average precipitation values for the daily, monthly, and annual time steps. For calculating the average annual load, the average annual precipitation from the period of 1981-2010 was used. PRISM average annual precipitation layers were available at 800-m raster resolution (PRISM Climate Group 2015) and can be seen in **Figure 2.1**. For event based modeling it is necessary for a user to know the amount of precipitation that corresponds to that event.

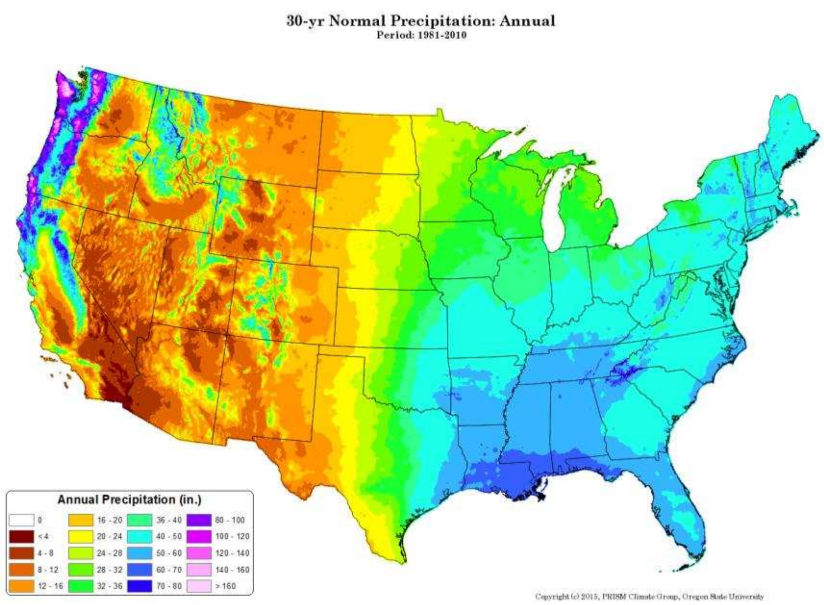

Figure 2.1: Map of PRISM annual normal precipitation for the period of 1981-2010

After precipitation values were collected, it is necessary to determine what value should be used for the fraction of annual precipitation which produces runoff, or Pr. Pr is a correction value that is used to account for the fraction of annual rainfall that does not produce measurable runoff. This occurs when storms do not drop enough rainfall to overcome depression storage and evaporates once the event is over, never producing runoff (Schueler 1987). Pr is a factor that is used when computing annual loads since there is some precipitation throughout the year which will never produce runoff because it does not overcome depression storage, but is large enough to be recorded by a rain gauge. According to Schueler, Pr should be set to 0.9 for calculating annual loads meaning that 10% of annual precipitation does not have the potential to become runoff. In the case of estimating nutrient loads for events Pr should be set to 1.0 since it is assumed that the event will produce runoff.

The next input required for the method is the runoff volume coefficient or Rv. Rv represents the amount of precipitation that actually becomes runoff, thus accounting for infiltration, initial abstraction, and depression storage that occurs in rainfall events that do produce runoff. The Rv coefficient differs from Pr in that it accounts for losses within events that produce runoff, where Pr accounts for precipitation events that do not produce any runoff in annual load estimations. The Rv coefficient was calculated based on the linear regression relationship with percent imperviousness presented in Schueler, 1987. The linear relationship was determined using 44 study sites and measuring the ratio of volume of runoff to total precipitation volume for multiple events at each of the study sites and using the mean value. Mean values of Rv were plotted versus the watershed imperviousness for each of the 44 sites as seen in **Figure 2.2**.

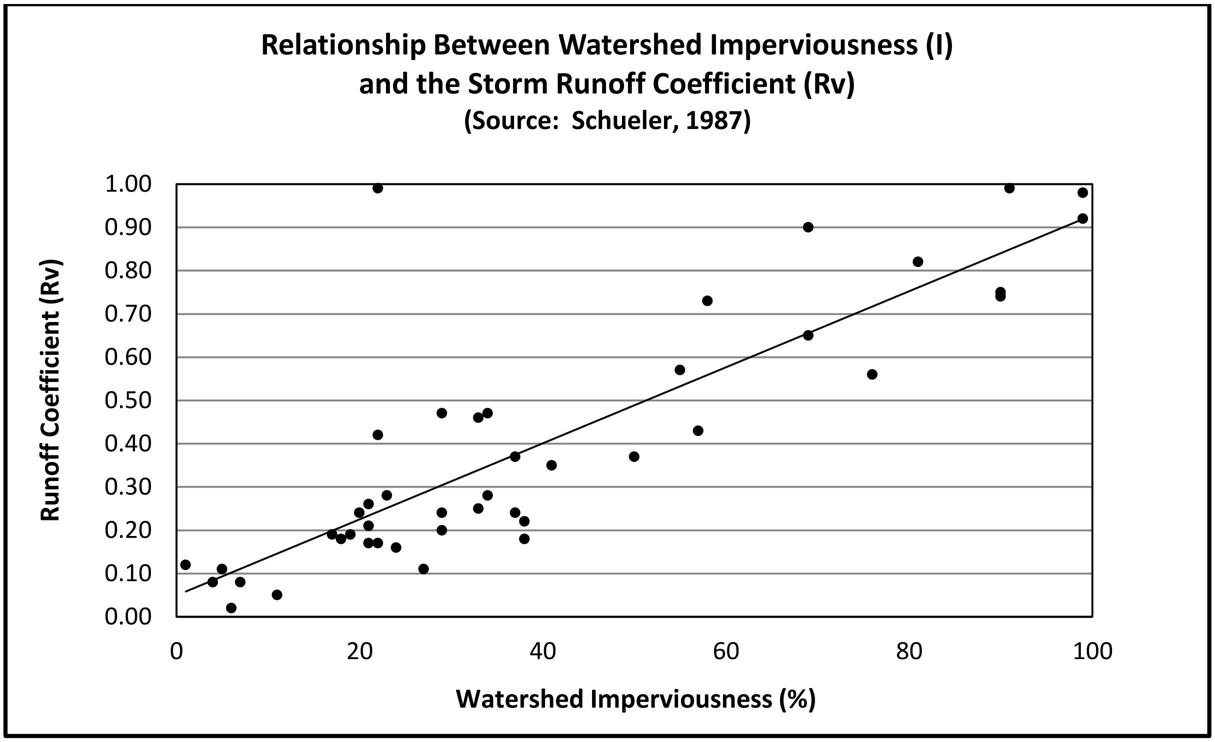

Figure 2.2: Relationship between watershed imperviousness and the mean storm runoff coefficient for the 44 sites with the best fit linear regression line Equation 2.2, presented in Schueler, 1987

After Schueler plotted the relationship between watershed imperviousness and mean runoff coefficient for each of the 44 sites, linear regression was used to determine the line of best fit. The linear equation determined by linear regression is shown in **Equation 2.2** with R^2 equal to 0.71 where Rv is the runoff coefficient and I is the percent watershed imperviousness.

$$Rv = 0.05 + 0.009 * I \qquad \textbf{Equation 2.2}$$

Percent imperviousness was collected from a National Land Cover Database (NLCD) layer. NLCD is a national land cover product created by a group of federal agencies known as the Multi-Resolution Land Characteristics consortium. NLCD land cover products are created from Landsat satellite data that has been consistently applied across the nation (MRLC 2015). Other researchers such as (Endreny and Thomas 2009a; Kalyanapu et al. 2010; Smith et al. 2010; Wu and Johnston 2007) have used NLCD layers to provide inputs for land cover type for different hydrologic models. NLCD provided two different layers for conducting this method;

the first is the percent impervious layer which displays a numeric value depicting the percent imperviousness for each 30-m grid cell. The second NLCD layer is the NLCD land cover product which will be described below.

The final input needed for calculating runoff volume using the Simple Method is area, which transforms the depth of runoff into a volume by multiplying area by precipitation, fraction of precipitation that produces runoff and the Rv coefficient. For this approach, the Simple Method was applied to each of the 30-m grid cells determined by the NLCD datasets where each grid cell was its own watershed. Therefore since each grid cell was 30m by 30m or 900 m^2, this was converted to acres yielding, 0.222 acres for each grid cell.

After the runoff volume was determined for each grid cell, that volume could be converted to a load by multiplying by the pollutant concentration. Concentrations were applied based on land use/land cover as determined by NLCD land cover layers. The layers are 30-m resolution raster datasets containing values that represents what land cover is associated with the majority of the cell. The classification system used by NLCD is a modified version of the Anderson Land Cover Classification System (Anderson et al. 1976). NLCD classifications contain a total of sixteen classifications which are displayed in **Table 2.1**. Since this approach is attempting to quantify stormwater nutrient loads, only the developed categories (21-24) were used to apply concentrations. All other classifications located within an area of interest were determined to not be stormwater loads and should be quantified using a different approach.

Table 2.1: List of NLCD land use codes with classifications from MRLC 2015

NLCD #	Land Use Classification
11	Open Water
12	Perennial Ice/Snow
21	Developed, Open Space
22	Developed, Low Intensity
23	Developed, Medium Intensity
24	Developed, High Intensity
31	Barren Land (Rock/Sand/Clay)
41	Deciduous Forest
42	Evergreen Forest
43	Mixed Forest
51	Dwarf Scrub *
52	Shrub/Scrub
71	Grassland/Herbaceous
72	Sledge/Herbaceous *
73	Lichen *
74	Moss *
81	Pasture/Hay
82	Cultivated Crops
90	Woody Wetlands
95	Emergent Herbaceous Wetlands

* Alaska only

Concentrations were applied as event mean concentrations (EMCs) based on land use classifications designated by NLCD data. EMC values for different land uses were collected from Wright Water Engineers who collected runoff data from each of the different land use classification sites as a part of a regional study for the state of Colorado. **Table 2.2** displays the median recorded EMCs and the 95th percentile for total phosphorus and total nitrogen for each NLCD land use type. Also included in the table is the number of samples collected to determine the median and 95th percentile. Each site was located in Colorado and should only be used for Colorado, however, the National Urban Runoff Program (USEPA 1983) have suggested land use concentrations that could be used across the nation.

Table 2.2: Median runoff concentrations with 95th percentiles for TP and TN based on urban land use types from Wright Water Engineers

Land Use	Total Phosphorus (mg/L)	# of TP Samples	Total Nitrogen (mg/L)	# of TN Samples
Open Space	0.41 (0.22-0.65)	7	3.76 (1.58-5.83)	7
Low Intensity	0.47 (0.11-0.65)	211	3.76 (1.58-13.68)	166
Medium Intensity	0.4 (0.16-2.08)	43	3.76 (1.04-7.56)	25
High Intensity	0.22 (0.03-1.34)	316	3.76 (0.75-11.20)	191

After all inputs were collected, loads could be calculated for each 30-m grid cell and aggregated over an area of interest to provide a total nutrient load from stormwater. Using this method provides estimates for runoff loads from different land uses, but does not include the effect of BMPs. Due to regulations, new developments in municipal separate stormwater sewer systems (MS4s) must contain structural best management practices (BMPs) for stormwater runoff (USEPA 2000a). In order to allow the method to include the effects of BMPs, the approach was modified.

2.2.2: Incorporating BMPs into the Simple Method

After becoming aware of the strain that urban areas can place on water quality, the United States began to pass laws and regulations addressing the problem. Newer regulations have been adopted targeting urban stormwater. Many local public agencies are now required to insure that structural best management practices (BMPs) are being built and maintained in any newly developed or redeveloped areas (USEPA 2000b). Studies have found that structural BMPs are affecting both the quantity and quality of runoff within an urban watershed (Ahiablame et al. 2012; Dietz 2007; Leisenring et al. 2014; Poresky et al. 2011). Therefore, any attempt to model urban watersheds should contain information regarding the extent of urban areas being treated by structural water quality BMPs.

When accounting for BMPs, the percentage of urban area within an area of interest being treated by each type of BMP, must be known. The percent of BMP treatment area, or T is a required parameter for applying the effects of BMP to the Simple Method. However, many agencies do not know the exact locations being treated by BMPs or how much area is being treated by BMPs due to the required time and resources to develop a geospatial layer with this information. Since agencies generally don't know which areas are being treated, the effects of T are distributed uniformly throughout the urban area. Effects of T are applied by modifying the Simple Method to account for changes in volume as well as changes in the concentration of the runoff.

In order to understand the changes being made to the Simple Method, it is important to understand the process of most structural BMPs. **Figure 2.4** displays a model of the general operation of a BMP. In this model stormwater flows from the service area into the BMP, however, most BMPs are not designed to treat all the stormwater for every event. Instead BMPs are optimized to capture a volume that would provide the best water quality treatment without using too much urban area. In Colorado, the Urban Drainage and Flood Control District (UDFCD) determined that the optimal amount of events to capture should be approximately 85% (Guo et al. 2014; UDFCD 2011). This value of 0.85 was used to represent a parameter referred to as BMP efficiency, or ϵ, and represents the fact that approximately 15% of the annual runoff which drains to a BMP is not actually treated by the BMP but ends up as overflow keeping its previous concentration. Also, some BMPs provide opportunities for stormwater that enters the

BMP to infiltrate and thus leave the stormwater runoff system. This is requires adjustments to quantity of stormwater runoff being calculated by the Simple Method.

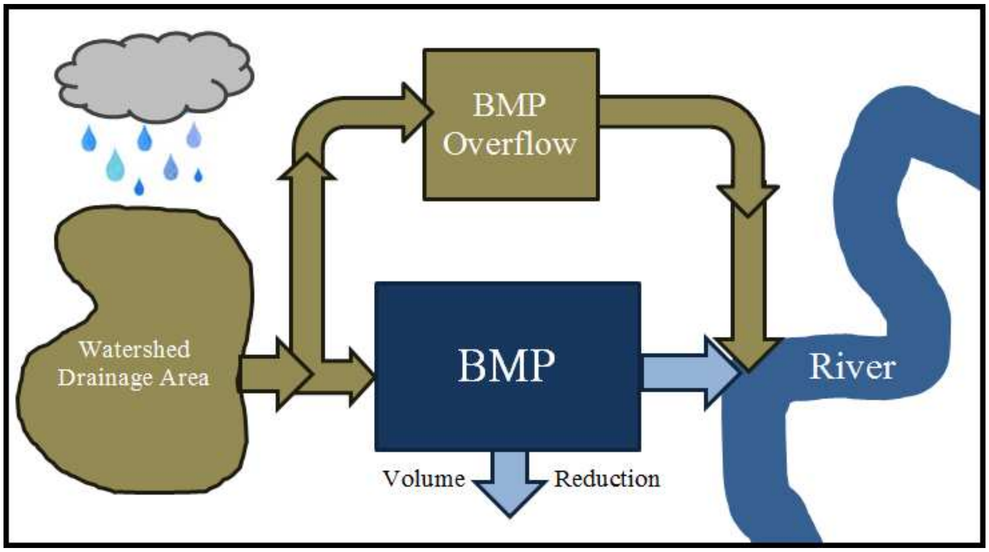

Figure 2.3: Diagram depicting the basic operations of a structural BMP

The volume of runoff is adjusted due to the infiltration benefits that some BMPs such as rain gardens provide. The International BMP Database has published a study conducted in 2010 for which Wright Water Engineers compiled data to summarize the volume reduction effects provided by several BMPs (Poresky et al. 2011). By knowing what percent of the total runoff volume reduced by each BMP, Vr, and knowing T it can be determined how much overall stormwater volume is reduced due to effects of that type of BMP. In order to include this into the Simple Model a new parameter, ΔV was introduced. ΔV is the volume reduction coefficient and represents the amount of volume remaining after the reduction of the i^{th} BMP. ΔV is calculated using **Equation 2.3** where values for Vr could be found in **Table 2.3** from the Wright Water Engineer report (Poresky et al. 2011).

$$\Delta V = 1 - \sum_{i=1}^{n} [T_i * Vr_i] \qquad \textbf{Equation 2.3}$$

Table 2.3: BMP parameters for the adopted version of the Simple Method from the International BMP Database

BMP Type	Median Concentrations (mg/L)		Volume Reduction (Vr)
	TN	TP	
Biofilter - Grass Strip	1.13	0.17	34%
Biofilter - Grass Swale	0.87	0.17	42%
Bioretention	0.92	0.24	57%
Detention Basin	1.6	0.2	33%
Porous Pavement	NA *	0.1	-
Retention Pond	1.2	0.09	-
Wetland Basin	1.19	0.09	-
Wetland Channel	1.21	0.14	-

* No treatment, same concentration as land use

- No effective volume reduction

Concentrations were changed by calculating a weighted average of the amount of volume being treated by each BMP and the amount of water bypassing each BMP. This uses ϵ, which determines how much of the water entering the BMP is actually treated. For annual modeling this value should be 0.85 assuming that BMPs are designed according to similar standards as proposed in Urban Drainage and Flood Control District (UDFCD 2011). For event based modeling this number can remain 85%, but it is dependent on the runoff volume of the event, whether the event is large or small. Small events will have greater treatment efficiency and large events will have less treatment efficiency. In order to understand ϵ for different events, a more detailed knowledge of the BMPs is required. The new concentration to be used in the Simple Method, C^*, is calculated using **Equation 2.4**. The first term of the equation represents the amount of the stormwater volume being treated by BMPs within the watershed and requires that the median effluent concentration of each BMP is known. **Table 2.3**, above, displays median effluent concentrations of different BMPs from the International BMP Database (Leisenring et al. 2014). The second term of the equation represents the amount of the stormwater volume bypassing all BMP treatment and remaining at the value of the previous land use concentration, C_{LU}.

$$C^* = \sum_{i=1}^{n}\left(T_i * \epsilon_i * C_{BMP,i}\right) + C_{LU}\left[\left(1 - \sum_{i=1}^{n} T_i\right) + \sum_{i=1}^{n}\left(T_i * (1 - \epsilon_i)\right)\right] \quad \textbf{Equation 2.4}$$

After including BMPs into the Simple Method, the final equation was developed and displayed as **Equation 2.5**. The only changes between this equation and the one displayed in **Equation 2.1** is the ΔV parameter which is accounting for the changes in stormwater quantity that BMPs provide and C^*, which accounts for the changes in stormwater quality due to treatment provided by BMPs.

$$L = 0.226 * P * Pr * Rv * Vr * C^* \quad \textbf{Equation 2.5}$$

By collecting the inputs for **Equation 2.5** for each 30-m cell, applying the equation and then aggregating the results of an area of interest, the nutrient load from stormwater could be determined including any effects BMPs may have on the final load.

2.2.3: Evaluating the Method with Study Sites in Fort Collins

Once the approach for estimating nutrient loads from stormwater with and without including BMPs was created, it was necessary to evaluate the approach and determine the level of accuracy a simple methodology such as this could provide. In order to test the approach two sites, Howes and Udall, were evaluated within Fort Collins, CO. Both sites were urban watersheds of approximately 1 sq. mile and each drain to a wetland basin BMP. **Figure 2.4** displays a map showing the relative location of the Howes and Udall sites.

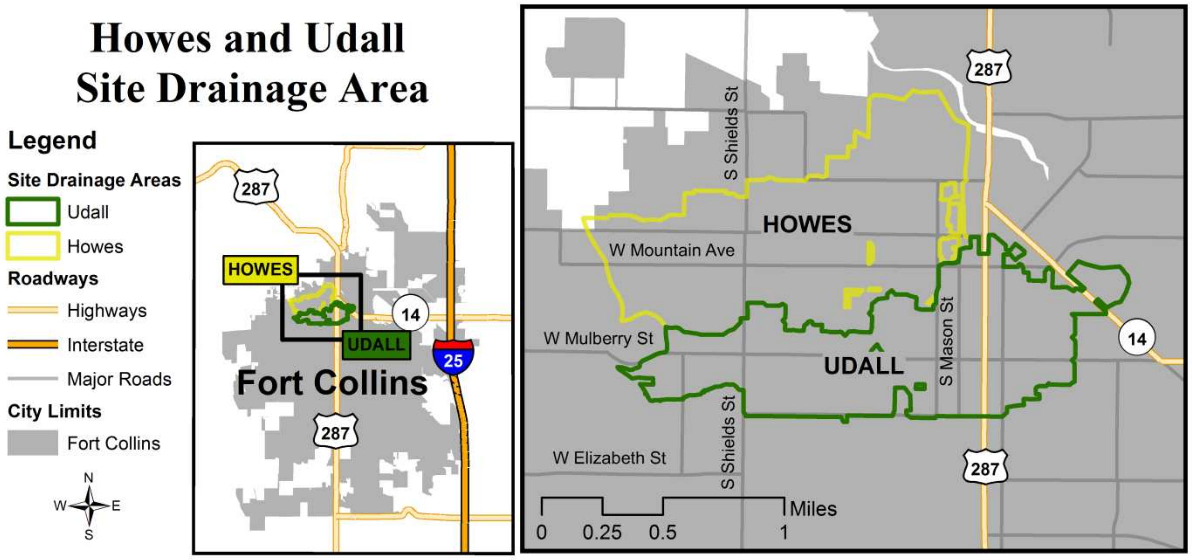

Figure 2.4: Howes and Udall BMP Drainage Areas in Fort Collins

These sites were chosen because of their readily available concentration and flow data for several events in the years 2009, 2010 and 2011. Concentration and flow data was available at both the inflow and outflow of the wetland basin BMP. The inflow of the wetland BMP represented the runoff load for the entire drainage area of the watershed and was compared to the Simple Method proposed in **Equation 2.1**. The outflow of the wetland BMP represented the runoff load including the effects of the BMP and was compared to the Simple Method modified to include the effects of BMPs and calculated using **Equation 2.5**. **Appendix A** displays the data that was available for both the Howes and Udall sites at the inflow and outflow of each.

Both sites were used to evaluate the models performance for predicting an average annual load using PRISM precipitation normals, an annual load using calculated annual precipitations from PRISM, and an event load using recorded event precipitations at the site. One problem that arose from using these sites however was that neither of the sites provided concentration and runoff flow values for every event in a given year. Therefore any attempt to evaluate the proposed approaches ability to model annual loads could not be done with the available monitored data. In order to overcome this obstacle annual loads were estimated from measured events and were used to compare to the annual results of the proposed approach.

For both sites, average annual loads as well as annual loads were predicted for years 2009, 2010, and 2011 using the proposed approach for both runoff loads without including the effect of BMPs and runoff loads including the effect of BMPs. Since there was no annual data available for either site, the results of the model were compared deterministically to results acquired by performing other analysis. The comparison was made to annualized loads from the observed data at the Howes and Udall sites. These annualized loads were created by using **Equation 2.6**. **Equation 2.6** uses the measured loads with their corresponding precipitations as a proportion to be used with the measured annual precipitation to determine an annual load. Using this method assumes that the monitored events represent a proportionate sample of the annual load.

$$Annual\ Load = \frac{\sum Event\ Loads}{\sum Event\ Precipitation} * Annual\ Precipitation \qquad \textbf{Equation 2.6}$$

Since annual loads could not be compared to any measured loads directly, it was important to test the validity of the approach for event loads which were measured. Event loads were predicted for each event for both sites and for runoff without the influence of BMPs and runoff with the influence of BMPs using the proposed approach. When using the approach for event based modeling, there are a few differences from the annual process. The main difference is that Pr is assumed to be 1 instead of 0.9 since it is known that runoff occurred for the event. Also in event loads there is more variability due to the processes of nutrient build up and wash off, storm intensities and even storm distribution over large watersheds.

Expected values for predicted event loads were compared to measured event loads for both sites. All values were compared and measured for relative bias, relative error, as well as root mean square error using **Equation 2.7**, **Equation 2.8**, and **Equation 2.9** respectively (Gupta et al. 1998). Relative bias was used as a measure to determine whether the model was providing an overestimate or underestimate of the event loads. Relative error compared the mean observed to the mean predicted load and was a valuable metric for providing insight into how the model could possibly perform on an annual basis since annual loads tend to follow trends of the mean of the event loads. Finally, the root mean square error normalized by the mean observed value was used a value for overall error of the model versus the observed event loads.

$$Relative\ Bias = \frac{1}{n}\sum_{i=1}^{n}\frac{Observed_i - Predicted_i}{Observed_i}$$ **Equation 2.7**

$$Relative\ Error = \frac{\overline{Observed} - \overline{Predicted}}{\overline{Observed}}$$ **Equation 2.8**

$$nRMSE = \frac{\sqrt{\frac{1}{n}\sum_{i=1}^{n}(Observed_i - Predicted_i)^2}}{\overline{Observed}}$$ **Equation 2.9**

2.2.4: Performing the Monte Carlo Simulation

After errors were calculated deterministically, uncertainty bands were calculated for each event stochastically using Monte Carlo simulation. For the Monte Carlo simulation, the land use concentrations, BMP effluent concentrations, and parameters of the fitted linear regression used for calculating the Rv coefficient were considered random. Concentration values for both TN and TP for each land use category and the effluent of the wetland basin were fitted to lognormal distributions from data provided by Wright Water Engineers from their Regulation 85 Data Gap Analysis (Pitt and Roesner 2013), and from the International BMP Database (Leisenring et al. 2014). Distributions for the parameters of the linear regression were created from the 44 sites used to create the linear regression presented in Schueler 1987.

The Monte Carlo simulation was ran for 4 different load types, total nitrogen without including BMPs, total phosphorus without including BMPs, total nitrogen including BMPs and total phosphorus including BMPs. For each event within the different load types the Monte Carlo simulation performed 10,000 runs of the model. For the 6-7 inputs that were considered random, 10,000 random selections for each input were chosen from their respective distributions. From the 10,000 model runs uncertainty bands were created for each event from each of the load types. Observed loads from each event within the different load types were compared to its respective 95% prediction interval from the Monte Carlo simulation to test for inclusion.

2.2.5: Performing the Bayesian Statistical Analysis

After the Monte Carlo simulation was ran for each of the 4 different load types, a Bayesian statistical analysis was performed in order to reduce the uncertainty bands. The Bayesian method is based on the Bayes Theorem which allows for the distribution of random variables to be modified by considering observed data.   Bayes Theorem, as presented in **Equation 2.10**, states that a new posterior distribution of a random variable is proportional to the product of the prior probability of a given random variable $P(\theta)$, multiplied by the likelihood that the observed data occurred with that random variable, $l(\mathrm{E}|\theta)$ (Vrugt 2016).

$$P(\theta|y) \propto P(\theta) * l(\mathrm{E}|\theta) \qquad \textbf{Equation 2.10}$$

The likelihood function represents the likelihood of producing model residuals, E, for a given set of random variables that are model parameters (Box and Tiao 1992). Assuming that residuals are normally distributed and independent with a mean of zero the likelihood function is could be calculated using **Equation 2.11**. However, the errors from the Monte Carlo simulation were not normally distributed, but more lognormally distributed, which required that the likelihood function be transformed to the log likelihood function.

$$l(\mathrm{E}|\theta) = \prod_{i=1}^{n} \frac{1}{\sqrt{2\pi\sigma_e^2}} \exp\left[-\frac{(\hat{y}_i(\theta) - y_i)^2}{2\sigma_e^2}\right] \qquad \textbf{Equation 2.11}$$

The log-likelihood function is shown in **Equation 2.12** (Box and Tiao 1992). The log-likelihood function acted as a method for weighting the probability of each random variable being selected from its prior distribution and resulting in the observed load. After using the log likelihood function to determine a value proportional to the probability of the new posterior distribution, the values were normalized to reflect the actual probability of posterior distributions of the random variables. This process resulted in new distributions being created for all of the random variables with parameter sets yielding modeled loads closer to the observed given a more likely chance of being selected in the Monte Carlo simulation.

$$l^*(\mathrm{E}|\theta) = -\frac{n}{2}\ln(2\pi) - \frac{1}{2}\ln\sigma_e^{2n} - \frac{1}{2}\sigma_e^{-2} * \sum_{i=1}^{n}(\hat{y}_i(\theta) - y_i)^2 \qquad \textbf{Equation 2.12}$$

Once the new distributions were created, the Monte Carlo simulation was performed using the new distributions for generating the random variables. The results of the second run of the Monte Carlo simulation were compared to the first to provide a point of reference of how using observed data could potentially reduce the uncertainty within the model.

2.3: Results

The proposed approach of using the Simple Method for modeling stormwater loads and using a modified version of the Simple Method to include the effects of structural BMPs was evaluated at two different study sites in Fort Collins. The approach was evaluated for modeling both annual and event based loads from urban watersheds. As discussed above, observed annual loads were not available for comparison to the provided approach, but were estimated using an extrapolation of recorded events. Estimated loads were compared to modeled loads using PRISM average annual precipitation as well as PRISM annual precipitation. **Table 2.4** displays the results of the comparison for the total nitrogen estimations. From the table it is observed that the proposed method overestimates the amount of annual load without including BMPs and is much closer to the observed amount when including the effect of BMPs. There may even be an underestimation of total nitrogen when including the effect of BMPs. However, both models do display the appropriate order of magnitude of loads.

Table 2.4: Comparison of annual total nitrogen loads

Scenario	Year	Total Nitrogen Load (lbs)		
		Annual load from proportion of event data	Simple Method using average annual precipitation	Simple Method using measured annual precipitation
Howes without BMPs	2009	-	2300	3182
	2010	1241		2005
	2011	1232 *		2530
Udall without BMPs	2009	3918 *	2418	3361
	2010	1753		2118
	2011	1329 *		2672
Howes with BMPs	2009	1268 *	930	1287
	2010	786		811
	2011	1974 *		1023
Udall with BMPs	2009	3967 *	1033	1436
	2010	1340		905
	2011	934		1142

** Annual load was created using proportion of 2 or fewer observed events*

Table 2.5 displays the results for the total phosphorus estimations. With phosphorus, the predicted loads followed more closely the estimated observed loads, but still contained a general over-prediction of total phosphorus without including BMPs and a slight under-prediction of loads when including BMPs. However, the proposed approach was able to capture the general magnitude of the annual phosphorus load.

Table 2.5: Comparison of annual total phosphorus loads

Scenario	Year	Total Phosphorus Load (lbs)		
		Annual load from proportion of event data	Simple Method using average annual precipitation	Simple Method using measured annual precipitation
Howes without BMPs	2009	-	249	345
	2010	159		217
	2011	50 *		274
Udall without BMPs	2009	459 *	266	370
	2010	176		233
	2011	45 *		294
Howes with BMPs	2009	123 *	81	112
	2010	91		71
	2011	478 *		89
Udall with BMPs	2009	329 *	90	125
	2010	43		79
	2011	125 *		99

** Annual load was created using proportion of 2 or fewer observed events*

Annual nutrient loads represent an easier metric for users to identify BMP practices that have the potential to reduce or, in some cases, increase nutrient loads based on implementation. Also, in the case of creating nutrient budgets, it is annual loads which are beneficial for comparing the contribution of urban stormwater to other sources. As seen from the comparison of the model to extrapolated events, the magnitude of the estimated load is approximately correct. It should also be noted that for many of the extrapolated loads 2 or fewer events were used to create the estimate of observed loads.

Events for stormwater loads without the effect of BMPs and for stormwater loads including the effects of BMPs were compared to observed loads from the Howes and Udall watersheds. After comparing the predicted outputs using the proposed approach and the observed loads, bias and RMSE were calculated. **Table 2.6** displays the relative bias, relative error and normalized RMSE calculated for the event loads.

Table 2.6: Relative bias, relative error and normalized RMSE between observed and estimated event loads

Scenario	Relative Bias	Relative Error	nRMSE
Total Nitrogen without BMPs	-130%	-57%	107%
Total Phosphorus without BMPs	-351%	-70%	124%
Total Nitrogen with BMPs	-36%	5%	77%
Total Phosphorus with BMPs	-99%	23%	113%
All Total Nitrogen Events	-83%	-32%	100%
All Total Phosphorus Events	-239%	-40%	125%

After performing the statistics on the event data, it is seen that there is a negative relative bias in the method for calculating nutrient loads without including BMPs and nutrient loads including BMPs. This means that the method is demonstrate a bias for over predicting the amount of nutrient load from urban stormwater. Since events contain much more variability then annual loads the errors of the mean observed load and mean estimated load were calculated and displayed as the relative error statistic. Smaller values of relative error as seen could mean that the method would produce better results for an average annual load as opposed to the event modeling since trends in the average annual loads are better seen in trends of the mean event loads. Also, as displayed by the nRMSE it was determined that the method can predict event loads to the order of magnitude resolution.

However, since these models are built around uncertain and random variables, particularly when considering the pollutant concentrations and runoff volume coefficient, it was desired to evaluate some of the uncertainty associated with the proposed approach. For each of the events uncertainty bounds were created using a Monte Carlo simulation approach by creating 10,000 random parameters from the available distributions of the random variables. The 10,000 random parameters were then used with the method to develop an estimate of the total nitrogen and total phosphorus load for each event.

After performing the Monte Carlo simulation, large uncertainty bands were discovered when using this method to estimate stormwater loads. Even with the large uncertainty bands, when the 95th percentile was calculated for each event it was found that the inclusion rates were lower than expected. The inclusion rate for each of the scenarios depicted by the figures is 45%, 45%, 90%, and 73% respectively. Most of the points that did not fall within the 95th percentile resulted from an overestimation of the nutrient load; however, there are a few scenarios where the observed event load exceeded the 95th percentile range.

Since the method yielded such large bands of uncertainty, it was determined that an approach should be analyzed for reducing the uncertainty bounds. This was accomplished using the Bayesian statistical method. After performing the method new distributions for the known random variables were changed. **Figure 2.5** displays a subplot of how each of the distributions changed. **Figure 2.5** contains the prior and posterior CDFs of each of the accounted for random variables. The steeper CDF in the posterior distribution represents a narrower distribution that was created by including the observed loads for the events using the Bayesian statistical analysis.

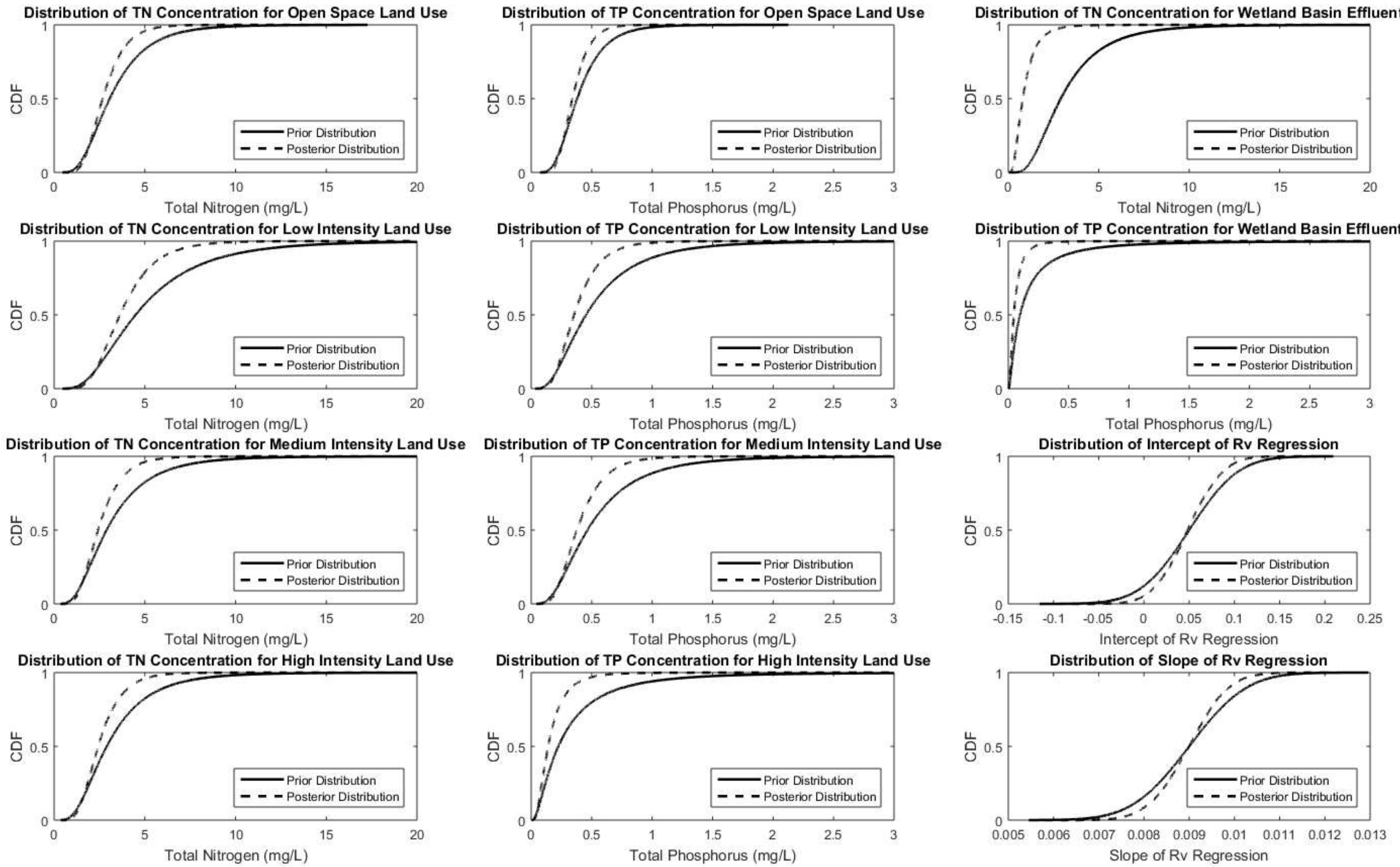

Figure 2.5: CDFs of prior and posterior distributions of all random variables for the Monte Carlo simulation

These narrower posterior distributions resulted in smaller uncertainty bands after using the posterior distributions to run another Monte Carlo simulation. For the second Monte Carlo simulation 10,000 random parameter sets were selected from the posterior distributions of the random variables instead of the prior distributions. This resulted in a dramatic reduction for the spread of the predicted loads from the Monte Carlo simulation. **Figure 2.6-2.9** display the uncertainty bands as characterized by the 95^{th} percentile prediction interval or the interval between the 2.5 percentile and the 97.5 percentile. The uncertainty bands from the Monte Carlo simulation using both the prior and posterior distributions are displayed in the figures as well as the median from the Monte Carlo simulations and the observed load for each event.

Figure 2.6-Figure 2.9 display the uncertainty bands for each of the four scenarios, total nitrogen without including BMPs, total phosphorus without including BMPs, total nitrogen with including BMPs and total phosphorus with including BMPs respectively. The uncertainty bands using the posterior distributions can be seen as much narrower than bands created using the prior distribution. However, with the decrease in the uncertainty bands there was also a reduction of the inclusion rates in the both scenarios including the effects of BMPs. The inclusion rates decreased to 60% for total nitrogen and 40% for total phosphorus in the models including the effects of BMPs.

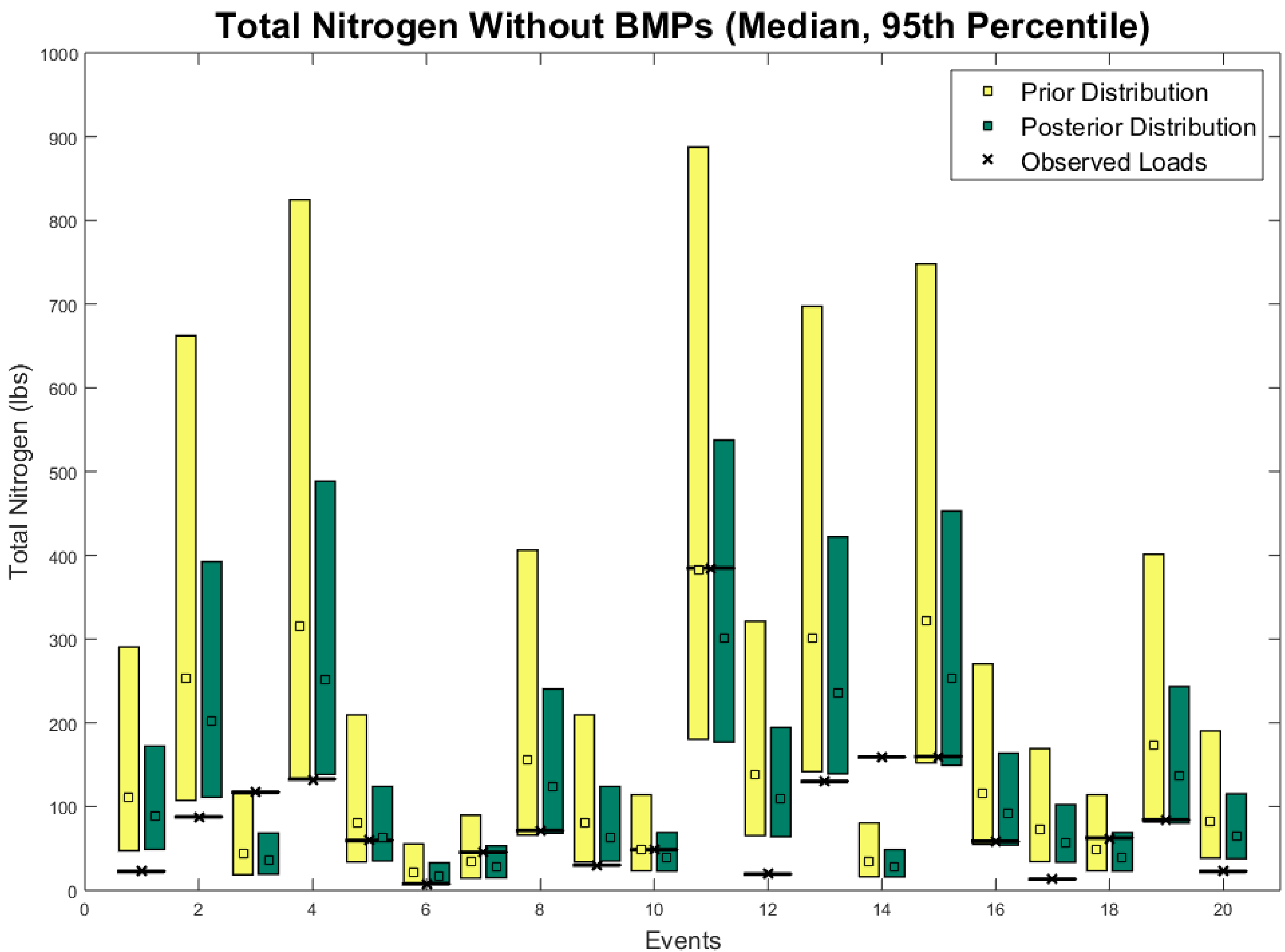

Figure 2.6: Uncertainty bands represented by the 95th percentile prediction interval for both the prior and posterior runs of the Monte Carlo simulation for total nitrogen events without BMPs

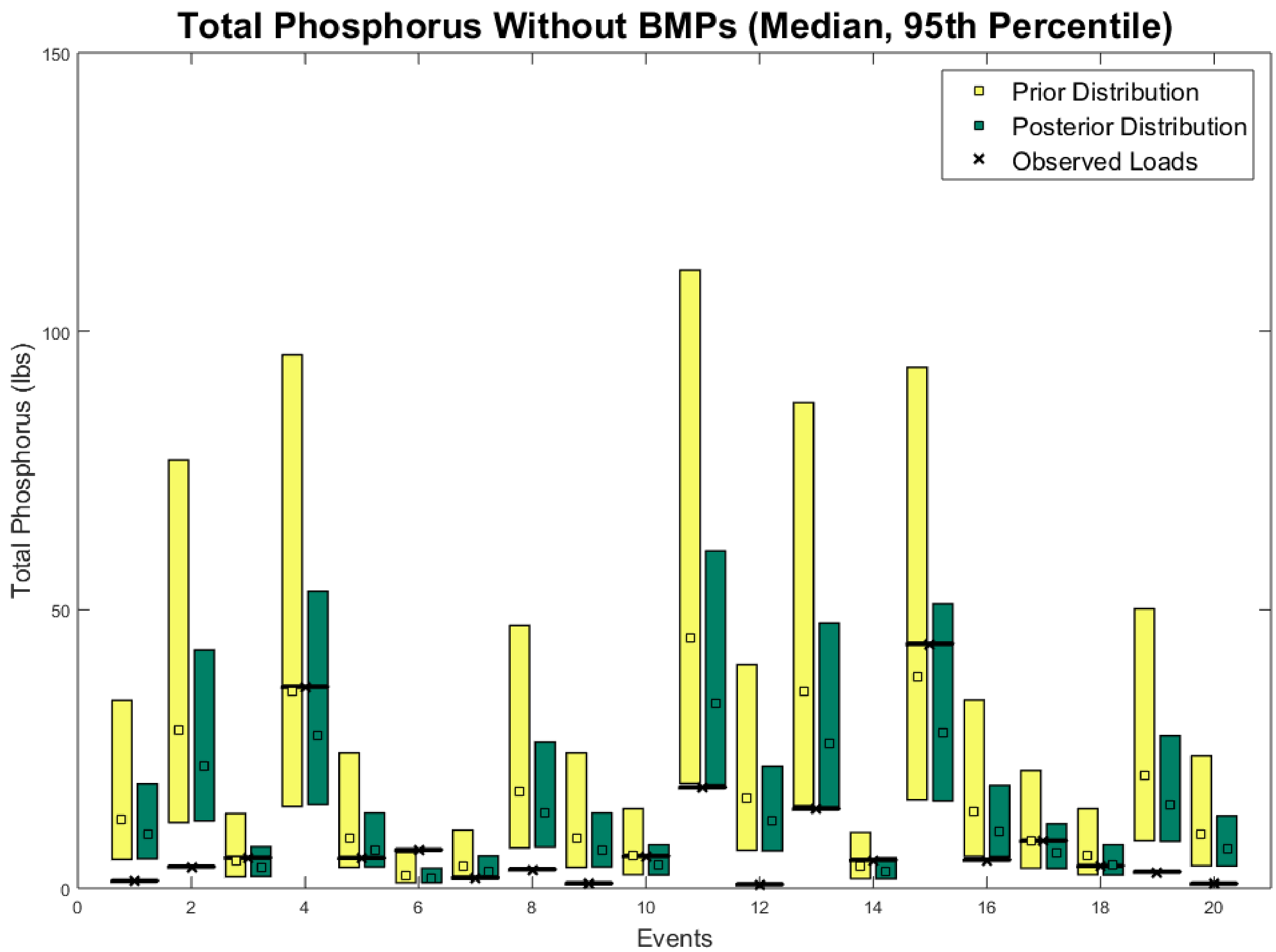

Figure 2.7: Uncertainty bands represented by the 95th percentile prediction interval for both the prior and posterior runs of the Monte Carlo simulation for total phosphorus events without BMPs

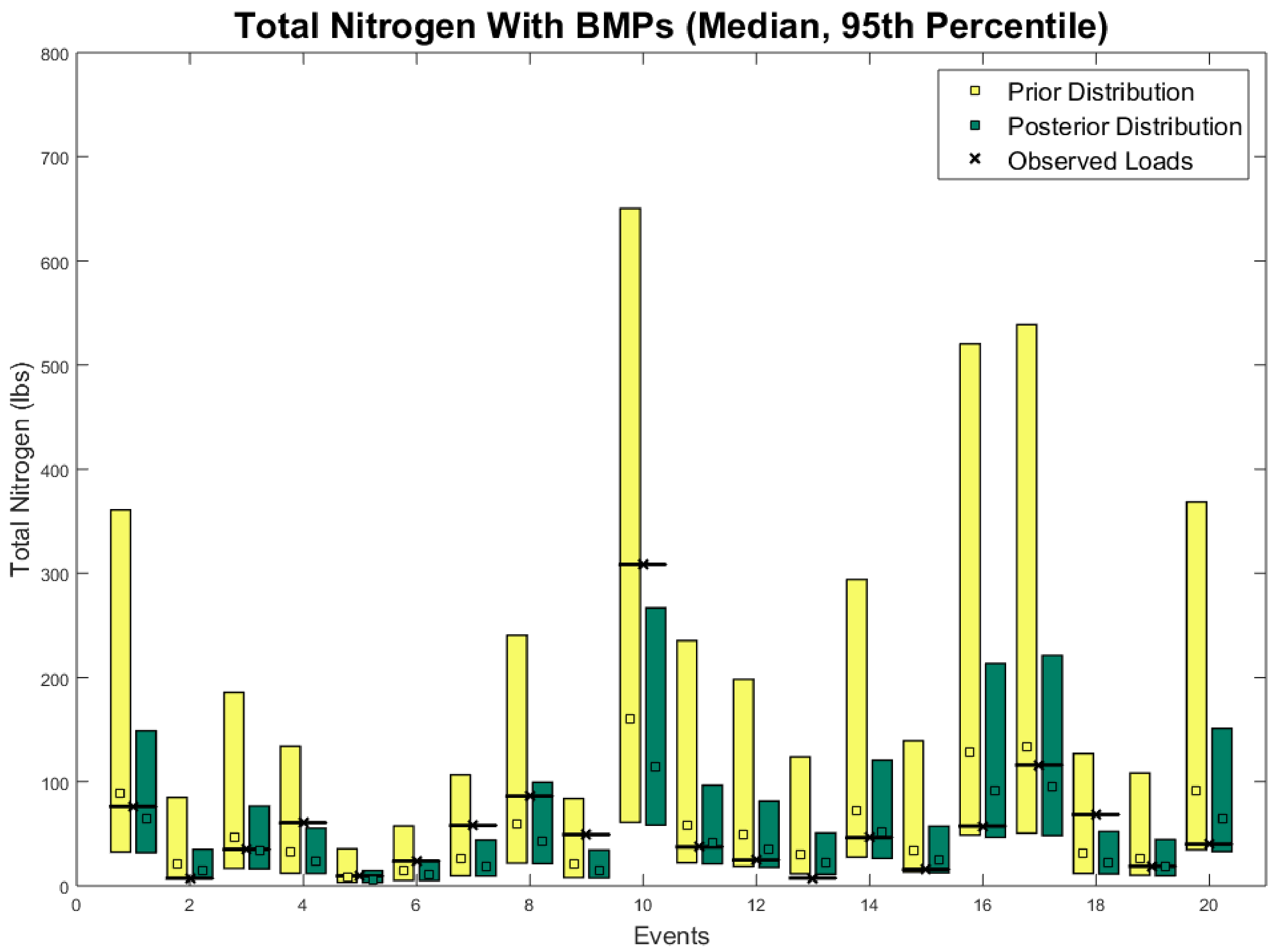

Figure 2.8: Uncertainty bands represented by the 95th percentile prediction interval for both the prior and posterior runs of the Monte Carlo simulation for total nitrogen events with BMPs

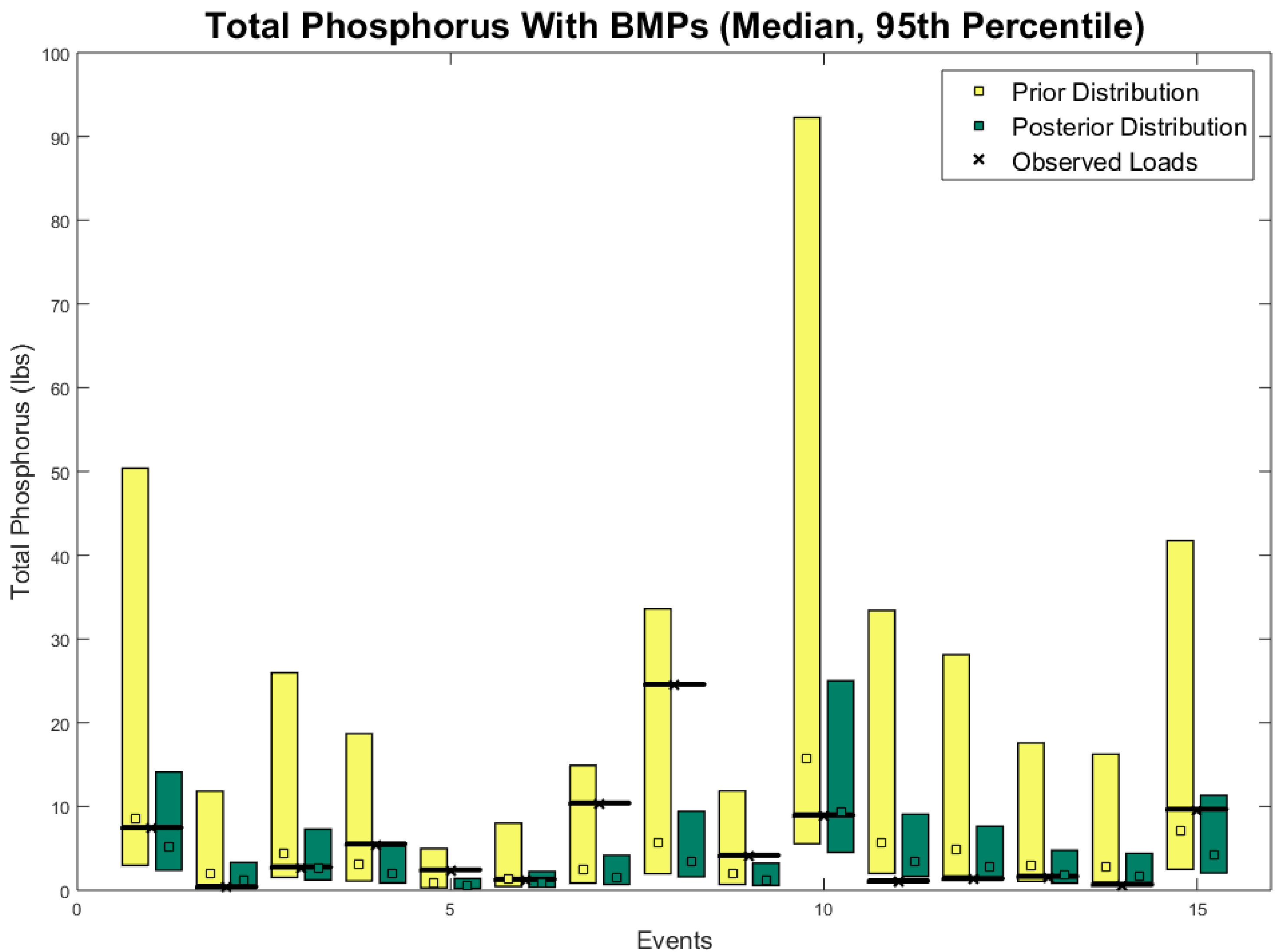

Figure 2.9: Uncertainty bands represented by the 95th percentile prediction interval for both the prior and posterior runs of the Monte Carlo simulation for total phosphorus events with BMPs

2.4: Discussion

As stated in the objectives, it was desired to develop a simple approach to rapidly estimate nutrient loads from urban stormwater using readily available inputs from national datasets to allow for adoption of the method across the nation. It was also desired to allow the method to be modified to incorporate the effects of structural BMPs. After evaluating the proposed method as outlined, several conclusions were made based on the validity of the approach, limitations of the approach, as well as propositions for future work.

2.4.1: Validity of Proposed Method

After evaluating the proposed approach for annual loads, it was determined that the method could be used for planning level analysis for urban stormwater plans. This was concluded based on the comparison of predicted loads with the estimated observed loads for the two sites. This method has two main uses, developing a prediction of the annual urban stormwater load for creating nutrient budgets, or for allowing users to understand approximate changes that could result from implementing different BMPs across the watershed. However, do to the large amounts of uncertainty found from the event based modeling, the result from a simple approach such as this is not recommended to be used for final decision making. Instead a simple method like this should only inform the user what BMP technologies could be explored further using some of the more advanced modeling programs like SWMM.

Evaluating the method for event based loadings was conducted due to the lack of observed annual loads, and the need to be able to evaluate the performance of the method and determine what level of uncertainty was associated with the method. The main difference between event loads and annual loads is the nature of the variability that is present in event loads. When loads are annualized there is a level of variability that is reduced due to the combination of events that result in greater than expected loads and smaller than expected loads. Also, for each storm there are characteristics of the storm such as storm intensity, rainfall distribution, pollutant build-up and inter-event time that can affect the amounts of runoff as well as the quality of the runoff.

After performing the Monte Carlo simulation for the method it was observed that the uncertainty bands of the method were quite large when compared to the magnitude of the estimated value. This large uncertainty band was the result of uncertain parameters regarding the Rv coefficient and pollutant concentration for each land use type as well as for the effluent concentration from the BMP. Rv coefficients contain uncertainty as a result of trying to capture complex infiltration patterns with a single number based on imperviousness, but does not include soil types or water content characteristics. Rv coefficients also do not capture any run on processes that occur when runoff from impermeable surfaces flows over permeable surfaces where water is given additional opportunity to infiltrate. There is also uncertainty in the pollutant concentration for each land use and for the BMP effluent. This uncertainty is a result of different uses of land resulting in varying levels of build-up of pollutant. By applying concentration values to land use groups help reduce this uncertainty, but as seen from the analysis still contains substantial uncertainty.

By looking at the poor inclusion rate it was also determined that there was a level of uncertainty not captured in the Rv coefficient and the pollutant concentration. Since 95^{th} percentile prediction intervals were calculated, the inclusion rate should have been approximately 95%. One additional source of uncertainty which could expand the prediction interval to capture more of the observed values could be precipitation, which was assumed to be known. Each observed load had a recorded precipitation value from a nearby rain gauge. There is uncertainty in the accuracy of the measurement of the gauge, in how closely the rain gauge value represents the value for the area of interest, and the spatial distribution of rainfall across the entire area of interest. Though it is understood that these uncertainties exist, it was not possible to accurately quantify the uncertainty from these sources.

In the approach used to evaluate nutrient loads including the effect of BMPs, there were also parameters that were assumed to be known but which actually contained uncertainty. These included the volume reduction coefficient and BMP treatment efficiency as well as the uncertain variables described above. However since there was no available data to justify an assumption of a distribution or even bounds for these variables, uncertainty from these variables were not included in the Monte Carlo simulation. Even though some variables were not included in the analysis, the Monte Carlo simulation still revealed a large amount of uncertainty that would need to be addressed if this approach was desired to be used for more than planning purposes as recommended.

One reason why it is recommended for users to use this method for planning purposes is a direct result of the large bands of uncertainty and the increase in cost associated with it. If a user would want to make a decision for the amount of BMPs to install, they would need to install enough BMPs to treat the stormwater to the most conservative amount as developed by the uncertainty bounds. When uncertainty bands are large, it results in increased costs. A user may be able to diminish the uncertainty bands using observed data with a Bayesian statistical analysis as displayed in this paper. Another way a user could diminish uncertainty would be by using a more complex model before making a final decision.

Even though all of the uncertain variables were not included in the Monte Carlo and Bayesian analysis, it was still useful to determine what effect having observed values could do for reducing the bands of uncertainty of the method. The Bayesian analysis resulted in dramatic reduction of the uncertainty and, assuming all of the random variables were included in the analysis, would have been able to narrow the bands of uncertainty around the observed loads.

Though this model is not recommended to use for a final decision regarding BMP implementation, it could be used to determine which BMPs should be evaluated more intensively. The proposed approach provides a user with an order of magnitude estimate for runoff loads as well as how that load could potentially change as a result of BMP adoption. It should be noted that with the large positive bias without BMP inclusion and slight negative bias with BMP inclusion that comparing one model to the other could result in an appearance of greater nutrient removal than actually provided by the BMP. Overall, this approach accomplished the objectives of creating a simple framework or approach that could be easily understood by users without much modeling experience for calculating urban stormwater nutrient loads for watersheds using readily available national datasets.

2.4.2: Limitations of the Approach

Even though the described approach accomplished the objectives set forth in this paper, there are some limitations to using the approach. The first limitation or consideration is found in the level of accuracy of the input data from the NLCD national datasets and PRISM datasets. Both datasets provide some of the best currently available data for their respective fields, however, there is still an amount of error in land use classification, imperviousness, and precipitation amount. There are also errors in the provided concentration data, particularly trying to use concentrations collected at other sites with different climate conditions and different site characteristics. As discussed above there is also uncertainty in the model process when using simple factors like Rv and Pr to describe complex processes.

Another limitation of this study is the accuracy of the comparison event load data. For this study, observed loads were treated without uncertainty when in reality there is uncertainty in the recorded EMC and in the measured runoff volume. There is also uncertainty in creating a load by multiplying the runoff volume by an EMC. So even though there were cases where the observed nutrient load was not included in the uncertainty band, there is a chance that some of the true values may fall within the 95^{th} percentile prediction interval. There is also the possibility, however, that the true value of measured loads which currently are contained by the 95^{th} percentile actually fall outside of the 95^{th} percentile.

The Simple Method also has some limitations incorporated with it. The Simple Method's main use is for assessing and comparing the relative stormwater pollutant load, and though it may come close to the true value, it ultimately should only be used when an understanding of the relative magnitude of the load is needed (SMRC, 2014). The Simple Method also does not include any baseflow considerations, which comes into effect when considering larger watersheds. Since the goal of this method was to quantify the stormwater runoff nutrient load, baseflow was not a consideration, but in order to correctly budget the watershed load, baseflow should be included in some analysis. Baseflow will also have a larger effect if structural BMPs were installed in a watershed providing more infiltration which would ultimately result in more groundwater flow.

The final limitation of the proposed method is that it cannot incorporate double treating a particular area of the watershed. Therefore if there is ever runoff treated by a BMP and that BMPs effluent runs into another BMP, it is not possible to include that redundant treatment. This limitation once again places emphasis on using the proposed method for planning purposes looking at how loads will relatively change with new BMP treatment in untreated areas.

2.4.3: Future Work

In response to some of the limitations of the proposed method is future research that could be done to address these limitations. One of which is improving some of the inputs of the method such as imperviousness (Endreny and Thomas 2009b). There are other enhancements to the method that could be investigated such as changing the amount of precipitation used for load estimation (Ulasir and Kaiser 2011). There are other possibilities of adjusting the process used by the Simple Method for predicting runoff either by using different Rv values (California Department of Transportation (CalDOT) 2015), or even by using a different method such as the curve number method.

Other work that needs to be done is the observation of nutrient loads from large urban watersheds draining to urban creeks where there are only stormwater and baseflow sources. This requires more monitoring efforts, not necessarily at sites but at the outflows of watersheds. Also when these outflows are monitored it is important to catalog the locations and treatment drainage area of current BMPs within the watershed to allow for the inclusion of their effects in the modeling effort. With more observed data, it could be possible to estimate the distributions of some of the additional random variables in the method as well as allow the uncertainty of the method to be reduced using Bayesian statistical analysis. More observed data is also needed to evaluate the method with multiple structural BMPs and varying sized watersheds.

2.5: Conclusions

By understanding the magnitude of nutrient loads a source is providing it becomes possible to understand where and how to address nutrient pollution effectively. For this study, the source of interest was urban stormwater. As a first approach, a simple framework for which a level of magnitude estimate of nutrient load from stormwater could be determined was developed. Included in the approach were the capabilities of incorporating the effects of structural BMPs since structural BMPs are playing a larger role in the treatment of stormwater.

The provided approach accomplished the objectives of creating a simple model which could rapidly estimate nutrient loads from stormwater in any given watershed or area of interest. By using a simple approach, it is easy to understand regardless of a user's background in modeling. Also, since all of the inputs for the method are available through national datasets, it accomplished the objective of being an approach that could be applied to anywhere within the United States. Even though, the approach could be applied anywhere in the United States, it should be noticed from the evaluation of the method, that applying it in locations with comparison data could potentially decrease the uncertainty of the method. This was displayed in the dramatic reduction of the uncertainty bands after performing the Bayesian statistical analysis. The Simple Method was also adapted to include the effects of stormwater BMPs, allowing users to conduct a planning level analysis for which BMPs have the potential to reduce nutrient loads.

Once the framework was developed it was necessary to evaluate the accuracy of the method for predicting nutrient loads. Since there was no available annual nutrient data, it was not possible to validate the model on the annual basis, but was evaluated by comparing event loads. From this analysis it was determined that the proposed approach would only be applicable for estimating the order of magnitude of nutrient loads. This was determined from the recorded root mean square error when comparing observed event loads to the estimated values from the model deterministically. Another error statistic, relative error, displayed a measure of the error in the means of the observed events to the mean of the estimated event loads. Since this error statistic was lower than the other statistics it demonstrates that errors in the annual loads may also be smaller than the event loads since annual loads follow the trends of the mean event loads.

The Monte Carlo simulation revealed large bands of uncertainty surrounding the prediction which was expected due to the simplicity of the model. However, after conducting a Bayesian statistical analysis it was found that the uncertainty bands around the estimate could be substantially reduced using observed data within an area of interest. From the large uncertainty bands, overall, it was determined that the proposed approach be used for planning level purposes only where order of magnitude estimates are appropriate.

Further research should include evaluating the proposed approach for load estimation in other urban watersheds of varying sizes utilizing different structural BMPs and green infrastructure. This would require a watershed to have readily available data regarding the nutrient load being exported by urban sources within the watershed. Additional work could also be conducted to further quantify uncertainty in some of the random variables such as precipitation.

CHAPTER 3: QUANTIFICATION OF THE IMPLEMENTATION OF STRUCTURAL STORMWATER BEST MANAGMENENT PRACTICES USING NATIONAL LAND COVER DATABASE LAYERS

3.1: Introduction

Over the past several decades countries around the world have been urbanizing non-urban areas. This increase in urbanization has resulted in the degradation of water quality. After becoming aware of the strain that urban areas can place on water quality, the United States began to pass laws and regulations addressing the problem. Newer regulations have been adopted targeting urban stormwater. Many local public agencies are now required to insure that structural best management practices (BMPs) are being built and maintained in any newly developed or redeveloped areas. Studies have found that structural BMPs are affecting both the quantity and quality of runoff within an urban watershed. Therefore, any attempt to model urban watersheds should contain information regarding the extent of urban areas being treated by structural water quality BMPs.

3.1.1: Background

Over the past century urbanization has increased in the United States. The population living in urban areas has increased from 40 percent in 1900 to more than 80 percent in 2010 (USEPA 2011). Larger populations living in cities has resulted in a 59% increase in the amount of urban area from 1982 to 2012 (USDA 2015). Urbanization causes the amount of impervious area to increase which increases the volume of runoff, increases peak runoff rates, as well as increases the flow velocity (Hall and Ellis 1985). According to Novotny (2011), urbanization results in an increase of flooding, increase in diffuse pollution , and the deterioration of the habitat of urban streams. The National Urban Runoff Program (NURP) found that urban areas also result in an increase in pollution loads that can be harmful to receiving water bodies (USEPA 1983). The U.S. Geological Survey (1999) found that urban streams have higher frequencies of occurrence of harmful pollutants such as DDT, complex mixtures of pesticides, and elevated phosphorus levels.

3.1.2: Regulations

As the U.S. government became aware of the harmful effects of urbanization, it began to pass laws and regulations to mitigate these effects. Laws and regulations resulted in the development of the national Pollutant Discharge Elimination System (NPDES) permit program to control the discharge of pollutants from point source discharges. The Water Quality Act of 1987 resulted in an expansion of NPDES permits to include urban stormwater for large municipal separate storm sewer systems (MS4s) (USEPA 2000a). MS4s are defined as any conveyance or system of conveyances that are owned or operated by a State or local government entity and are designed for collecting and conveying stormwater and are not part of a publicly owned treatment work or combined sewer. The Stormwater Phase I Final Rule, implemented in 1990 for MS4s serving populations of 100,000 or more required that permitted MS4s reduce pollutants in urban stormwater to the “Maximum Extent Practical (MEP)”. MS4s also must control stormwater discharges from new developments and redevelopments greater that one acre (USEPA 2000a).

In 1999, the EPA released the Stormwater Phase II Final Rule. The Phase II program expanded the Phase I program by requiring additional operators of small MS4 systems (serving a population of less than 100,000) to also be issued and comply with an NPDES permit (USEPA 2000b). Similar to the Phase I permits, Phase II NPDES stormwater permits required operators to reduce pollutants in urban stormwater to the “Maximum Extent Practical (MEP)” and that MS4s control stormwater discharges from new urban development and redevelopment greater that one acre (USEPA 2000c). Phase II NPDES permits also required the development of a program to ensure the installation of water quality Best Management Practices (BMPs) in any new developments or redevelopments (USEPA 2000d).

3.1.3: Effects of Water Quality BMPs

After the regulations, the EPA published a list of BMPs recommended to MS4 permittees (USEPA 2002). Structural BMPs that meet measures for newly developed or redeveloped areas included dry and wet ponds, constructed wetlands and Low Impact Development practices (LID). LID refers to practices that allow an urban watershed to mimic a natural watershed in quantity and quality through processes of infiltration, evapotranspiration, and filtration (Prince George's County 1999). Ahiablame et al. (2012) found that commonly used LID practices included bioretention, permeable pavement, green roofs, and swale systems. There has been an extensive effort to learn how structural BMPs and LID practices improve urban watersheds.

Extensive efforts to evaluate the effectiveness of BMP practices has shown that structural BMPs affect both the quantity and quality of runoff (Baird et al. 2014; Bliss et al. 2009; Carleton et al. 2000; Collins et al. 2010; Davis et al. 2009; Deletic and Fletcher 2006; Dietz 2007; Leisenring et al. 2014; Poresky et al. 2011) . BMP effectiveness requires the need to include BMP practices into simulation models to evaluate urban stormwater at varying spatial and temporal scales. The Strom Water Management Model (SWMM), and System for Urban Stormwater Treatment and Analysis INtegration (SUSTAIN) already include the ability to include BMP practices for urban stormwater modeling (Ahiablame et al. 2012). SWMM and SUSTAIN models have been used to simulate, evaluate and even optimize BMP practices within a given urban watershed (Damodaram et al. 2010; Lee et al. 2012; Liu et al. 2016; Perez-Pedini et al. 2005; Zahmatkesh et al. 2015). However, neither of these models attempt to predict where BMPs are currently in use. In most cases, previously built structural BMPs are simulated only when there is a detailed knowledge of where and how each practice is being implemented [see Chesapeake Bay Model, (USEPA 2010), or (Emerson et al. 2005), for example].

When public agencies or municipalities create a stormwater plan to fulfill MS4 requirements, they typically place the responsibility of building BMPs to the land owners or developers [see Fort Collins (City of Fort Collins 2016), for example]. These water quality BMPs (private BMPs) are privately owned and privately maintained. As such, many agencies do not have readily available digitized information of the locations of private BMPs or the total contributing drainage area being treated by private BMPs due to the required time and resources to develop a geospatial layer with this information. This resulting gap of information must be filled in order to provide accurate information to be used in an urban stormwater model.

3.1.4: Objectives

Regulations have been passed requiring structural BMPs be deployed in new developments and redevelopments, and BMPs affect both the quantity and quality of urban stormwater runoff. Therefore, urban stormwater models that need to accurately simulate the current built environment should account for the extent of urban areas being treated by structural BMPs. These BMPs are typically built by private land developers and their locations and drainage areas are not available as a digitized layer. The objectives of this study were to develop and evaluate a novel approach for determining the extent of urban areas for which stormwater runoff is treated by private BMPs. This approach investigates using National Land Cover Database (NLCD) layers to predict areas of new urban development and redevelopment which, by regulations, should also represent areas being treated by water quality BMPs.

3.2: Methods

There were two main objectives of this study. The first objective developed an approach for determining the extent of urban areas being treated by water quality BMPs. The second objective evaluated that approach by comparing all known urban areas being treated by BMPs to estimated values provided by the developed approach within a study area in Fort Collins. The approach involves calculating new urban areas developed after an MS4 enforced all necessary actions of their permit for newly developed and redeveloped areas. Since the MS4 regulations require all new developments and redevelopments to include water quality BMPs, the approach assumes that any new urban land developed after the regulation is treated by BMPs. This assumption was then evaluated by calculating new urban area within a study site, assuming that new urban area represented area being treated by private BMPs, and then comparing the estimated private BMP treatment area with observed areas being treated by water quality BMPs.

3.2.1: Select an Area of Interest for Analysis

The developed approach begins by selecting an urban area for which the drainage area of private BMPs is desired to be estimated. Area of interests could be areas contained by any shape or size, but must be available as a geospatial layer so that all other layers can be analyzed to the same geographic extent as the area of interest. Areas of interest could be delineated by a watershed or sub-basin, by city, county, or state boundaries, or by MS4 boundaries determined by the MS4 permitting authority. The area of interest can be any size; but any parameters or metrics developed by the method will be reported in terms of total urban area and not in terms of the total area of interest. However, if the area of interest is completely classified as urban area as specified by National Land Cover Database (NLCD) layers, then parameters or metrics developed by the method could also be applied in terms of the total area of interest.

3.2.2: National Land Cover Database (NLCD) Layers

NLCD is a national land cover product created by a group of federal agencies known as the Multi-Resolution Land Characteristics consortium. NLCD land cover products are created from Landsat satellite data that has been consistently applied across the nation (MRLC 2015). Currently there are products available as layers for the entire nation for the years 1992, 2001, 2006, and 2011(Fry et al. 2011; Homer et al. 2007, 2015; Vogelmann et al. 2001), and the consortium has plans to continue developing layers for each five year increment. The layers are 30-m resolution raster datasets containing values that represents what land cover is associated with the majority of the cell. The classification system used by NLCD is a modified version of the Anderson Land Cover Classification System (Anderson et al. 1976). NLCD uses two different levels of classification. Level I classifications use eight land cover groups. Level II classifications expand some of the groups to contain a total of sixteen classifications which are displayed in **Table 3.1**.

In evaluating the accuracy of the NLCD products, Wickham et al. (2010) quantified accuracy for how well NLCD correctly classified the 8 groups as well as each of the 16 individual classification. Accuracies for the 1992 NLCD product was measured to be 80% for Level I and 58% for Level II (Stehman et al. 2003; Wickham et al. 2004). In 2001 the NLCD accuracies improved to 85% for Level I and 79% for Level II (Wickham et al. 2010). Accuracies of the 2006 NLCD products were reported as 84% and 78% for Level I and Level II respectively (Wickham et al. 2013). At the time of this research, accuracy calculations were not available for the 2011 NLCD product.

Table 3.1: List of NLCD land use codes with classifications from MRLC 2015

NLCD #	Land Use Classification
11	Open Water
12	Perennial Ice/Snow
21	Developed, Open Space
22	Developed, Low Intensity
23	Developed, Medium Intensity
24	Developed, High Intensity
31	Barren Land (Rock/Sand/Clay)
41	Deciduous Forest
42	Evergreen Forest
43	Mixed Forest
51	Dwarf Scrub *
52	Shrub/Scrub
71	Grassland/Herbaceous
72	Sledge/Herbaceous *
73	Lichen *
74	Moss *
81	Pasture/Hay
82	Cultivated Crops
90	Woody Wetlands
95	Emergent Herbaceous Wetlands

* Alaska only

NLCD is a free and accessible product providing national coverage which results in it being widely used as land cover input data for runoff and concentration modeling (Endreny and Thomas 2009a; Smith et al. 2010). NLCD layers were used to determine areas that were previously non-urban and then later became urban by comparing different years of data. The selection of NLCD layers for comparisons was accomplished using the flow chart in **Figure 3.1**. In order to select the proper NLCD layers to use in the method, it is important to know the year MS4 regulations were adopted requiring water quality BMPs.

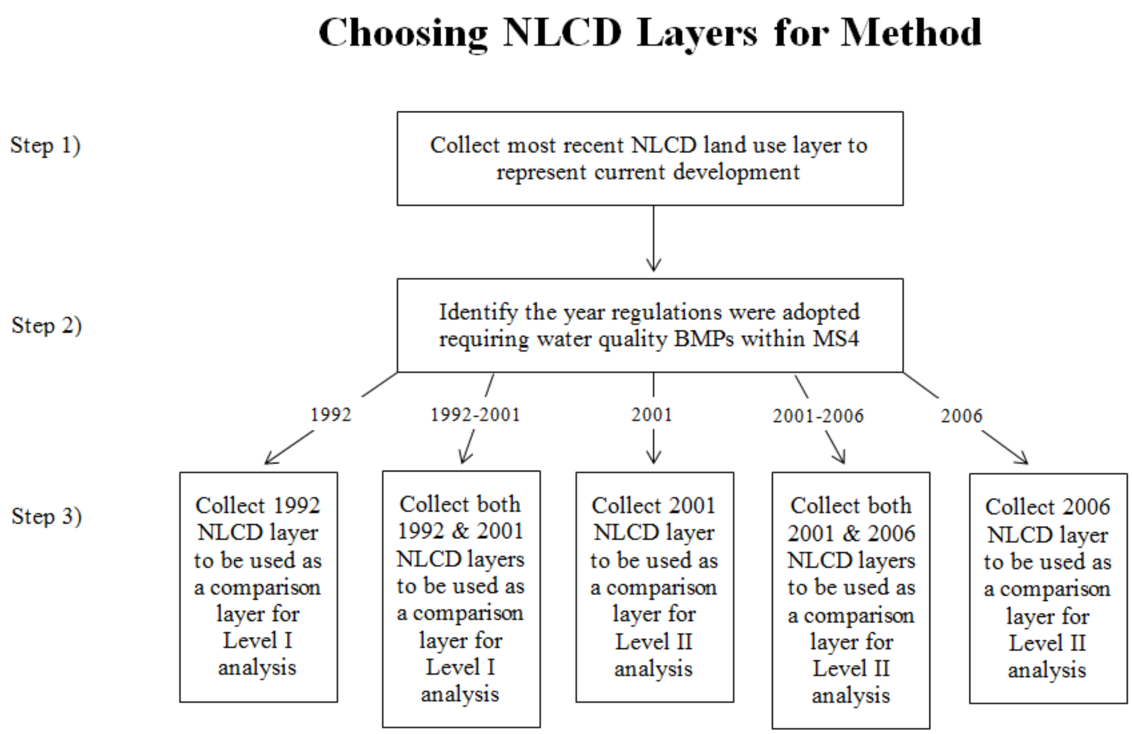

Figure 3.1: Flowchart displaying process for selecting NLCD layers for method

Once the correct years of NLCD data were collected, the raster datasets were reclassified in ArcGIS according to the values shown in **Table 3.2**. Two layers were created for each year of NLCD data, except 1992, one layer contained reclassified values specifying non-urban or urban. The second layer was reclassified to specify non-urban as well as the different classifications within the group of urban which included open space, low-intensity, medium- intensity and high-intensity. NLCD data from 1992 was only classified for Level I, as non-urban or urban, since the categories within urban used in the 1992 data were different then following years.

Table 3.2: NLCD Level I & Level II reclassifications for analysis

Classification	No.	Description
Level I		
Non-Urban	0	Any pixel designated as a land use other than developed by NLCD was reclassified as 0 for the Level I comparison.
Urban	20	Any pixel designated as developed by NLCD was reclassified as 20 for the Level I comparison.
Level II		
Non-Urban	0	Any pixel designated as a land use other than developed by NLCD was reclassified as 0 for the Level II comparison.
Urban - Open Space	21	Any pixel designated as developed, open space by NLCD remained classified as 21 for the Level II comparison. Developed, open space includes areas with a mixture of some constructed materials, but mostly vegetation in the form of lawn grasses (i.e. parks, golf courses, large-lot single-family housing units).
Urban – Low Intensity	22	Any pixel designated as developed, low intensity by NLCD remained classified as 22 for the Level II comparison. Developed, low intensity includes areas with a mixture of constructed materials and vegetation, with impervious surfaces accounting for 20% - 49%, most commonly including single-family housing units.
Urban – Medium Intensity	23	Any pixel designated as developed, medium intensity by NLCD remained classified as 23 for the Level II comparison. Developed, medium intensity includes areas with a mixture of constructed materials and vegetation, with impervious surfaces accounting for 50% - 79%, most commonly including single-family housing units.
Urban – High Intensity	24	Any pixel designated as developed, high intensity by NLCD remained classified as 24 for the Level II comparison. Developed, high intensity includes areas where people reside or work in high numbers with impervious surfaces accounting for 80% - 100%, most commonly including apartment complexes, and commercial and industrial areas.

3.2.3: Comparing NLCD Layers to Estimate BMP Implementation

Once both NLCD layers were collected and reclassified, the NLCD layers could be compared to determine areas of new urbanization. As shown above in **Figure 3.1**, a Level I or Level II analysis is determined by which years of NLCD data are being. **Figure 3.2** displays what is being compared in NLCD layers for a Level I analysis. Comparing different years of NLCD Level I data finds areas that were previously undeveloped and became developed according to the NLCD Landsat images.

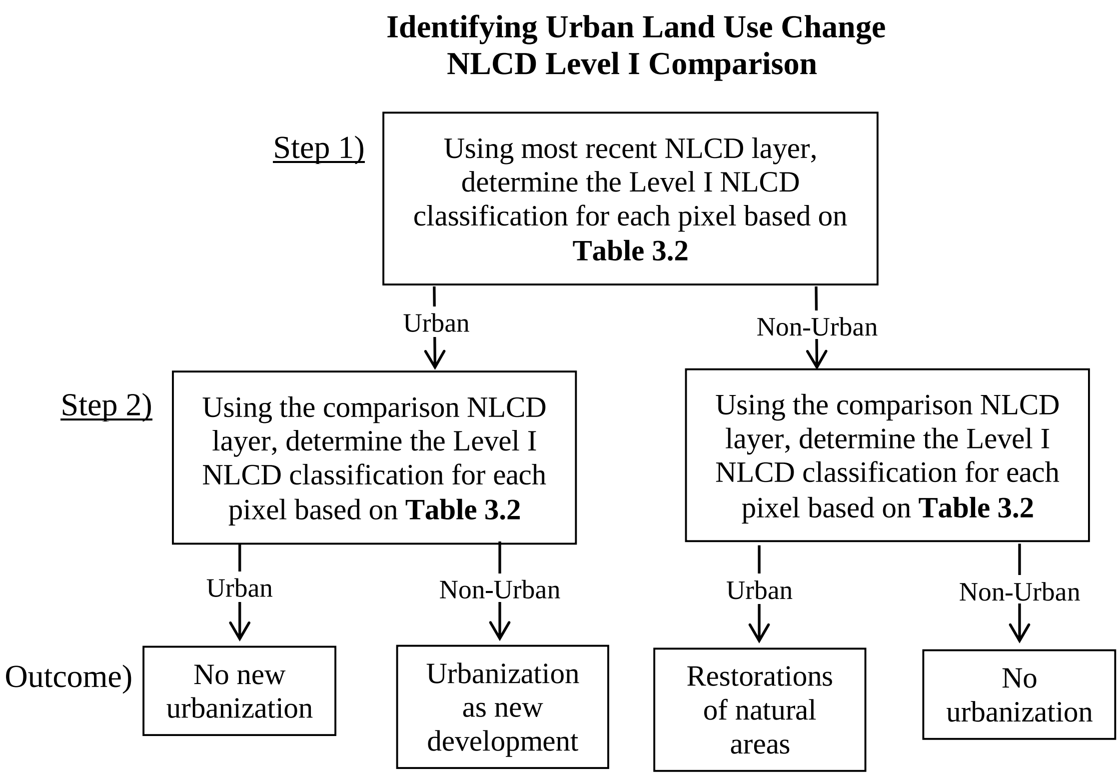

Figure 3.2: Flowchart displaying Level I comparison of NLCD layers

Figure 3.3 displays what is being compared in NLCD layers for a Level II analysis. Comparing different years of NLCD Level II data shows areas that were undeveloped and became developed, and also includes areas where the land use has changed between urban classifications showing redevelopment (i.e. changing from urban-open to urban-low density).

Level II changes were investigated as a method for finding newly developed areas and redeveloped areas which, according to MS4 permits should also contain structural BMPs.

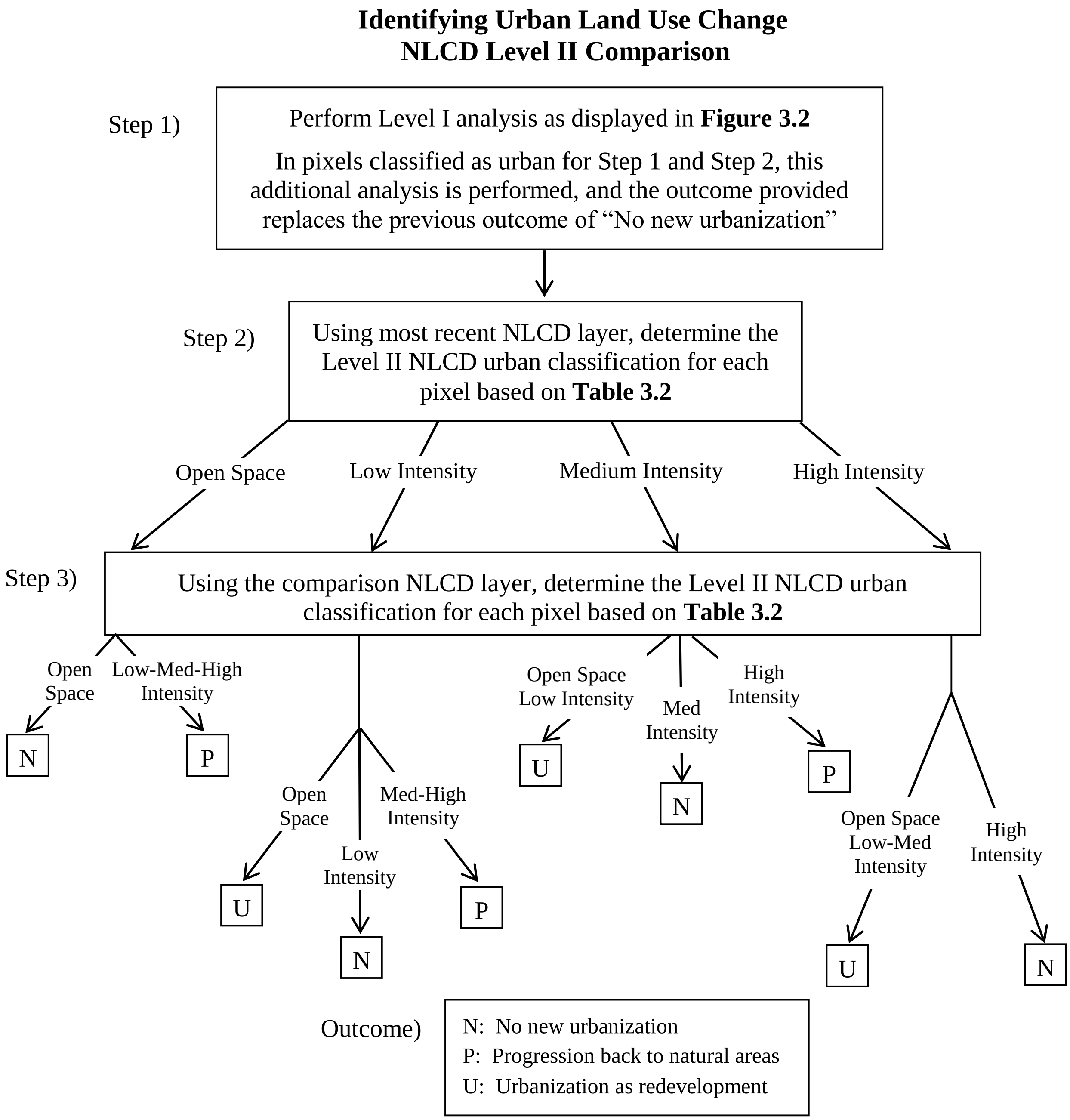

Figure 3.3: Flowchart displaying Level II comparison of NLCD layers

The comparison of NLCD layers was applied using **Equation 3.1** in the raster calculator in ArcGIS which performs the mathematical functions to the value of each pixel. When the two

NLCD layers were compared using the raster calculator a new layer was created where each pixel contained the output X from **Equation 3.1**. A value of zero would represent no new urbanization and a value less than zero represents a progression back to natural areas. For the purpose of this method, only values greater than zero, displaying new urbanization, were of interest. Since the MS4 regulations require all new urbanization to include water quality BMPs, the approach assumed that any pixel with a value greater than zero represents area that is treated by private BMPs.

$$NLCD_{recent} - NLCD_{comparison} = X \qquad \textbf{Equation 3.1}$$

Since the method is only trying to determine whether the area within the cell is estimated to be treated or not, the created layer from the raster calculator was reclassified. The layer from the raster calculator was reclassified to contain the value of 1 if the pixel represented area estimated to be treated and a 0 if the pixel represented area not estimated to be treated. The reclassified layer from the raster calculator, which was created by finding new urbanization between two years of NLCD data, was used and will be referred to as the estimated treatment area (ETA) layer. By using a binary layer of 0s and 1s metrics for geospatial quantitative statistics could be easily performed.

3.2.4: Removing Drainage Area from Public BMPs

As stated in the study objective, the approach is only meant to determine the drainage area of private BMPs that are built by land developers in areas of new urbanization after the adoption of MS4 permit regulations. However, private BMPs for water quality may not be the only BMPs located within an MS4. Some public agencies have also been installing water quality BMPs to treat urban areas that were developed before the adoption of MS4 permit regulations. Water quality BMPs built and maintained by a public agency are referred to in this study as public BMPs. Public BMPs treat urban areas that were determined to have a harmful impact on water quality. These are generally built in urban areas that were developed prior to MS4 requirements and did not contain any prior type of stormwater runoff treatment. The amount of public BMPs that are present within an urban area varies between each public agency. Some agencies designate a large budget to build and maintain public BMPs, and some agencies may not designate any funds to build and maintain public BMPs.

Since public BMPs are primarily treating areas that were already classified as urban before the adoption of MS4 regulations, the methodology proposed could not properly estimate their drainage area. Even though public BMPs drainage area cannot be estimated using this method, it is possible for the drainage area of public BMPs to be known. Since public BMPs are built and maintained by a public agency, the public agency should have the capabilities to determine the drainage area being treated by the BMP. Therefore it was assumed that drainage areas of public BMPs either are known, or could be readily available to any public agency and does not need to be included in the method.

Areas have also been observed where a public BMP treats urban areas that were developed prior to MS4 regulations but also includes areas that were developed after MS4 regulations. This could occur when a public agency built a public BMP to provide treatment to a previously untreated urban area, but the drainage area of the public BMP also included additional land not yet developed. Ordinarily, as the land became developed, MS4 regulations would require that the land developer build private BMPs to treat the newly developed area. However, since the new urban area is already treated by a public BMP, land developers are not required to build additional private BMPs. Therefore, even though public BMPs were not predicted in the method, they can affect how private BMPs are deployed within new urbanization. Therefore, any new urbanization predicted by the method that overlaps drainage area from a public BMP should be removed from the ETA layer creating a modified ETA layer.

3.2.5: Calculate Estimated Treatment Percentage (ETP)

Using the modified ETA layer a final metric of estimated treatment percentage (ETP) could be calculated. ETP is the estimated treatment area per total urban area and was determined by first calculating the total estimated treatment area (ETA). ETA was determined by counting all of the cells containing a value of 1 from the modified ETA layer and multiplying by the area of the cell. A value of 1 meant that the area of the cell was estimated to be treated. Determining the total amount of urban area could be accomplished by limiting the analysis to the extent of city limits, MS4 permit boundaries, or by counting the total cells classified as urban in the most recent NLCD layer available within the area of interest. ETP is determined by dividing the total ETA by the total amount of urban area. ETP is the proposed metric to account for water quality BMPs in urban stormwater models. For example, ETP could provide a measure that could be used as the percent of an urban sub-catchment that is estimated to be treated by BMPs within calculation of ETP. **Figure 3.4** displays a summary of the process used for estimating BMP implementation from private BMPs.

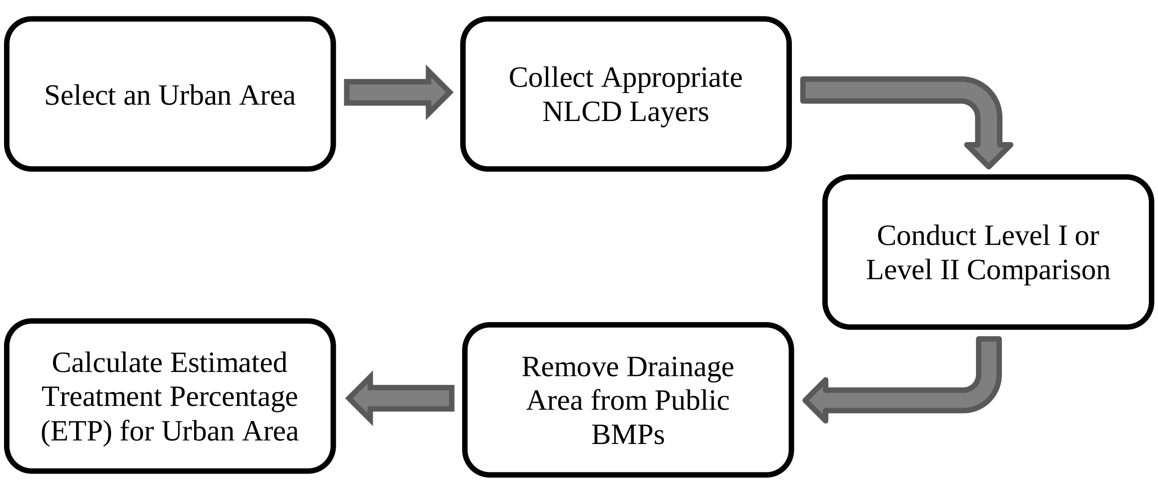

Figure 3.4: Flowchart displaying main steps for proposed methodology

3.2.6: Study Site for Evaluation of Method

In order to determine if the proposed method is valid it must be tested at a site where the adoption year of water quality BMP standards and drainage area being treated by structural water quality BMPs is already known. This method was selected to test against the study area of Fort Collins, Colorado. After consulting city ordinances and an Environmental Regulatory Specialist with the City of Fort Collins, it was determined that Fort Collins began to require design and construction of water quality BMPs to appropriate water quality standards in the year 1999 (City of Fort Collins 2016; Strong 2016). Therefore, according to the method, all new development that occurred after 1999 should contain some form of structural water quality BMPs. **Figure 3.5** displays the study site, Fort Collins, with its 12 sub-basins that were used for evaluating the proposed method.

Fort Collins was also chosen as a study site because it has developed a geospatial catalog of its structural BMP implementation throughout the City for both public and private BMPs. The geospatial catalog includes a polygon layer of the structural BMPs drainage area, which is rare due to the time and resources required to develop such a catalog. The Fort Collins BMP layer, developed in 2010 through 2011, was obtained from the City of Fort Collins. The catalog contained all structural BMPs that have been built within the city. The City of Fort Collins has built public BMPs whose drainage area is included in the catalog. Since calculating the drainage area of public BMPs does not fall within the scope of this method, public BMPs were removed from the catalog for this analysis. After removing public BMPs from the layer cataloging BMPs in Fort Collins, all remaining BMPs were assumed to be built as a response to regulations made by the City to comply with MS4 permit standards. The layer containing the remaining BMPs would be comparable to the output provided by the proposed method.

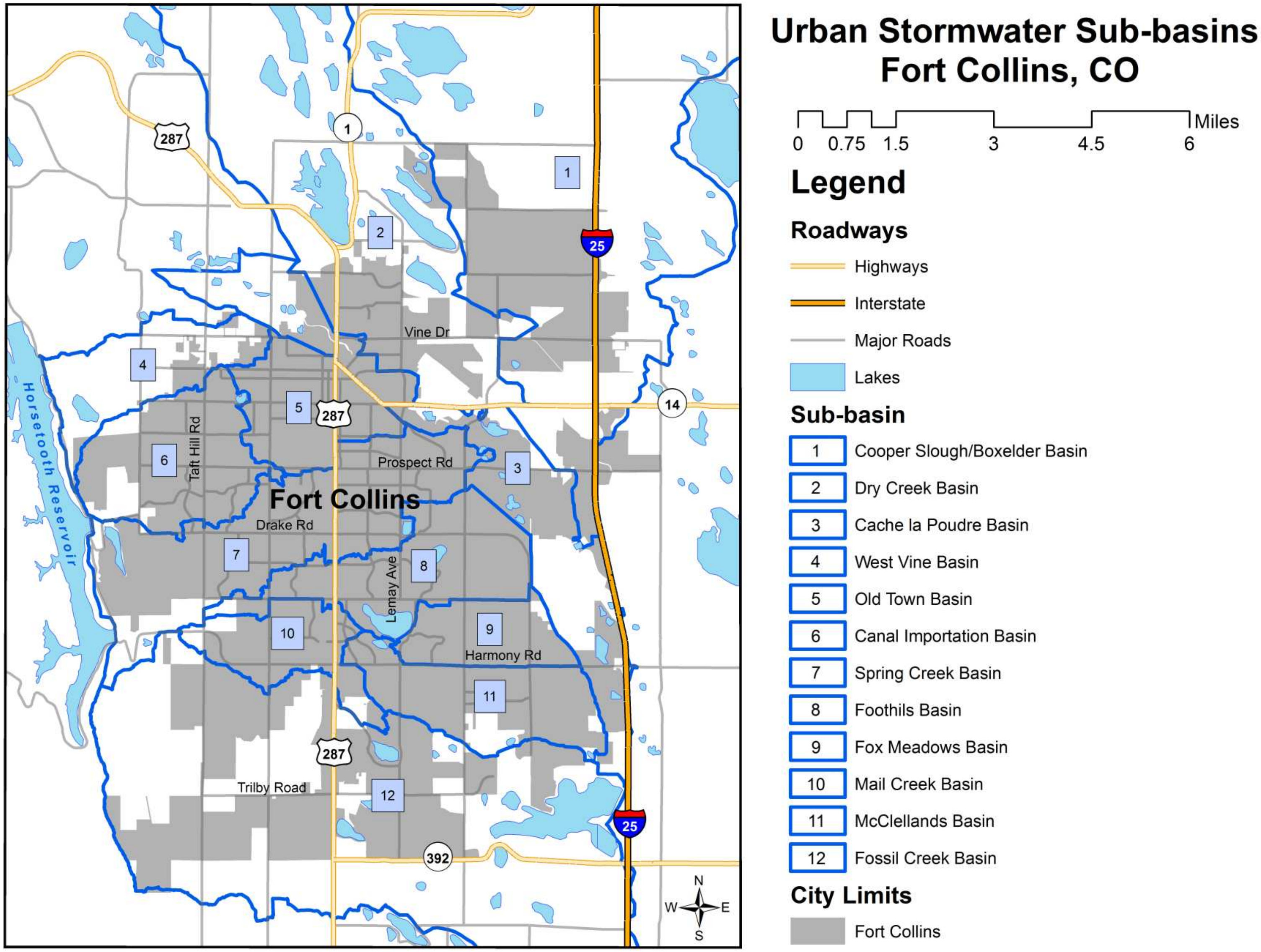

Figure 3.5: Map of the Fort Collins study area with labeled sub-basins

3.2.7: Performing the Method for Fort Collins

The method was performed for the selected urban area of Fort Collins, and the geospatial layer outlining the project area was the Fort Collins city limits layer obtained from the City of Fort Collins. NLCD layers were chosen using the process chart displayed in **Figure 3.1**. The 2011 NLCD land use layer was the most recent layer representing current urban development. **Figure 3.6** displays the Level I and Level II 2011 NLCD land use layers for Fort Collins. Since water quality BMPs began to be installed in new developments and redevelopments in the year 1999, both 1992 and 2001 NLCD layers were also collected as comparison NLCD layers for a Level I analysis. After the NLCD layers were collected, they were all reclassified according to the **Table 3.2** and clipped to the same geographic extent of the project area.

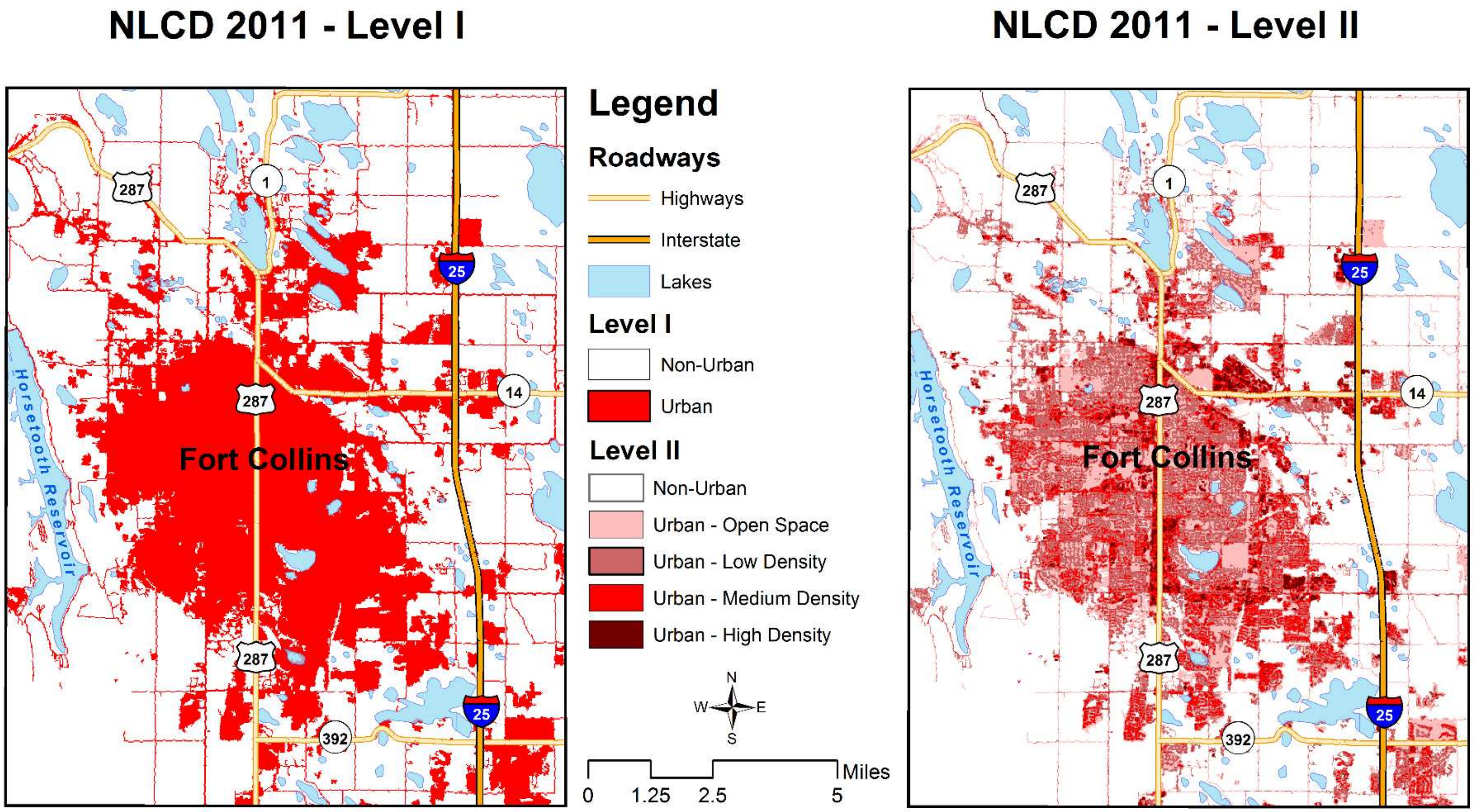

Figure 3.6: Map displaying reclassification of the 2011 NLCD layers based on Level I and Level II classifications

The NLCD 2011 reclassified layer was compared to both the NLCD 1992 reclassified land use layer and the 2001 reclassified land use layer according to the procedure outlined in **Figure 3.3**. The resulting layers displaying new developments were then used as ETA layers. **Figure 3.7** displays an example of the ETA layers created for changes in land use between 2011 and 2001 for both Level I and Level II land use layers. Since Fort Collins contains public BMPs, all areas of new development being treated by public BMPs were removed from both ETA layers creating two modified ETA layers. Using the modified ETA layers, values for ETP were calculated for Level I changes in urban land use between 2011 and 1992 as well as 2011 and 2001.

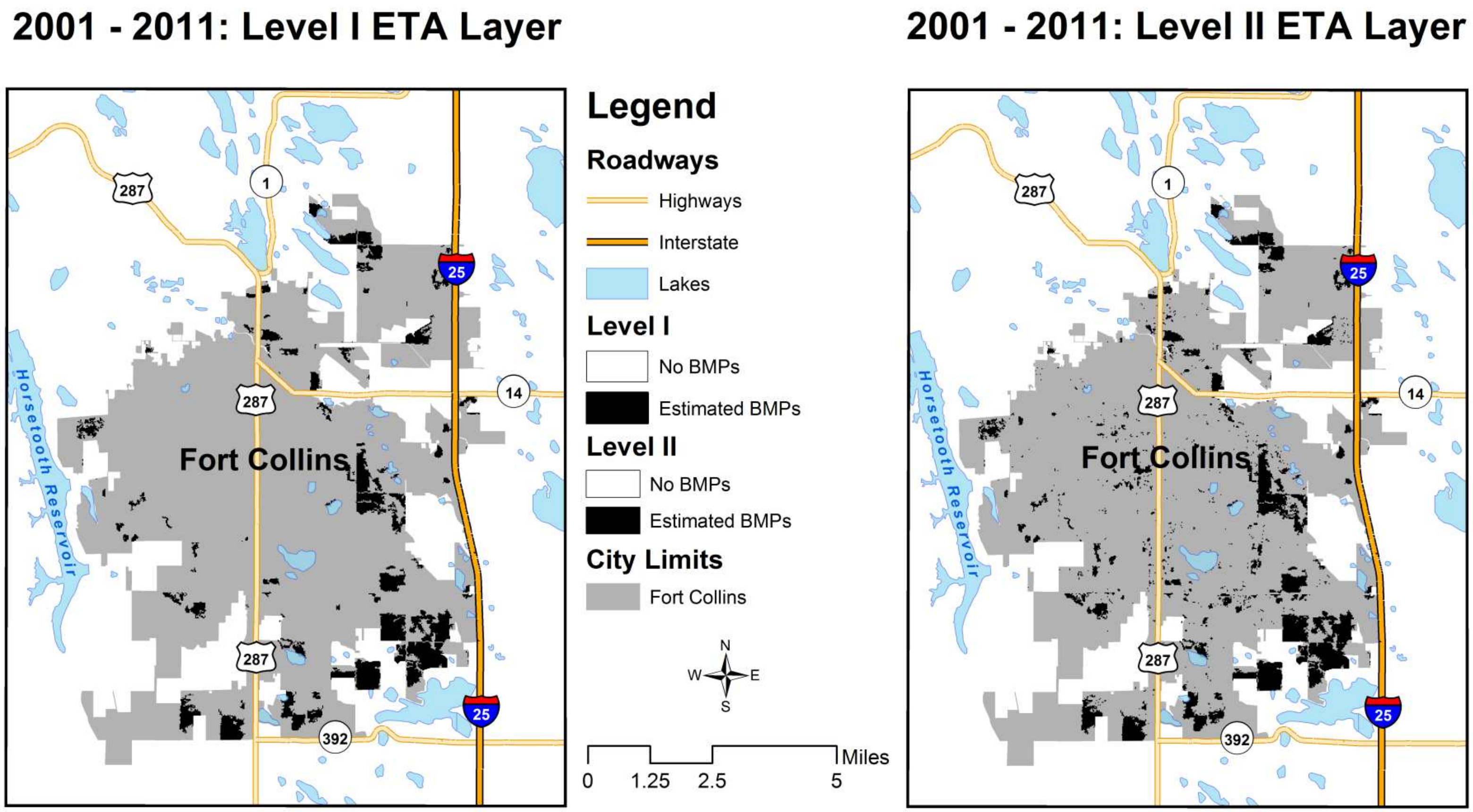

Figure 3.7: Map of ETA layers using NLCD land use change between 2011 and 2001 for Level I and Level II

3.2.8: Evaluating the Methodology

In order to evaluate the proposed methodology the amount of urban area estimated to be treated by private BMPs was compared to the observed drainage area being treated by private BMPs. Using the proposed methodology, two values of ETP were calculated, one comparing new developments between 2011 and 1992 (Scenario 1) and the other comparing new developments between 2011 and 2001 (Scenario 2). These values of ETP were compared to observed treatment percentages (OTP). Two additional scenarios were also considered to evaluate the methodology. Scenario 3 involved performing the entire procedure using a Level II analysis between 2011 and 2001. Scenario 4 provided an estimate using a year based interpolation of the ETPs produced by Scenario 1 and Scenario 2 since MS4 regulations were adopted in 1999 for the City of Fort Collins. By interpolating between Scenario 1 (1992) and Scenario 2 (2001) Scenario 4 (1999) provides an alternative that was evaluated against the observed drainage area being treated by private BMPs for numeric accuracy only since it was not created using geospatial layers. **Table 3.3** summarizes each of the scenarios used to evaluate the proposed approach.

Table 3.3: Summary of the four scenarios used to evaluate the proposed method

Scenario	Years of Analysis	NLCD Level	Description
Scenario 1	1992 – 2011	I	Scenario 1 compared observed BMP treatment drainage area to estimated BMP treatment drainage area as determined by the change in land use from the Level I NLCD analysis as displayed in **Figure 3.2** using 1992 and 2011 NLCD layers.
Scenario 2	2001 – 2011	I	Scenario 2 compared observed BMP treatment drainage area to estimated BMP treatment drainage area as determined by the change in land use from the Level I NLCD analysis as displayed in **Figure 3.2** using 2001 and 2011 NLCD layers.
Scenario 3	2001 – 2011	II	Scenario 3 compared observed BMP treatment drainage area to estimated BMP treatment drainage area as determined by the change in land use from the Level II NLCD analysis as displayed in **Figure 3.3**. Level II was used in order to provide a comparison for the differences between Level I and Level II analysis.
Scenario 4	1992/2001 – 2011	I	Scenario 4 calculated ETP by performing a year based linear interpolation of ETP between Scenario 1 and Scenario 2. Scenario 4 was a linear interpolation for the year 1999 between Scenario 1 using 1992 data and Scenario 2 using 2001 data. Since Scenario 4 does not contain any geospatial information but was created using an interpolation between the ETPs of Scenario 1 and Scenario 2, geospatial statistics could not be calculated for this scenario.

Each of the scenarios was used to evaluate the method by comparing observed treatment area (OTA) to what was estimated by the modified ETA layers. OTA was exhibited in the geospatial layer of known drainage areas of private BMPs for Fort Collins. **Figure 3.8** displays a map of the drainage area of the private and public BMPs in Fort Collins. Fort Collins has dedicated large amounts of funds in order to build and maintain public BMPs, which may not be the case in most municipalities. From the map it can also be seen that most of the private BMPs are clustered on the edges of the city limits demonstrating the idea that private BMPs are generally built in new urban areas developed after the adoption of MS4 permit regulations.

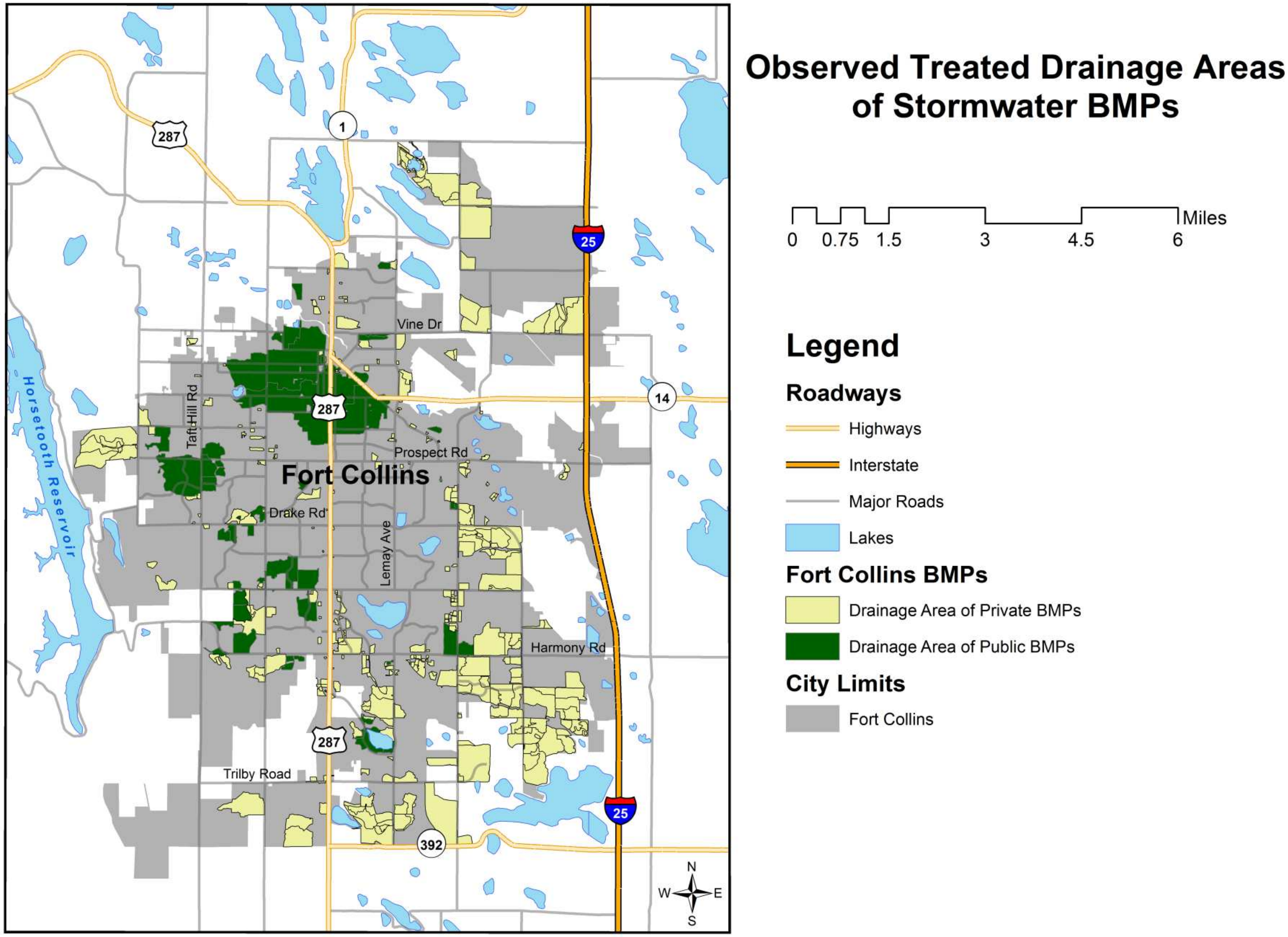

Figure 3.8: Map of private and public structural water quality BMP drainage areas in the City of Fort Collins

Once the layer of observed drainage area was collected, the public BMPs were removed and Moran's I index was calculated for the private BMPs only. Using the spatial autocorrelation tool in ArcGIS, a Moran's I index of 0.66 was calculated indicating that private BMPs tend to be clustered. Also, by comparing to aerial imagery, it can be seen that these BMPs do tend to be clustered in areas of new development. However, in order truly determine the correlation between new development and private BMP implementation, further analysis was conducted by comparing areas observed to be treated by private BMPs to areas estimated to be treated by private BMPs.

In order to compare the NLCD data to the observed BMP drainage areas it was important to ensure that all layers were the same geographic type and to the same geographic extent. Since modified ETA layers were originally NLCD raster datasets with a 30-m resolution, the Fort Collins BMP drainage area layer provided by the city was converted from a polygon layer to a raster layer with the same 30-m resolution. Once all of the layers were the same geospatial type and extent the modified ETA layers were compared to the Fort Collins OTA layer by classifying the layers using the present-absent matrix shown in **Figure 3.9**. For each sub-basin, a layer was created where each cell contained a designation of a, b, c, or d. If the cell was observed to be treated by a BMP and estimated to be treated by a BMP then the cell received the designation of Present/Present or a, according to the matrix in **Figure 3.9**. A cell that was observed to be treated by a BMP but not estimated to be treated by a BMP received the designation of Observed Only, or b. Likewise, a cell that was estimated to be treated by a BMP but not observed to be treated by a BMP received the designation of Estimated Only, or c. And finally, cells that were found to neither be observed nor estimated to be treated by a BMP received the designation of Absent/Absent or d.

		Estimated BMP Treated Cell		
		Present	Absent	
Observed BMP Treated Cell	Present	a	b	a + b
	Absent	c	d	c + d
		a + c	b + d	N

Figure 3.9: Present/Absent matrix used for comparing number of cells observed to be treated by a private BMP to cells estimated to be treated by a private BMP

Each modified ETA layer developed for Scenarios 1-3 were compared to the OTA layer using raster tools in ArcGIS to classify cells according to the matrix in **Figure 3.9**. Using the raster tools a new raster layer, Comparison Treatment Area (CTA) layers, were created when the modified ETA layers were compared to the OTA layers. CTA layers were used to measure how well the modified ETA layers were associated with the OTA layers, and whether this procedure could, to a degree of accuracy, predict both the quantity and location of drainage areas being treated by private BMPs. CTA layers were only developed for Scenarios 1-3. A CTA layer was not created for Scenario 4 because the ETP in Scenario 4 was not created based on a unique NLCD layer, but was created using a year based linear interpolation of the ETPs from Scenario 1 and Scenario 2. Each pixel in the CTA layers contained one of four values which corresponded to one of the four outcomes shown in **Figure 3.9**. An example of the CTA layer that was developed for Scenario 2 for all of Fort Collins is presented in **Figure 3.10**, and the corresponding Present/Absent matrix is displayed in **Figure 3.11**.

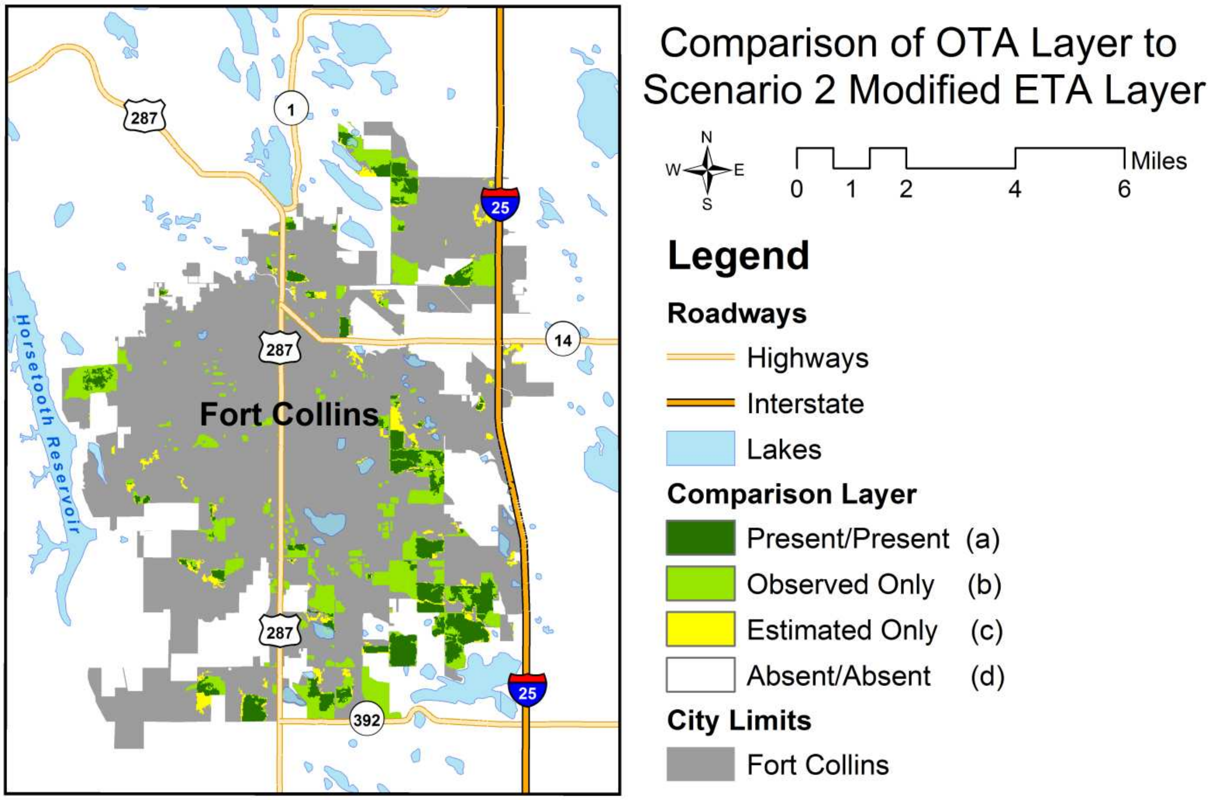

Figure 3.10: Example of a CTA layer for Scenario 2

		Estimated BMP Treated Cell		
		Present	Absent	
Observed BMP Treated Cell	Present	9,071	14,982	24,053
	Absent	3,226	126,208	129,434
		12,297	141,190	153,487

Figure 3.11: Example of Present/Absent Matrix for all of Fort Collins using the CTA layer from comparing the OTA layer to the modified ETA layer from Scenario 2

Once CTA layers were created and the Present/Absent matrix was populated for each scenario, several parameters for each sub-basin within Fort Collins as well as for all of Fort Collins could be calculated for each scenario to determine the legitimacy of the method. There were two main categories used to compare the performance of each scenario. The first category, numeric accuracy, involved calculating the errors between the Estimated Treatment Percentage

(ETP) and the Observed Treatment Percentage (OTP). Metrics and errors were calculated for each sub-basin and for all of Fort Collins and are summarized in **Table 3.4**.

Table 3.4: Metrics used to evaluate the method for numeric accuracy between ETP and OTP

Parameter Name	**Unit**	**Equation**	**Description**
Estimated Treatment Area (ETA)	Acres	$\sum \binom{Cells\ displaying}{new\ urbanization} * \binom{Area}{of\ Cell}$	ETA is the estimated amount of drainage area being treated by private BMPs within an area of interest which is determined by the amount of new urbanization calculated using the appropriate NLCD analysis.
Observed Treatment Area (OTA)	Acres	$\sum \binom{Cells\ displaying}{BMP\ treatment} * \binom{Area}{of\ Cell}$	OTA is the summation of all the observed drainage areas being treated by private BMPs within the area of interest.
Estimated Treatment Percentage (ETP)	%	$\frac{Estimated\ Treatment\ Area}{Total\ Urban\ Area}$	ETP is the estimated treatment area per total urban area. ETP is the proposed metric to account for water quality BMPs in urban stormwater models.
Observed Treatment Percentage (OTP)	%	$\frac{Observed\ Treatment\ Area}{Total\ Urban\ Area}$	OTP is the amount of observed treatment area per total urban area. OTP was used for evaluating the accuracy of ETP.
Relative Bias	%	$\frac{1}{n}\sum_{i=1}^{n}\frac{OTP_i - ETP_i}{OTP_i}$	Relative bias is the metric used to determine whether the method produces a systematic over or under estimate of the percentage of urban area being treated by private BMPs for each (i) of the 12 sub-basins in Fort Collins as well as for Fort Collins as a whole. Relative bias was calculated for all 4 scenarios.
Normalized Root Mean Square Error (nRMSE)	%	$\frac{\sqrt{\frac{1}{n}\sum_{i=1}^{n}(OTP_i - ETP_i)^2}}{\overline{OTP_i}}$	nRMSE is the metric used to quantify the error between ETP and OTP for each (i) of the 12 sub-basins in Fort Collins as well as for Fort Collins as a whole. The Root Mean Square Error (RMSE) was normalized by the mean OTP for each of the study areas in order to provide a metric displaying the percent error between ETP and OTP relative to the mean OTP.

The second category used to evaluate the performance of the scenarios and the method in general was geospatial similarity. As measures of geospatial similarity, quantitative geospatial statistics were used and included two similarity coefficients, a chi-square test for independence, as well as two metrics measuring the accuracy of the procedure in terms of both observed treatment areas and estimated treatment areas. All metrics were calculated using terms introduced in the Present/Absent matrix in **Figure 3.9**. **Table 3.5** summarizes the metrics used to test for geospatial similarity. Metrics of geospatial similarity were calculated for Scenarios 1-3, but were not calculated for Scenario 4 which did not have a CTA layer measures of ETP were created from linear interpolation instead of from unique NLCD layers.

Table 3.5: Metrics used to evaluate the method for geospatial similarity and correlation between ETP and OTP in terms of the Present/Absent matrix

Parameter Name	Unit	Equation	Description
Similarity *Yule's Coefficient*	-	$\frac{ad - bc}{ad + bc}$	A simple coefficient used to determine the similarity or association between the observed and estimated treatment area using notation from Present/Absent matrix.
Similarity w/o Absent/Absent *Jaccard's Coefficient*	-	$\frac{a}{a + b + c}$	A coefficient used to determine the association without including regions where data is absent for both the observed and estimated treatment areas. This metric was used to determine how closely ETA and OTA matched when only considering cells where treatment was either observed to be present or estimated to be present, and was used to determine whether the locations of the BMP treatment were accurately predicted as well as the quantity.
Chi-Square Test of Independence	χ^2	$\frac{(ad - bc)^2 N}{(a + b)(a + c)(c + d)(b + d)}$	The Chi-square test of statistical significance for a 2x2 Present/Absent Table, there being a single degree of freedom in such a table, was used to test for a statistical significant relationship between estimated and observed treated area layers for each scenario with geospatial data. For an α =0.05, the null hypothesis of spatial independence can be rejected with χ^2 > 3.841 with 1 degree of freedom.
Observed Treatment Area Accuracy	%	$\frac{a}{a + b}$	A metric displaying percent of Observed Treatment Area cells that were accurately estimated to be treated by private BMPs.
Estimated Treatment Area Accuracy	%	$\frac{a}{a + c}$	A metric displaying the percent of Estimated Treatment Area cells that were actually observed to be treated by private BMPs.

3.2.9: Sub-basin Analysis

Each scenario was analyzed for the twelve sub-basins located within Fort Collins. This required parameters from **Tables 3.3-3.4** to be calculated for the urban area within each sub-basin. Parameters were calculated for each sub-basin in order to see how the method worked for different areas of development within Fort Collins. It was also done to provide multiple basins that could be used for evaluating differences between ETP and OTP. All tables and figures displayed in the results section show results for each of the sub-basins as well as for Fort Collins as a whole.

3.3: Results

The results of the analysis conducted to determine the legitimacy of the method are presented in this section. The objective of this study was to develop and evaluate a novel approach for determining the extent of urban areas for which stormwater runoff is treated by private BMPs. For this method, ETP, determined by finding areas of land use change between years of NLCD data, was used to estimate the extent of urban areas being treated by private BMPs. For the study site of Fort Collins, the most recent years of NLCD data was 2011 and the years available surrounding the enactment of a MS4's requirements were 1992 and 2001. Overall, four different scenarios were used for the analysis of the method. **Table 3.3**, displayed above, summarizes each of the four scenarios. OTPs, and ETPs, were calculated for each sub-basin as well as for the entire City of Fort Collins. **Table 3.6** displays the OTP as well as the ETP that was calculated for each scenario. From the table it could be seen that Scenario 4 provided the closest prediction when compared to the actual for most of the sub-basins, but in particular for the City of Fort Collins as a whole.

Table 3.6: Percent of BMP treatment per total urban area observed and estimated within a sub-basin/city

Area of Analysis	OTP	ETP			
		Scenario 1	Scenario 2	Scenario 3	Scenario 4
Cooper Slough/Boxelder	17%	26%	9%	10%	13%
Dry Creek	18%	28%	9%	10%	13%
Cache la Poudre	4%	20%	5%	6%	8%
West Vine	2%	22%	2%	2%	6%
Old Town	1%	9%	0%	2%	2%
Canal Importation	13%	28%	2%	3%	8%
Spring Creek	3%	27%	1%	3%	7%
Foothills	18%	39%	12%	14%	18%
Fox Meadows	19%	51%	8%	11%	17%
Mail Creek	18%	41%	2%	6%	11%
McClellands	44%	63%	20%	24%	29%
Fossil Creek	24%	34%	15%	16%	19%
Fort Collins	*16%*	*32%*	*8%*	*10%*	*13%*

As discussed above, categories of parameters were calculated for evaluating the proposed methodology. The first category, numeric accuracy, was evaluated by first calculating OTP and then ETP for each of the 4 scenarios. For Scenarios 1-3 ETP was calculated using the modified ETA layers, but for Scenario 4, ETP was calculated as a year based linear interpolation between Scenario 1 and Scenario 2. The error between OTP and each ETP were then calculated and using the equations from **Table 3.4**, relative bias and normalized Root Mean Square Error (nRMSE) were calculated. **Table 3.7** displays the relative bias and nRMSE that were calculated for each of the scenarios using the errors between OTP and ETP for each sub-basin and for the entire City of Fort Collins.

Table 3.7: Numeric accuracy metrics for each of the four scenarios

Metric	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Relative Bias	-261%	51%	25%	-19%
nRMSE	123%	68%	56%	37%

From **Table 3.7**, it can be seen that ETP from Scenario 1 contained a bias of the OTP of -260% meaning that Scenario 1 cumulatively over predicted the OTP by 2.6 times the actual value. Scenario 2 and Scenario 3 both tended to underestimate OTP. This difference largely results from the fact that Scenario 1 used a comparison between 2011 and 1992 NLCD layers, where Scenario 2 – 3 used a comparison between 2011 and 2001 NLCD layers. Differences in errors between Scenario 2 and Scenario 3 are the result of using a Level I compared to a Level II analysis of the NLCD layers. Scenario 4 had the smallest magnitude of bias as well as the smallest nRMSE. nRMSE represents a measure of error between ETP and OTP. For Scenario 4, the nRMSE value of 37% represents that the error between OTP and the ETP from Scenario 4 tended to be contained with 37% of the mean OTP for all of the sub-basins.

The second category of metrics for evaluating the proposed methodology was geospatial similarity. Geospatial similarity was measured using quantitative geospatial statistics, particularly using the metrics from **Table 3.5**. Each of the different metrics provides different information for the appropriateness of the proposed method. The first two metrics, both similarity coefficients represent how similar the modified ETA layers were to the OTA layers. The first similarity coefficient, Yule’s Coefficient, measures similarity between the layers with including cells containing the outcome of Absent/Absent, d, from the Present/Absent matrix in **Figure 3.9**. Yule’s Coefficient was used alongside a Chi-Square test to determine whether the OTA layers and ETA layers had a statistically significant amount of similarity in order for the method to be appropriate. Jaccard’s Coefficient measured the similarity only in cells where either observed or estimated BMP treatment was occurring or both. Jaccard’s Coefficient was used as a metric to evaluate how the method did without including the several cells where there was no BMP treatment observed or estimated by the method. Finally two measures of accuracy for both the observed and estimated treatment areas were calculated. Observed treatment area accuracy was used to determine the percent of observed treatment area cells that were correctly estimated using the method. Estimated treatment area accuracy measured the percent of cells estimated to provide BMP treatment that actually were observed to be treated by private BMPs. **Table 3.8-10** displays geospatial similarity metrics that were calculated for each sub-basin for Scenarios 1 – 3 respectively. Geospatial similarity metrics could not be calculated for Scenario 4 because Scenario 4 was not created based on a unique NLCD layer, but was created using a year based linear interpolation of the ETPs from Scenario 1 and Scenario 2.

Table 3.8: Geospatial similarity metrics for Scenario 1

Area of Analysis	Yule's Coefficient	Jaccard's Coefficient	Chi-Square Test of Independence	OTA Accuracy	ETA Accuracy
Cooper Slough/Boxelder	0.80	0.36	2982.3	65%	44%
Dry Creek	0.36	0.20	184.6	42%	27%
Cache la Poudre	0.89	0.14	1007.3	79%	14%
West Vine	0.77	0.07	56.0	67%	8%
Old Town	0.72	0.06	135.3	38%	6%
Canal Importation	0.43	0.17	293.8	46%	21%
Spring Creek	0.50	0.05	204.6	51%	6%
Foothills	0.78	0.32	1885.1	78%	35%
Fox Meadows	0.34	0.21	120.5	65%	24%
Mail Creek	0.52	0.24	329.4	64%	27%
McClellands	0.50	0.46	670.0	77%	53%
Fossil Creek	0.66	0.35	3179.4	62%	44%
Fort Collins	*0.68*	*0.27*	*14252.8*	*65%*	*32%*

Table 3.9: Geospatial similarity metrics for Scenario 2

Area of Analysis	Yule's Coefficient	Jaccard's Coefficient	Chi-Square Test of Independence	OTA Accuracy	ETA Accuracy
Cooper Slough/Boxelder	0.87	0.31	3076.5	36%	67%
Dry Creek	0.70	0.20	606.2	25%	50%
Cache la Poudre	0.97	0.36	3252.4	60%	47%
West Vine	0.99	0.44	700.7	52%	74%
Old Town	-	-	-	-	-
Canal Importation	0.99	0.19	2013.8	19%	98%
Spring Creek	0.85	0.08	474.1	11%	25%
Foothills	0.91	0.40	3775.0	48%	71%
Fox Meadows	0.94	0.32	1495.0	34%	83%
Mail Creek	0.82	0.09	282.9	9%	67%
McClellands	0.89	0.38	2170.0	40%	89%
Fossil Creek	0.91	0.43	8003.9	48%	79%
Fort Collins	*0.92*	*0.33*	*34135.6*	*38%*	*74%*

* *Scenario 2 does not contain geospatial metrics for the Old Town basin because it did not calculate any non-urban to urban land use change within that sub-basin between 2001 and 2011*

Table 3.10: Geospatial similarity metrics for Scenario 3

Area of Analysis	Yule's Coefficient	Jaccard's Coefficient	Chi-Square Test of Independence	OTA Accuracy	ETA Accuracy
Cooper Slough/Boxelder	0.87	0.32	3216.3	38%	66%
Dry Creek	0.66	0.20	560.3	27%	46%
Cache la Poudre	0.97	0.37	3507.3	72%	43%
West Vine	0.99	0.42	647.1	58%	61%
Old Town	0.93	0.14	485.0	24%	24%
Canal Importation	0.96	0.21	1953.0	21%	85%
Spring Creek	0.90	0.18	1751.5	32%	29%
Foothills	0.91	0.43	4110.0	54%	70%
Fox Meadows	0.94	0.43	2015.5	48%	79%
Mail Creek	0.86	0.22	838.0	25%	68%
McClellands	0.86	0.43	2347.3	46%	86%
Fossil Creek	0.90	0.42	7739.0	49%	76%
Fort Collins	*0.91*	*0.36*	*35869.2*	*43%*	*69%*

From the results in **Tables 3.8 – 3.10** it can be seen that the Yule's Coefficient displays a strong relationship between OTA and ETA layers for Scenarios 2 – 3 in most areas of analysis. Scenario 1 does not however display strong similarities. When observing the chi-square statistics, each scenario and each sub-basin far surpassed the critical value for χ^2, 3.841. From the results of the chi-square test of independence it can be assumed that the null hypothesis of OTP and ETP being independent of each other can be rejected. However, the magnitude of the chi-square values raises concerns that are addressed in the discussion portion of this paper. Finally by looking at the OTA and ETA accuracy metric, it can be seen that Scenarios 2 – 3 have higher ETA accuracy but lower OTA accuracy than Scenario 1, meaning that they are generally capturing less of the total area observed to be treated by BMPs, but the areas that they are estimating treatment to occur are more likely to actually occur.

3.4: Discussion

As previously mentioned, the overall purpose of this study was to develop and evaluate a novel approach for determining the extent of urban areas for which stormwater runoff is treated by private BMPs. After reviewing the results from the 4 scenarios, several points were concluded. The first was the effectiveness of the method to develop a range for private BMP treatment area and for some scenarios the geospatial locations of the treatment area. Scenario 1 and Scenario 2 represent the outputs determined from conducting the proposed method, and based on the method, represent the estimated range of area treated by private BMPs. From **Table 3.6**, it is seen that in almost each sub-basin, the proposed range captured the observed area being treated. The Cache la Poudre sub-basin was the only sub-basin within Fort Collins that the OTP was outside of the range created by the ETP of Scenario1 and Scenario 2. Geospatial similarity metrics displayed in **Tables 3.8 – 3.10**, particularly ETA accuracy showed that in Fort

Collins 74% of estimated treated area in Scenario 2 coincided with area observed to be treated by BMPs. One reason explaining why the method is predicting areas to be treated that are not treated could be as a result of error in the NLCD data which for Level I has a reported accuracy of 84% and 79% for Level II for 2001 layers. However, since there are sub-basins reporting ETAl accuracies below 50% it is not recommended that the estimated location of treatment areas by BMPs be used at this time.

According to the chi-square values reported for each scenario in each area of analysis, it should be reasonable to assume that independence between OTA and ETA layers can be rejected. However, the magnitude of chi-square values raises concerns. One explanation for the large chi-square values can be found in the skewed amount of Absent/Absent values. Since such large amounts of each watershed contains Absent/Absent values it may be biasing the common metrics used for evaluating geospatial similarity and dependence. Because of the large amounts of Absent/Absent cells in each of areas of analysis, Jaccard's coefficient was also used to evaluate whether it would be appropriate to use ETA layers to represent OTA layers. From the values of Jaccard's coefficient being closer to 0 than to 1 displays a tendency for the location of BMP treatment to not agree more often than they agree. For this reason it is also not recommended to use ETA layers as measures of the exact locations private BMP drainage area.

Even though ETA layers should not be used for representing the exact location of BMPs, values of ETP calculated from the ETA layers could still be useful. With a calculated range of ETP, stormwater modelers would be able to apply private BMPs into models such as SWMM which asks for a percent of BMP treatment within sub-catchments (Rossman 2015). It would then be up to the modeler to determine whether they would want to use a conservative estimate and use the lower bound of the range of ETP, or to use an average or interpolation within the range, similar to what was done for Scenario 4. For areas that adopted MS4 regulations in a year of available NLCD data, the method does not produce a range, but an estimate using only the most recent NLCD layer and comparing it to the NLCD layer from the year of MS4 regulations.

Based on the ETP values, from **Table 3.6**, the lower bound of the range produces an underestimate of BMP treatment and an interpolation of the range produced a 19% overestimate for Fort Collins. Using a Level II analysis, Scenario 3, had less error than Scenario 2, for the study area revealing a slightly closer estimate to the amount of area being treated by BMPs. Given the small amounts of error, particularly in Scenario 4 between ETP and OTP, especially when considering the overall accuracy of the NLCD layers, it is recommended that method be a useful option for providing an initial estimate for the amount of private BMPs being used to treat stormwater.

One explanation for errors between ETP and OTP were based on the adoption year of the MS4 regulations. As mentioned above, Fort Collins required the construction of private BMPs in all new urbanization in 1999; NLCD land use layers were only available for 1992 and 2001. Since 1992 was seven years before the regulation, all of the land development that occurred between 1992 and 1999 would not be required to contain stormwater BMPs so any development that was captured by the method during those 7 years would create an overestimate. Likewise, since 2001 was 2 years after the regulation, all of the land developed between 1999 and 2001 would contain stormwater BMPs, but the method would not be able to account for the change. This resulted in the creation of Scenario 4, an interpolation between Scenario 1 and Scenario 2, which provided the best numeric accuracy of all the methods.

Another reason why Scenario 2 and Scenario 3 under-predicted the amount of BMP drainage area occurred because of the nature of drainage areas. When land is developed and a new BMP installed, it is required for the BMP to be sized large enough to handle the entire area that drains to it. This may result in more area being treated than being newly developed whether this is undeveloped area that is treated or area developed prior to the regulation. Overall this would result in the method not being able to pick up the entire drainage area of a treatment BMP and could account for the low levels of OTA accuracy for Scenarios 1 – 3.

When looking at the different sub-basins and how ETP compared to OTP it was observed in **Tables 3.7 – 3.10** that for sub-basins that contained a majority of non-urban prior to the regulation had the lowest errors and best ETA accuracy. The reverse can be seen in sub-basins such as the Old Town sub-basin, which was completely developed prior to 2001, the method could not pick up any land use change and as a result did not estimate any BMPs in the area. Also in the Cache la Poudre sub-basin it may not be required to build a structural BMP as long as the developer does a satisfactory job of preserving buffer strips and/or natural area wetlands resulting in an overestimate of structural BMPs in this area (City of Fort Collins 2008).

The presence of public BMPs also provide an obstacle to applying the method. Since public BMPs were present in the study area of Fort Collins, they had an effect on both the OTA layer and the ETA layer, requiring that the drainage area from public BMPs be removed from the OTA layer and ETA layers. Public BMPs and their drainage area are typically known because they are built and maintained by a public agency that has the capabilities to collect the information. Since the treatment area provided by public BMPs is known, it can easily be removed before calculating an ETP as mentioned in step 4 of the proposed method. After the ETP from private BMPs is calculated using the proposed method, a modeler could include the percent of treatment area within an urban area provided by public BMPs.

It is also important to understand how errors in ETP would affect being able to apply the method for stormwater modeling. If the method resulted in an overestimation of ETP, using this value in any model would result in more benefits being provided by BMPs, whether that is for flood control or pollution control. An underestimation of ETP would result in less benefits provided by BMPs and would ultimately be the more conservative approximation. Since the source of NLCD data for calculating ETP already has uncertainties any value of ETP would also contain levels of uncertainty correlated to the level of accuracy of the NLCD products.

One of the main drivers of the method depends on the adoption year of stormwater regulations. Typically this year corresponds to the year that the MS4 permit was issued to the MS4 operator; however, in places like Fort Collins, MS4 regulations could be applied before the MS4 permit. Whether it is pro-active action or an agency following EPA requirements, the year that water quality BMPs began to be deployed is one of the most crucial elements affecting the method. The closer the adoption year is to available NLCD data the more accurate the method should become. One of the limitations of this study was that it was only able to be conducted for one municipality due to availability of the geospatial layer cataloging the drainage area and locations of structural stormwater BMPs. Future analysis should be conducted for additional municipalities that have a geospatial layer cataloging the drainage area and locations of structural stormwater BMPs and that know the year structural stormwater BMPs for water quality were required. This analysis would provide additional data points for analyzing the numeric and geospatial accuracy of the proposed method.

3.5: Conclusions

As urbanization has increased, so has the implementation of structural BMPs for stormwater. In order to accurately model stormwater, these BMPs should be included since they affect both the quality and the quantity of stormwater runoff. Cataloging these BMPs can become an enormous task that requires vast amounts of time and resources for a municipality and therefore creates a need for a method that could be used to quickly estimate the amount of newly developed or redeveloped land that is being treated by private stormwater BMPs. It was determined that comparing changes in land use as measured by NLCD land cover products could provide a measurement of the area being treated by private BMPs. After performing the analysis for Fort Collins it was found that changes in urbanization as measured by NLCD data provides a range of ETP that captured OTP in 11 of the 12 sub-basin in Fort Collins as well as for Fort Collins as a whole.

After evaluating the method using quantitative geospatial statistics it was determined that there was geospatial similarity between new urban areas of development and observed areas being treated by BMPs as shown by Yule's coefficient. However, even though there is similarity between the ETA and OTA layers, and even though ETP and OTP values are relatively close as seen by the error metrics calculated for Scenario 4, it is not recommended that this method be used to determine the exact location of BMP implementation. Instead, the proposed method should be used as a tool for providing an initial estimate of the percent urban area being treated by private BMPs that have been constructed as a result of new urban development. From this research it may be noticed that no mention has been made of the method being able to predict which type of structural BMPs are being implemented. Acquiring this information would fall to the user of the method, but is generally something that can be gathered from stormwater professionals within a municipality or by studying which common BMPs are used in different climates and regions. Further research should be conducted to investigate whether the accuracies of the method found in this study apply to other locations or if they are unique to Fort Collins.

CHAPTER 4: CONCLUSIONS

As nutrient pollution becomes a growing problem across the world, it becomes increasingly important to be able to quantify the amount of nutrients each of the different sources contributes. By understanding how much nutrients stormwater is providing it becomes possible to understand how to address the problem effectively especially when considering the growing impact that structural stormwater BMPs are having on urban stormwater. Developing a simple framework for which a level of magnitude estimate of nutrient load from stormwater could be determined was the principal purpose of this research. Also, since structural BMPs are playing a larger role in the treatment of stormwater, it was necessary to both determine how to incorporate their effects into the framework as well as estimate the current amount of drainage area being treated by BMPs.

The provided approach accomplishes the objectives of creating a simple model which could rapidly estimate nutrient loads from stormwater in any given watershed or area of interest. By using a simple approach, it is easy to understand regardless of a user's background in modeling. Also, since all of the inputs for the method are available through national datasets, it accomplishes the objective of being an approach that could be applied to anywhere within the United States. Even though, the approach could be applied anywhere in the United States, it should be noticed from the evaluation of the method, that applying it in locations with comparison data could potentially decrease the uncertainty of the method. The Simple Method was also adapted to include the effects of stormwater BMPs, allowing users to conduct a planning level analysis for which BMPs have the potential to reduce nutrient loads.

Once the framework was developed it was necessary to evaluate the accuracy of the method for predicting nutrient loads. Since there was no available annual nutrient data, it was not possible to validate the model on the annual basis, but was evaluated by comparing to observed event loads. From this analysis it was determined that the proposed approach would only be applicable for estimating the order of magnitude of nutrient loads. The Monte Carlo simulation revealed large bands of uncertainty surrounding the prediction which was expected due to the simplicity of the model. However, after conducting a Bayesian statistical analysis it was found that the uncertainty bands around the estimate could be substantially reduced using observed data within an area of interest. Overall it was determined that the proposed approach be used for planning level purposes only where order of magnitude estimates are appropriate.

In order to apply BMPs into the method it was necessary to know how much drainage area is currently being treated by BMPs. It was determined that comparing changes in land use as measured by NLCD land cover products could provide a measurement of the estimated treatment drainage area. After performing the analysis for Fort Collins it was found that changes in urbanization as measured by NLCD data provides an underestimate of drainage area being treated by BMPs, but could be a useful starting point in understanding the amount of structural BMP implementation currently in an urban environment. Even though the estimated amount of drainage area being treated by BMPs could be determined, it would still be the responsibility of the user to research which type of BMPs are typically applied in their respective area of interest.

Further research should include evaluating the proposed approach for load estimation in other urban watersheds of varying sizes utilizing different structural BMPs and green infrastructure. This would require a watershed to have readily available data regarding the nutrient load being exported by urban sources within the watershed. Additional work could also be conducted to further quantify uncertainty in some of the random variables such as precipitation. Further research should also, include conducting the BMP treatment area estimation approach in other urban watersheds to determine whether the method is applicable in other regions and municipalities other than Fort Collins.

In order to summarize the application of the proposed methods in this research, a case study for the entire state of Colorado was completed. For this study, it was assumed that MS4 regulations were adopted in each major MS4 system by 2006, a conservative estimate. Using 2006 as the MS4 adoption date, the estimated treatment percentage (ETP) was found using the method proposed in Chapter 3. ETP was applied on the basis of the 2010 MS4 layer provided by the Colorado Department of Public Health and Environment (CDPHE). Once ETP was calculated for each MS4 from the CDPHE layer, the values were used for treatment area (TA) in the method outlined in Chapter 2. In Colorado, the most common private structural stormwater BMPs are extended detention basins. Effluent total phosphorus and total nitrogen concentrations were collected from the international BMP database for extended detention basins as well as the volume reduction. Combining these values with PRISM average annual precipitation, and using the 2011 NLCD layers for land use type and imperviousness, the method proposed in Chapter 2 was completed for the entire state of Colorado. Completing the method produced a 30m raster grid for both total phosphorus and total nitrogen where each 30m cell contained the average annual load estimated to be produced by that cell. The cells where then accumulated based on HUC 8 watersheds in Colorado. **Figure 4.1** and **Figure 4.2** display an example of the total phosphorus and the total nitrogen layers produced for the case study described using the methodology outlined in Chapters 2 and 3.

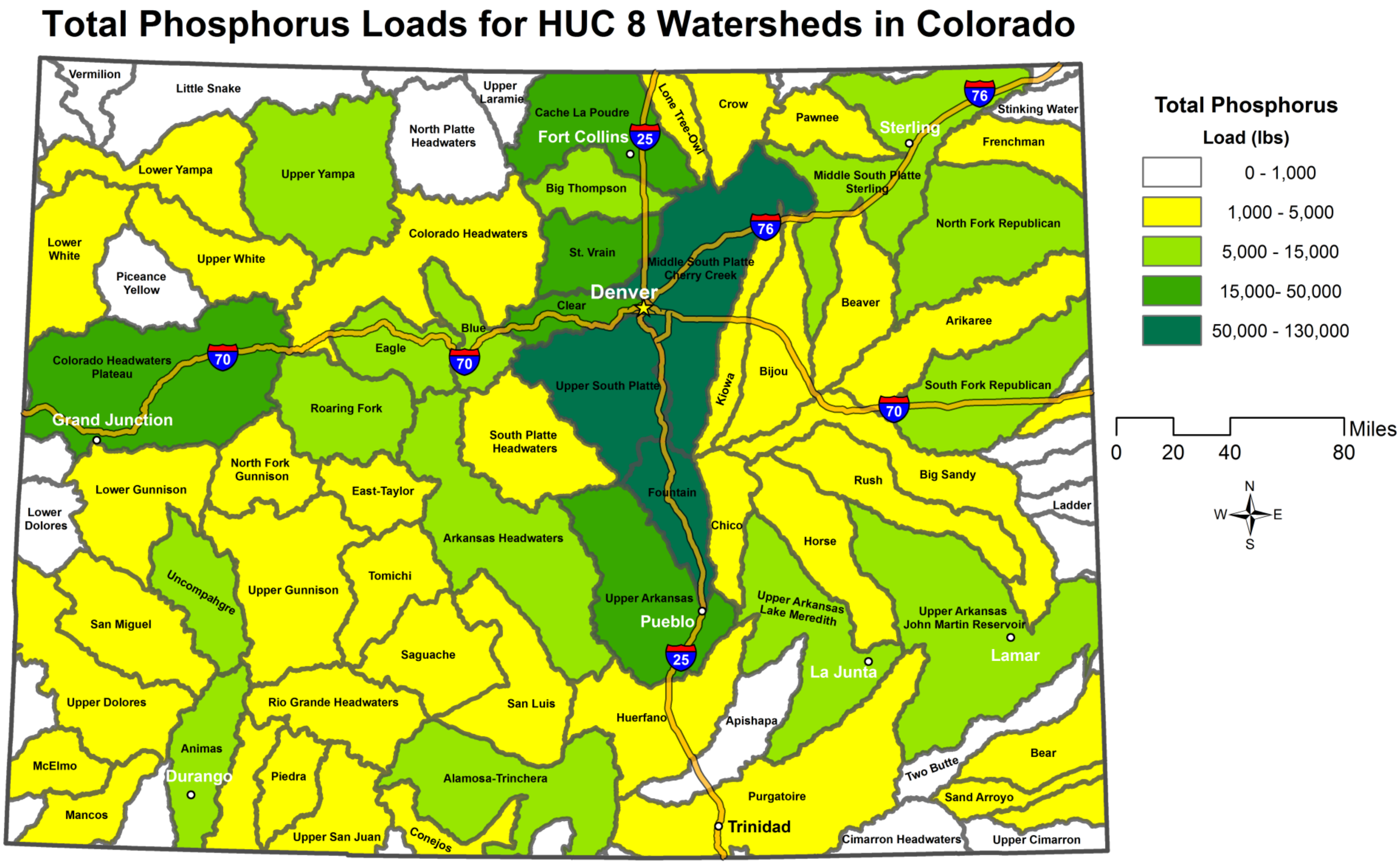

Figure 4.1: Map displaying the average annual total phosphorus load for each HUC 8 watershed in Colorado

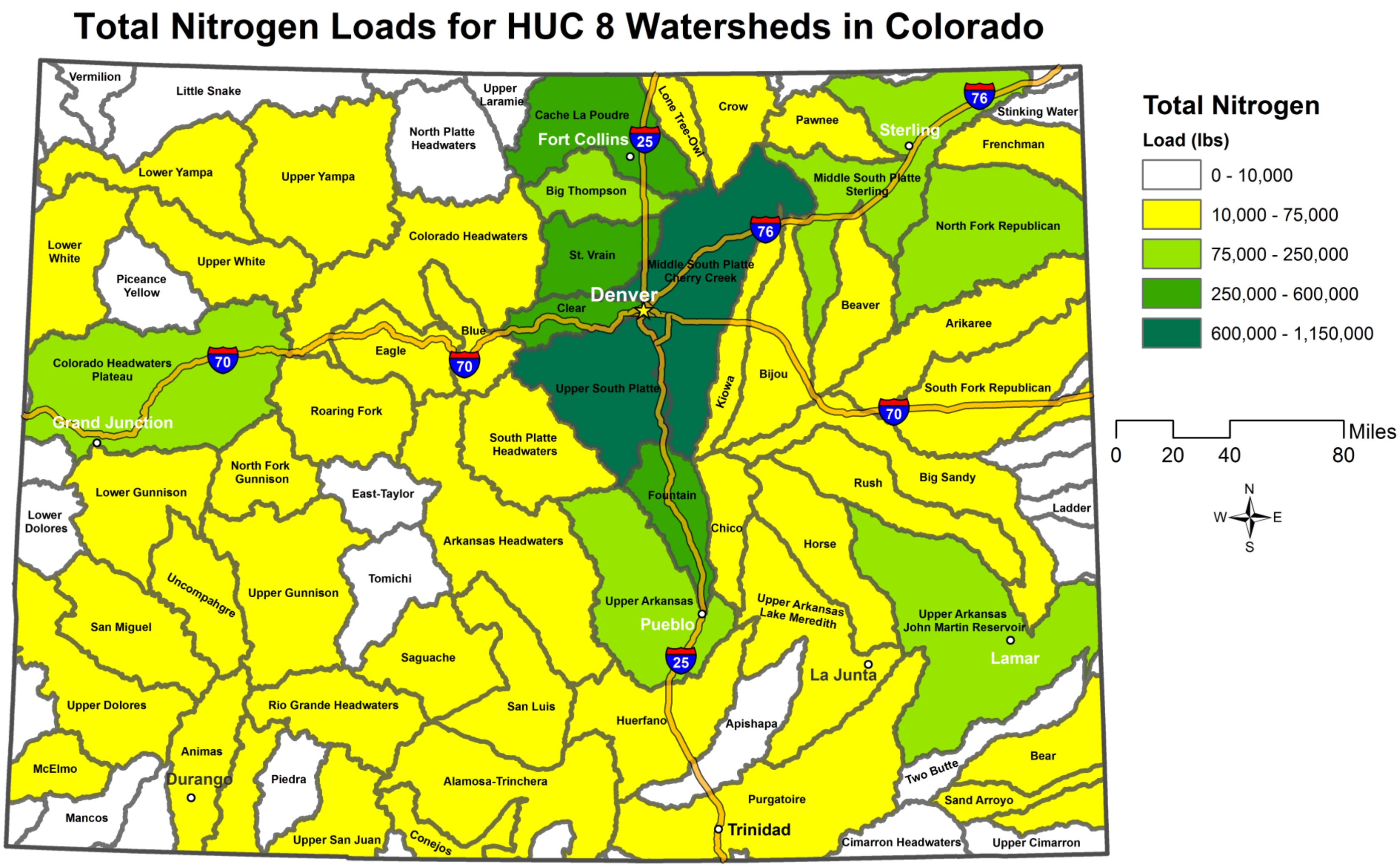

Figure 4.2: Map displaying the average annual total nitrogen load for each HUC 8 watershed in Colorado

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APPENDIX A: OBSERVED EVENT DATA FOR HOWES AND UDALL

Appendix A displays the tables of collected data for developing the observed loads for both the Howes site, in **Table A.1** and the Udall site in **Table A.2**. Included in these tables are the measured precipitation values from nearby rain gauges, recorded volume either entering or leaving the wetland basin as well as the total nitrogen and total phosphorus concentrations. Parameters recorded entering the wetland basin represent stormwater runoff without any BMP treatment, and water leaving the wetland basin represents stormwater runoff with the effect of BMP treatment. Event loads were calculated by multiplying the total volume by event mean concentration (EMC).

Table A.1: Observed event precipitation, volume, and EMC for the inflow and outflow of Howes Wetland Basin

Event	Start Date	Precipitation (in)	Inflow					Outflow				
			Volume (L)	EMC (mg/L)		Load (lbs)		Volume (L)	EMC (mg/L)		Load (lbs)	
				TN	TP	TN	TP		TN	TP	TN	TP
1	10/27/2009	1.32						5,776,627	5.983	0.580	76.20	7.39
2	3/20/2010	0.31						2,321,978	1.421	0.066	7.27	0.34
3	4/28/2010	0.68	5,026,232	2.019	0.110	22.37	1.22	9,273,752	1.709	0.131	34.94	2.68
4	5/11/2010	1.55	13,252,262	3.000	0.130	87.65	3.80					
5	5/25/2010	0.27	5,097,024	10.415	0.480	117.03	5.39					
6	6/11/2010	1.93	27,244,613	2.207	0.601	132.56	36.07					
7	7/4/2010	0.49	6,682,765	4.030	0.363	59.37	5.35	7,390,685		0.333		5.43
8	8/8/2010	0.13	2,143,384	1.597	1.439	7.55	6.80	3,256,432	1.320	0.327	9.48	2.35
9	11/9/2010	0.21	1,500,790	13.680	0.550	45.26	1.82	2,109,602	5.101	0.257	23.72	1.20
10	4/13/2011	0.95	6,116,429	5.31	0.25	71.60	3.30					
11	4/24/2011	0.49	3,313,066	4.10	0.11	29.91	0.80					
12	5/18/2011	1.73	21,361,054									
13	5/24/2011	0.19						2,306,398				
14	6/16/2011	0.35	3,344,421									
15	7/6/2011	0.28	3,650,297									
16	9/7/2011	0.39						6,801,350	3.860	0.688	57.88	10.32
17	9/14/2011	0.88	13,111,861					17,730,961	2.200	0.627	86.00	24.51

Table A.2: Observed event precipitation, volume, and EMC for the inflow and outflow of Udall Wetland Basin

Event	Start Date	Precipitation (in)	Inflow						Outflow				
			Volume (L)	EMC (mg/L)		Load (lbs)			Volume (L)	EMC (mg/L)		Load (lbs)	
				TN	TP	TN	TP			TN	TP	TN	TP
1	10/27/2009	0.27	3,907,523	5.629	0.660	48.49	5.69		5,431,602	4.10	0.34	49.10	4.07
2	10/30/2009	0.96	586,661			0.00	0.00						
3	4/21/2010	2.10	35,539,854	4.912	0.230	384.86	18.02		30,971,978	4.52	0.13	308.63	8.88
4	4/28/2010	0.76	13,948,835	0.625	0.020	19.22	0.62		7,695,917	2.20	0.06	37.24	1.02
5	5/11/2010	1.65	25,771,807	2.286	0.250	129.88	14.20						
6	5/26/2010	0.19	4,497,823	16.038	0.500	159.03	4.96						
7	6/11/2010	1.77	32,510,492	2.228	0.611	159.69	43.79						
8	7/4/2010	0.64	10,278,110	2.575	0.220	58.35	4.99		5,908,873	1.89	0.10	24.67	1.30
9	8/8/2010	0.40	4,139,243	1.455	0.924	13.28	8.43		2,147,642	1.56	0.33	7.38	1.56
10	10/22/2010	0.37							2,544,419		0.11		0.62
11	11/9/2010	0.27	4,778,786	5.911	0.370	62.27	3.90						
12	4/13/2011	0.95	10,862,722	3.51	0.12	84.11	2.87		6,896,233	3.05	0.63	46.29	9.58
13	4/24/2011	0.45	3,747,643	2.71	0.09	22.37	0.74		2,546,629	2.81	0.08	15.78	0.45
14	5/10/2011	1.68							16,636,402	1.56		57.22	
15	5/18/2011	1.74	39,339,470						29,139,374	1.80		115.89	
16	5/24/2011	0.17	5,366,201										
17	6/16/2011	0.37	6,681,096										
18	6/30/2011	0.41	5,383,680						3,667,949	8.44		68.25	
19	7/6/2011	0.35	6,587,700						4,456,465	1.91		18.77	
20	7/12/2011	0.67	14,592,264										
21	9/6/2011	0.63	7,091,344										
22	9/14/2011	1.19	17,228,106						10,975,837	1.65		39.93	

APPENDIX B: COMPARISON DATA BETWEEN OBSERVED AND ESTIMATED BMP DRAINAGE AREA

Comparison of estimated BMP treatment area to observed treatment area was conducted using a raster analysis in ArcGIS. NLCD data was used to determine where estimated BMPs would be located using the method described in Chapter 3. These were compared to a shapefile of BMP treatment drainage areas collected form the City of Fort Collins and converted to a raster with the same cell size and extent as the NLCD data. **Table B.1** contains the total cell counts within each sub-basin in Fort Collins as well as the total amount of cells being treated by water quality BMPs, the amount of private water quality BMPs and the amount of public water quality BMPs. Also included in **Table B.1** are the total amounts of cells estimated to be treated by water quality BMPs for Scenarios 1-3. Values in **Table B.1** were used for calculating numeric accuracy metrics. **Tables B.2-B.4** include the geospatial similarity data for Scenarios 1-3. Each table displays the amount of cells where there was agreement or disagreement between areas estimated to be treated by BMPs and areas actually treated by private BMPs and were created using the developed comparison treatment area (CTA) layers created for the Present/Absent matrix used for calculating the different metrics.

Table B.1: Observed raster cell counts for amount of observed BMPs and predicted BMPs for numeric accuracy calculations

Fort Collins Sub-basin	Total Cells Within Sub-basin	Total BMP Cells					
		Fort Collins			NLCD		
		WQ BMPs Total	Private WQ BMPs	Public WQ BMPs	1992 Level I Prediction	2001 Level I Prediction	2001 Level II Prediction
Cooper Slough/Boxelder	17314	2956	2956	0	4416	1595	1707
Dry Creek	9090	1842	1664	178	2558	821	952
Cache la Poudre	12417	1076	455	621	2532	573	762
West Vine	1957	48	48	0	424	34	46
Old Town	9618	6638	144	6494	891	0	148
Canal Importation	12472	3464	1585	1879	3436	303	398
Spring Creek	22051	1093	651	442	5852	287	709
Foothills	14086	3448	2472	976	5534	1662	1906
Fox Meadows	6551	1616	1223	393	3350	507	747
Mail Creek	7030	2159	1232	927	2892	166	447
McClellands	10740	4736	4723	13	6806	2124	2534
Fossil Creek	28444	7421	6889	532	9593	4198	4414
Fort Collins	153487	36576	24053	12523	48666	12297	14801

Table B.2: Raster cell counts of geospatial agreement between observed and predicted BMP locations for Scenario 2

Fort Collins Sub-basin	Total Cells Within Sub-basin	Fort Collins WQ BMPs to NLCD 1992 - L1			
		FC - Yes NLCD - Yes	FC - Yes NLCD - No	FC - No NLCD - Yes	FC - No NLCD - No
Cooper Slough/Boxelder	17314	1933	1023	2483	11875
Dry Creek	9090	694	970	1864	5562
Cache la Poudre	12417	361	94	2171	9791
West Vine	1957	32	16	392	1517
Old Town	9618	54	90	837	8637
Canal Importation	12472	722	863	2714	8173
Spring Creek	22051	332	319	5520	15880
Foothills	14086	1929	543	3605	8009
Fox Meadows	6551	799	424	2551	2777
Mail Creek	7030	792	440	2100	3698
McClellands	10740	3635	1088	3171	2846
Fossil Creek	28444	4250	2639	5343	16212
Fort Collins	153487	15539	8514	33127	96307

Table B.3: Raster cell counts of geospatial agreement between observed and predicted BMP locations for Scenario 2

Fort Collins Sub-basin	Total Cells Within Sub-basin	Fort Collins WQ BMPs to NLCD 2001 - L1			
		FC - Yes NLCD - Yes	FC - Yes NLCD - No	FC - No NLCD - Yes	FC - No NLCD - No
Cooper Slough/Boxelder	17314	1067	1889	528	13830
Dry Creek	9090	411	1253	410	7016
Cache la Poudre	12417	272	183	301	11661
West Vine	1957	25	23	9	1900
Old Town	9618	0	144	0	9474
Canal Importation	12472	296	1289	7	10880
Spring Creek	22051	71	580	216	21184
Foothills	14086	1187	1285	475	11139
Fox Meadows	6551	421	802	86	5242
Mail Creek	7030	111	1121	55	5743
McClellands	10740	1889	2834	235	5782
Fossil Creek	28444	3310	3579	888	20667
Fort Collins	153487	9071	14982	3226	126208

Table B.4: Raster cell counts of geospatial agreement between observed and predicted BMP locations for Scenario 3

Fort Collins Sub-basin	Total Cells Within Sub-basin	Fort Collins WQ BMPs to NLCD 2001 - L2			
		FC - Yes NLCD - Yes	FC - Yes NLCD - No	FC - No NLCD - Yes	FC - No NLCD - No
Cooper Slough/Boxelder	17314	1129	1827	578	13780
Dry Creek	9090	442	1222	510	6916
Cache la Poudre	12417	326	129	436	11526
West Vine	1957	28	20	18	1891
Old Town	9618	35	109	113	9361
Canal Importation	12472	340	1245	58	10829
Spring Creek	22051	207	444	502	20898
Foothills	14086	1325	1147	581	11033
Fox Meadows	6551	590	633	157	5171
Mail Creek	7030	304	928	143	5655
McClellands	10740	2173	2550	361	5656
Fossil Creek	28444	3371	3518	1043	20512
Fort Collins	153487	10282	13771	4519	124915