WATERSHED-SCALED MODELING METHODOLOGIES FOR ESTIMATING HIGHWAY STORMWATER TMDLS

by

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ABSTRACT

ZHAOCHUN MENG. Watershed-scaled modeling methodologies for estimating highway stormwater TMDLs. (Under the direction of DR. JY S. WU)

Highway networks represent a type of linear land use crossing streams and sensitive water bodies. Stormwater runoff generated from highway surface has long received much attention due to the presence of a variety of contaminants, such as sediments, heavy metals, hydrocarbons, and nutrients. Mandated by the Clean Water Act and U.S. EPA's regulations, state transportation agencies are required to secure their National Pollution Discharge and Elimination System stormwater permits; these permits issued to the agencies shall also incorporate the implementation requirements of established TMDLs. Compliance with the increasing TMDLs has brought a great pressure to the agencies in stormwater management and becomes an emerging issue requiring technically sound watershed-scaled TMDL modeling methodologies to estimate pollutant loads from the highway right-of-way land use.

To meet this demand, this research adopts a new approach to develop the watershed-scaled probabilistic volume-to-breakthrough water quality model, i.e., PVbtWQM. It consists of three components: a) a hydrologic connectivity evaluation component; b) a TN (i.e., NO3-N and TKN) loading and TMDL assessment component; and c) a TP loading and TMDL assessment component. Prior to model construction, a comprehensive review is provided to include existing methodologies in modeling highway stormwater runoff quantity and quality, and a watershed TMDL modeling case by using WARMF in the context of highways, *Falls Lake Watershed Analysis Risk Management Framework Development*. Then, the algorithms of PVbtWQM are derived to evaluate the hydrologic

connectivity of highways to receiving streams and quantify highway stormwater runoff pollutant loadings reaching streams as well as their associated uncertainties. They are further programmed in spreadsheets of Microsoft Excel and an 8-step procedure of model manipulation is presented. In addition, an approach to performing a comprehensive terrain analysis with known streams and lakes on a LiDAR-based DEM are also provided to extract the information of highway runoff drainage systems and measure the lengths of diffuse flow pathways by using the Arc Hydro tools and ArcMap.

PVbtWQM has been applied to assessing stormwater runoff nutrient TMDLs from the NCDOT road land use for the 26.74-mi^2 (17,114-acre) Lake Orange watershed in Orange County of North Carolina. It yields 0.413 $\pm$0.407 kg/d (1.426 $\pm$1.408 lb/ac.yr) of TN and 0.090 $\pm$ 0.121 kg/d (0.312 $\pm$ 0.417 lb/ac.yr) of TP. Without considering the nutrient reduction through diffuse flow paths, it yields 0.918 $\pm$0.715 kg/d (3.172 $\pm$2.473 lb/ac.yr) of TN and 0.182 $\pm$0.208 kg/d (0.628 $\pm$0.719 lb/ac.yr) of TP source loadings. For the same NCDOT land use, WARMF yields 0.139 kg/d (0.480 lb/ac.yr) of TN and 0.021 kg/d (0.072 lb/ac.yr) of TP source loading. Comparing nutrient loadings of these two models to those estimated by the simple method, PVbtWQM's simulation results fall in the range between the minimal EMCs based and the mean EMCs based estimates of the simple method, lower than and approaching the upper quartile of that range for both TN and TP loadings. If considering the reduction via diffuse flow pathways, PVbtWQM's results are 21% and 11% higher than the minimal EMCs based estimates of the simple method for TN and TP loadings, respectively. WARMF's results are significantly lower than the minimal EMCs based estimates of the simple method by 59%

and 79% for TN and TP, respectively, and also lower than the national low values and NC secondary road runoff nutrient loads.

This study has shown that PVbtWQM provides more acceptable simulation results and is more reliable than WARMF for estimating nutrient loading from the same highway land uses, and that both TN and TP loadings of stormwater runoff from NCDOT highways have been underestimated in the *Falls Lake WARMF Development* where the corresponding system coefficients should be further calibrated. Meanwhile, the simulation results of PVbtWQM have shown that the road-to-stream hydrologic connectivity will increase as precipitation increases, and that different types of flow pathways have significant impact on highway stormwater runoff nutrient loadings. In the Lake Orange watershed, the overall hydrologic connectivity of the highway network to receiving streams is 0.32 ± 0.14, ranging from 0.23 to 0.86 during the simulation period between 2004 and 2007; the original road runoff TN and TP loadings are reduced through diffuse flow pathways by 55% and 51%, respectively. Also, it has been shown that the propagation uncertainties in the final results for both TN and TP are quite large, ranging from 78% to 134%, and would be a big concern in highway stormwater TMDL assessment. In short, PVbtWQM has been proven as an informative watershed-scaled highway stormwater TMDL modeling methodology. It provides a new option for state transportation agencies to assess highway stormwater pollutant loads and support their stormwater management decision making.

DEDICATION

To my family

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LIST OF ABBREVIATIONS

AADT or ADT	annual average daily traffic
ADP	antecedent dry periods
ANSWERS	Areal Non-point Source Watershed Environment Response Simulation
BMP	Best Management Practices
CSTR	Continuously Stirred Tank Reactor
CWA	Clean Water Act
DA	drainage area
DEM	Digital Elevation Model
DOT	Department of Transportation
DSS	Decision Support System
EMC	Event Mean Concentration
EPA	U.S. Environmental Protection Agency
EPRI	Electric Power Research Institute
FHWA	Federal Highway Administration
GIS	Geographic Information System
HC	Hydrologic connectivity
ILWAS	Integrated Lake-Watershed Acidification Study
LA	Load Allocation
lb/ac.yr	Pounds per acre per year
LiDAR	Light Detection And Ranging
mg/L	milligram per liter
MLR	multiple linear regression
MOS	Margin of Safety

NCDOT	NC Department of Transportation
NH4	Ammonium
NHD	National Hydrography Dataset
NLCD	National Land Cover Data
NO_3-N	Nitrate as nitrogen
NPDES	National Pollutant Discharge and Elimination System
NPS	Nonpoint Sources
NRCS	Natural Resources Conservation Service
NURP	Nationwide Urban Runoff Program
PCBs	Polychlorinated Biphenyls
PS	Point Sources
PVbtM	Probabilistic “Volume to Breakthrough” Model
PVbtWQM	Probabilistic “Volume to Breakthrough” Water Quality Model
SCR	seasonal cumulative rainfall
SCS	Soil Conservation Service
SMC	Site mean concentration
SSURGO	Soil Survey Geographic database
SWMM	Storm Water Management Model
SWMP	Storm Water Management Plan
SWPPP	Storm Water Pollution Protection Plan
TDS	Total Dissolved Solids
TER	total event rainfall
TKN	Total Kjeldahl Nitrogen
TMDL	Total Maximum Daily Load
TN	Total Nitrogen

TP	Total Phosphorus
TSS	Total Suspended Sediment
USEPA	United States Environmental Protection Agency
USDA	U.S. Department of Agriculture
Vbt	Volume to break through
WARMF	Watershed Analysis Risk Management Framework
WASP	Water Quality Analysis Simulation Program
WLA	Waste Load Allocation
WQ	Water quality

LIST OF SYMBOLS

A	Drainage area
A_d	Drainage area of a directly connected road segment
A_{df}	Drainage area of a diffusely connected road segment
A_T	Total drainage area of a road or road network right of way
C	Concentration of a pollutant in stormwater runoff
C_{V_X}	Concentration of a pollutant in the runoff reaching a stream network
E	Uncertainty term in general
E_W	Uncertainty of a pollutant load or loading rate
I_a	Impervious fraction of drainage area
l_{pred} *or* l	Predicted mean length of a flow plume
P	Precipitation
P_e	Effective precipitation
R_v	Runoff coefficient
V_{out}	Volume of runoff or out flow leaving the outlet or road edge
V_{bt5}	Mean volume of overland flow required for a flow plume to extend 5 m from a road edge or a road drain
V_T	Total volume of road runoff
V_{X_d}	Predicted volume of runoff reaching stream for directly connected flow paths
$V_{X_{df}}$	Predicted volume of runoff reaching stream for diffuse overland flow paths
V_x	Mean volume of overland flow to pass any point a distance x downslope of the outlet or road edge
V_{X_0} or V_X	Mean volume of overland flow reaching the stream network
V_{X_T}	Total predicted volume of runoff reaching stream

W	General Term for pollutant loads or loading rates
x	Length of an overland flow pathway or a distance downslope of the outlet
$X\ or\ X_0$	Length of a diffuse flow path from road edge or outlet to the stream network
z	A factor reflecting the desired level of confidence
ε_l	Maximal absolute uncertainty relative to V_{out}
ε_X	Absolute uncertainty of V_{X_0}
ε'_X	Fractional uncertainty or percent uncertainty of V_{X_0}
σ_l^2	Variance associated with l_{pred}
σ^2_{vbt5}	Variance associated with V_{bt5}
$\sigma^2_{V_x}$	Variance associated with V_x
$\sigma^2_{V_X}$	Variance associated with V_{X_0}
σ_T^2	Total variance of the predicted runoff from the entire road network
ψ	Road-to-stream connectivity for individual road segments
Ψ	Overall road-to-stream connectivity for the entire road network

CHAPTER 1: INTRODUCTION

A Total Maximum Daily Load (TMDL) is a technical calculation of the maximum amount of a pollutant that a waterbody can receive and still safely meet water quality (WQ) standards. The TMDL program was initially prescribed by the U.S. Congress in the Clean Water Act (CWA) of 1972. Under section 303(d) of the CWA and the U.S. Environmental Protection Agency (EPA)'s WQ Planning and Management Regulations (40 Code of Federal Regulations Part 130), states, territories, and authorized tribes are required to identify and develop lists of impaired waters. These are waters that are too polluted or otherwise degraded to meet the WQ standards set by states, territories, or authorized tribes after the application of technology-based or other required controls. The law and regulations require that these jurisdictions submit biennially to EPA their lists of impaired waters, establish priority rankings for these waters on the lists, and develop TMDLs for them.

However, although the TMDL program was enacted in the CWA of the early 1970s, it had not been started until the early 1990s (Wu and Meng 2010). Since the middle of 1990s, the TMDL program, in conjunction with the National Pollutant Discharge and Elimination System (NPDES) permitting program, has dramatically developed to be one of two major programs serving to restore the nation's impaired waters.

Nationally, the number of waterbodies listed as impaired doubled from 21,749 in 1998 to 43,446 in 2008 (Taylor 2009); Nearly 44,000 TMDLs have now been developed and approved, addressing more than 46,000 listed impairments (Figure 1.1 and Table 1.1).

Currently, there are 40,283 impaired waters that have been placed on the 303(d) list due to 71,495 causes of impairment (USEPA 2011). Among various causes of impairment covering both addressed and listed (Table 1.1 and Table 1.2), the top 13 groups of pollutant account for 92.5% of the total, including pathogen (17.1%), metals (other than mercury) (13.1%), nutrients (10.8%), mercury (9.1%), sediment (8.8%), organic enrichment/oxygen depletion (7.2%), polychlorinated biphenyls (PCBs, 5.6%), pH/acidity/caustic conditions (4.7%), temperature (4.1%), turbidity (3.6%), cause unknown - impaired biota (3.1%), salinity/ total dissolved solids (TDS)/chlorides/sulfates (2.8%), and pesticides (2.5%). The remaining 21 groups of classified pollutants only accounted for 7.5% of the total number of impairment.

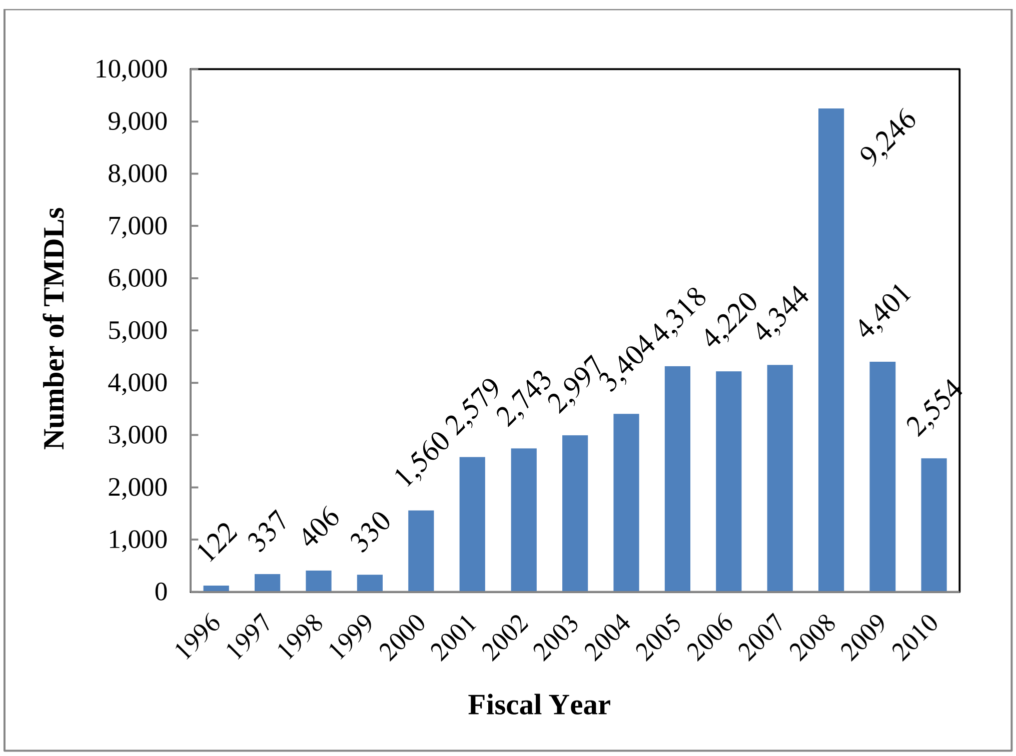


Figure 1.1: Numer of TMDLs approved by fiscal year

Table 1.1: Top 13 groups of pollutants addressed in the national TMDLs

Pollutant Group	Number of TMDLs	Number of Causes of Impairment Addressed	% of Total
Pathogens	9,013	9,248	19.9%
Metals (other than Mercury)	7,768	7,936	17.1%
Mercury	6,933	6,965	15.0%
Nutrients	4,751	5,663	12.2%
Sediment	3,539	4,090	8.8%
Organic Enrichment/ Oxygen Depletion	1,910	2,013	4.3%
Temperature	1,812	1,820	3.9%
pH/Acidity/Caustic Conditions	1,721	1,758	3.8%
Salinity/TDS/Chlorides/Sulfates	1,533	1,582	3.4%
Ammonia	1,085	1,148	2.5%
Turbidity	1,045	1,181	2.5%
Pesticides	1,004	1,064	2.3%
PCBs	408	429	0.9%
Other 17 groups of pollutant	1,454	1,931	3.2%
Total	43,976	46,399	100%

Also, in terms of types of pollutant sources, the TMDLs completed to date for nonpoint sources far outnumber those established for point sources. As shown in Figure 1.2 (USEPA 2010), 51% of TMDLs have been developed for non-point sources; 5% for point sources; and 44% for a combination of both point and non-point sources. This trend mirrors the fact that non-point source causes of impairment have been dominated the nation’s impaired waters lists.

Based on the previously mentioned number of impaired waters on the current 303(d) lists, there are nearly 70,000 TMDLs identified by states, territories, and authorized tribes, which are required to develop in the next 8-13 years (USEPA 2008). Not surprisingly, as more and better receiving WQ data become available, it is likely that the number of additional impaired waterbodies requiring TMDLs will continue to increase.

Table 1.2: Top 13 groups of pollutants for 303(d) Listed Waters

Pollutant Group	Number of Causes of Impairment Reported	% of Total
Pathogens	10,963	15.3%
Metals (other than Mercury)	7,461	10.4%
Nutrients	7,031	9.8%
Organic Enrichment/Oxygen Depletion	6,526	9.1%
Sediment	6,272	8.8%
PCBs	6,179	8.6%
Mercury	3,781	5.3%
pH/Acidity/Caustic Conditions	3,733	5.2%
Cause Unknown - Impaired Biota	3,419	4.8%
Turbidity	3,085	4.3%
Temperature	3,012	4.2%
Pesticides	1,866	2.6%
Salinity/TDS/Chlorides/Sulfates	1,758	2.5%
Other 21 groups of pollutant	6,409	9.0%
Total	71,495	100%

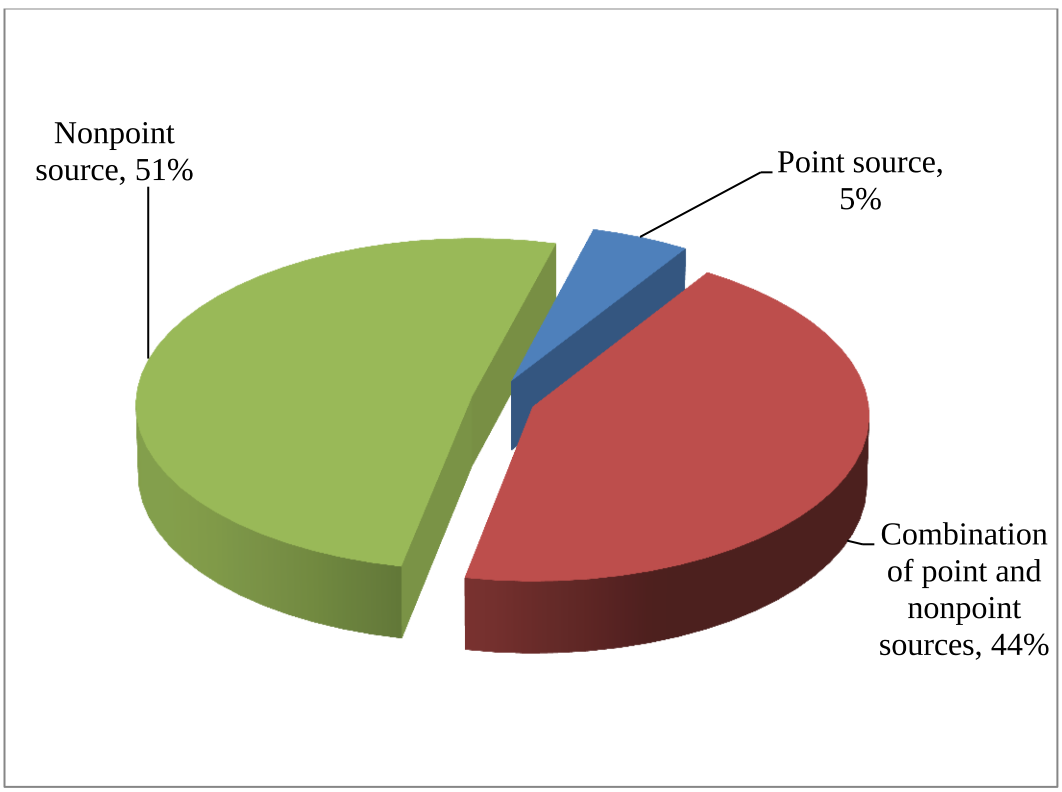


Figure 1.2: Nonpoint source, point source, and mixed TMDLs

Technically, the process of TMDL development and implementation for an impaired waterbody in a watershed typically involves the use of USEPA-supported models to determine the amount of a specific pollutant originating from major land-use types (e.g. agricultural, urban, and rural) and/or various pollutant sources (e.g. point sources and diffuse sources). These TMDL models incorporate land-based processes for runoff generation and pollutant delivery, and the resulting TMDL allocations are appropriate for watershed-level decisions.

Highways that are conventionally recognized as a nonpoint source are a unique type of land use development in that their impervious lanes span many miles and intersect most watersheds, frequently crossing both large and small drainage divides. The construction, operation, and maintenance of these highways have been proven to be one important source of pollutants including sediments, trace metals, nutrients, and others, which negatively affect the water quality of receiving waters (Gupta et al. 1981, Mar et al. 1982, USEPA 1983, Dupuis et al. 1985, Driscoll et al. 1990, Barrett et al. 1995 and 1998, Kayhanian et al. 2002, Wu and Allan 2001 and 2010a). Consequently, highway runoff has received much attention in the processes of TMDL development and implementation.

However, in the vast research literature concerning highway stormwater runoff, most studies were performed to characterize the event-based highway runoff pollutants on specific sites. Although many studies attempted to develop regression models from field and experimental data to predict event mean concentrations (EMCs) and/or loading rates for highway runoff constituents (Kobriger et al. 1981, Chui et al. 1982, Kerri et al. 1985, Driscoll et al. 1990, Barrett et al. 1998, Irish et al. 1998, Wu and Allan 1998 and 2004, Vaze and Chiew 2004, Kayhanian et al. 2007), few studies focused on quantification of the runoff, its associated pollutant loads, and/or loading rates from highways to stream systems at the watershed scale by taking into account the highway-to-stream hydrologic connectivity as well as the spatial relationships between the highway network and the stream network. Theoretically, although each land-use based watershed model can be used to classify highways into a separate category of land use/land cover, few are now characterize in that manner. As a result of a lack of the highway component in most TMDL calculations, it is difficult for highway management agencies or departments of transportation (DOTs) to manage TMDLs implemented in their jurisdictions. Especially with dramatic increase of the number of TMDLs that have been and will be developed, the implementation of these TMDLs becomes a pressing issue for most DOTs and would command larger portions of DOTs' resources (McGowen et al. 2009).

This research is intended to review an established model and develop a watershed-scaled modeling methodology to calculate TMDLs for highway runoff and its associated pollutants. It includes the following six chapters. Chapter 2 defines the major objectives of this research. Chapter 3 provides a comprehensive review of literature on the modeling methodologies for highway runoff and pollutant loading calculations. Chapter 4 introduces a watershed analysis risk management framework (WARMF) as a baseline watershed TMDL model for highways and then reviews a case in which this model is applied to estimating the highway TMDL components. Chapter 5 develops the algorithms for a new watershed TMDL model, named as the probabilistic volume-to-breakthrough water quality model, or PVbtWQM. Chapter 6 describes how to use the PVbtWQM model to estimate the highway nutrient loads and TMDLs for the Lake Orange watershed and provides a comprehensive terrain analysis method by using Arc Hydro Tools to extract the highway drainage system and flow-path information from the LiDAR-based Digital Elevation Model (DEM). The modeling results of PVbtWQM are also summarized in this chapter. Chapter 7 discusses the differences of the simulation results among PVbtWQM, WARMF and others, and finally provides some recommendations on model improvement as a conclusion.

CHAPTER 2: STUDY OBJECTIVES

As described in Chapter 1, hundreds of TMDLs have been developed each year. Compliance with these TMDLs has brought an increasing pressure to DOTs in highway stormwater management and becomes an emerging issue requiring technically sound watershed-scaled TMDL modeling methodologies to estimate pollutant loads of stormwater runoff from the highway land use.

This research is intended to explore the watershed stormwater modeling methodologies in TMDL estimations for highway runoff pollutants, by reviewing the up-to-date established highway stormwater models and develop a new and improved water quality model to estimate highway runoff pollutant loading rates and their uncertainties by extending a probability model, based on the concepts of "volume-to-breakthrough" and road-to-stream connectivity. The major tasks of this study include:

- To review a state-of-the-art watershed TMDL modeling case in the context of highways, *Falls Lake Watershed Analysis Risk Management Framework Development*, and adopt the Watershed Analysis Risk Management Framework (WARMF) as a baseline watershed TMDL modeling methodology for estimating pollutant loads from the entire road network in a watershed.
- To develop the algorithms for a new comprehensive watershed-scaled probabilistic volume-to-breakthrough water quality model (PVbtWQM) to quantify the total volume of stormwater runoff, the hydrologic connectivity, the

average pollutant loading rates, and their associated uncertainties from the entire road network to the stream network in a watershed.

- To populate the algorithms and program the PVbtWQM model into spreadsheets of Microsoft Excel and use it as an alternative highway stormwater TMDL modeling methodology for one upstream subwatershed, the Lake Orange watershed simulated in the *Falls Lake Watershed Analysis Risk Management Framework Development*, as a demonstration of how to implement the PVbtWQM model as well as model comparison between both PVbtWQM and WARMF. Meanwhile, the approach to performing a comprehensive terrain analysis on a LiDAR DEM is described in order to extract hydrological information and measure lengths of diffuse overland flow pathways of highway runoff, using Arc Hydro Tools and ArcMap.
- To compare the results obtained from PVbtWQM simulation to those estimated by the WARMF and other methods in modeling highway nutrient (i.e., total nitrogen and total phosphors) TMDLs at the same subwatershed and provide recommendations on model improvement for both PVbtWQM and WARMF.

CHAPTER 3: LITERATURE REVIEW ON HIGHWAY STORMWATER RUNOFF QUANTITY AND QUALITY MODELING METHODOLOGIES

According to U.S. EPA (2010), among over 40,000 TMDLs developed, 51% of them concern non-point sources (NPS) and 95% are related to NPS (Figure 1.2). In fact, stormwater runoff drained from various types of urban and agricultural land uses has been recognized for decades as a major NPS of pollutants impairing receiving waters (Novotny and Chesters 1981; Konrad 1985; Cunningham 1988; Novotny and Olem 1994; Characklis and Wiesner, 1997; Davis et al., 2001; Vaze and Chiew, 2004). Among others, the runoff from highways has received significant attention due to its abundance of contaminants, such as sediments, heavy metals, hydrocarbons, and nutrients. Mandated by the CWA and USEPA's regulations, state transportation agencies (i.e., DOTs) are required to secure their National Pollution Discharge and Elimination System (NPDES) stormwater permits. These NPDES permits issued to DOTs shall also incorporate the implementation requirements of established TMDLs. Hence, it is necessary to quantify and treat highway runoff as a separately identifiable contributor to the overall NPS pollutant loads rather than traditionally aggregating it into other watershed runoff, in the process of water quality modeling and TMDL development.

Currently, there are a variety of modeling methodologies that have been developed, in combination with field monitoring data, and widely adopted to estimate highway stormwater runoff quantity and quality since they can potentially save time, reduce cost, and minimize the need for experimentally evaluating management alternatives. This chapter will focus reviewing the methodologies commonly used for predicting pollutant loads from highway stormwater runoff, following a brief discussion on both the pollutant sources and the factors that influence highway stormwater runoff quantity and quality.

3.1 Highway runoff pollutants and their sources

Highway construction changes the natural landscape and leads to the hydro-modification of the existing drainage systems by cut and fill, compaction, and pavement. For established and widespread highways in a watershed, the volume of stormwater excess (i.e., runoff) has been dramatically increased due to their paved impervious road surfaces and compact settings; the runoff-entrained contaminants have also been increased due to vehicles traffic and road maintenance. Table 3.1 shows the typical highway runoff pollutants and their major sources (USEPA 1993).

Table 3.1: Highway runoff pollutants and their primary sources

Constituent	Primary Sources
Particulates	Pavement wear, vehicles, atmosphere
Nutrients (N, P)	Atmosphere, roadside fertilizer application
Pb	Tire wear, automobile exhaust
Zn	Tire wear, motor oil, grease
Fe	Auto body rust, steel highway structures, moving engine parts
Cu	Metal plating, brake lining wear, moving engine parts, bearing and bushing wear
Cd	Tire wear, roadside insecticide application
Cr	Metal plating, moving engine parts, brake lining wear
Ni	Diesel fuel and gasoline, lubricating oil, metal plating, brake lining wear, asphalt paving
Mn	Moving engine parts
Cyanide	Anticake compound used to keep deicing salt granular
Na, Ca, Chloride	Deicing salts
Sulphate	Roadway beds, fuel, deicing salts
Petroleum	Spills, leaks, or blow-by of motor lubricants, antifreeze and hydraulic fluids, asphalt surface leachate

In general, these pollutants fall into the following five different categories: a) organic carbon; b) suspended and dissolved solids; c) petroleum hydrocarbons; d) metals; and e) nutrients (Kayhanian et al. 2007).

In addition to wet and dry atmospheric deposition, the primary sources of highway runoff pollutants include: a) traffic activities; b) fluid leakage and spills; c) vehicular component wear; d) roadway maintenance; and e) pavement degradation (Wu and Allan 2010b).

3.2 Factors influencing highway runoff quantity and quality

Identification and understanding of the factors that influence highway runoff quantity and quality not only lay the firm foundation of highway runoff modeling but also help decision-makers take viable measures to mitigate and eliminate the impact of highway runoff pollutants. The analysis of cause and effect of pollutants on highway runoff can be performed either theoretically from scientific relevance suggestions, or statistically from field monitoring data, or in the combination of both (Irish et al. 1998). Numerous studies (Gupta et al. 1981; Driscoll et al. 1990; Kayhanian et al. 2007; Wu and Allan 1998, 2001, and 2010b) suggest that the factors affecting both quantity and quality of highway stormwater runoff include:

- Climatic conditions
    - Precipitation: precipitation form (rain, sleet, or snow); precipitation volume in a storm event, seasonally, or annually; precipitation intensity and duration; precipitation frequency and interval between storm events; and wet and try seasonal distribution of rainfall.
    - Surface wind speed and direction.

- Temperature.
- Ambient air quality condition: mainly atmospheric dry and wet deposition of pollutants including primary and secondary air pollutants such as particulate matter, i.e., small solid and liquid particles (dust, smoke, sand, pollen, mist, and fly ash) and gaseous substances (carbon monoxide, sulfur dioxide, nitrogen oxides, and volatile organic compounds).

- Highway site situations
  - Highway configuration: ground level, elevated/filled, and depressed/cut.
  - Road types and conditions: pavement materials (concrete or asphalt); pavement patterns (conventional, open-graded, or others); and road age and quality condition.
  - Vegetation on the road right-of-way: vegetation types (trees or shrubs) and growth/ health condition.
  - Drainage patterns and conditions: drainage spacing; drainage area and its imperviousness fraction; and the road-to-stream hydrologic connectivity or types of road runoff flow pathways (road-stream crossings, concentrated ditch/channel/pipe flow, or diffuse overland sheet flow).
- Operational situations
  - Traffic characteristics: traffic volume during a storm event and during its antecedent dry period; speed; and braking.
  - Vehicle characteristics: vehicle type; emission; age; and maintenance.
  - Vehicular transported, generated, and deposited inputs.

- Road maintenance practices: road repair; street sweeping; deicing; roadside grass mowing; and herbicides application.
- Institutional characteristics: anti-litter laws; speed limit enforcement; fuel additives regulations; and car emission regulations.
- Accidental spills.

- Surrounding land use
  - Land use types: residential, commercial, industrial, rural/agricultural, or forested.

The impact of highway stormwater runoff on a receiving waterbody basically results from its entrained pollutant loads or loading rates delivered to the waterbody, which are usually defined as the products of their event mean concentrations (EMCs) and the volume of delivered runoff or the products of their EMCs and the flow rate of delivered runoff, respectively. Both the delivered runoff and the associated pollutant concentrations are primarily determined by their initial amounts generated from source areas (i.e., highway land uses) and types of road runoff flow pathways. The results of NURP study (USEPA 1983) suggest that although pollutant EMCs are essentially uncorrelated with runoff volume, mass loads are very strongly influenced by runoff volume. Driscoll et al. (1990) stated that the relationship between runoff and rainfall exhibits a strong linear relation; however, at a given site, the runoff coefficient defined as the ratio of runoff volume to rainfall volume is independent of the rainfall amount and can be treated as a constant. In the meantime, they pointed out that although there are many possible influences on the runoff coefficient at a site, the most important is the percent imperviousness of the site. With the statistical analysis for highway stormwater runoff quality data collected from 34 urban and non-urban highway sites throughout California during 2000-2003, Kayhanian et al. (2007) found that the parameters that have significant impacts on highway runoff pollutant EMCs include total event rainfall, cumulative seasonal rainfall, antecedent dry period, contributing drainage area, and annual average daily traffic. Surrounding land uses and geographic regions also have a significant impact on runoff quality. Based on three studies in the NCDOT highway stormwater program, Wu and Allan (2010b) proposed that multiple causal variables can be divided into three essential data categories: a) hydrology; b) roadway traffic conditions; and c) atmospheric deposition; these causal variables which have been shown to correlated with runoff pollutant loads include: antecedent dry period (ADP); average rainfall intensity; five-minute peak intensity; runoff coefficient; traffic counts during storm events; traffic counts during the ADP; and bulk deposition. Although all the aforementioned factors have been confirmed to have impacts to some extent site-specifically and pollutant-specifically on either concentration or runoff or both, the authors of most studies obviously agree that the most important factors or parameters that impair highway stormwater runoff quantity and quality include traffic volume, rainfall size and intensity, antecedent dry period, impervious fraction of highway drainage area, and atmospheric deposition.

3.3 Methodologies in modeling highway runoff quantity and quality

Over the past three decades and perhaps longer, a variety of methodologies have been developed for addressing the characteristics and prediction of pollutions in stormwater runoff from highways. In the same period of time, more than 60 models have been developed to simulate stormwater runoff quantity and quality from urban and non-urban areas (USEPA 2005b). A number of these models can also be used to estimate pollutant loads from highway stormwater runoff. A comprehensive review of most of the methodologies for modeling highway runoff quantity and quality has been provided by Driscoll et al. (1990). In general, these methodologies can be grouped into the following two categories:

- Regression models, which are heavily reliant on field monitoring data and the analysis on the relationship of causal and explanatory variables by using statistical techniques and regression methods;
- Simulation models, which are typically inclined to generalize and utilize the principal mechanisms of generation, transport and fate of both stormwater runoff and its entrained pollutants.

3.3.1 Regression models of highway stormwater runoff

In the modeling domain of highway stormwater runoff quantity and quality, most methodologies or models fall into the former category because various regression methods and statistical techniques have been a long history, are widely and frequently adopted to analyze the origin and the loading rates of highway stormwater runoff pollutants as affected by each or a combination of causal variables. The major procedures of these approaches involve testing correlations between pollutant loads and multiple causal variables, eliminating variables with the least influence, and optimizing model sensibility and significance. The resulting regression models or equations are usually dependent on the specific road runoff contaminants of interest.

The earliest study using regression methods can be traced back to the early 1980s (Chui et al. 1982), followed by Kerri et al. (1985), Schueler (1987), Driscoll et al. (1990), Driver and Tasker (1990), Irish et al. (1998), Wu et al. (1998), Kayhanian et al. (2007), Wu and Allan (2010b), and many others.

Chui et al. (1982) developed a model to correlate a load of the total suspended solids (TSS) with runoff coefficients and vehicular traffic during storm events. The loads of other pollutants were then estimated from the TSS load based on a multiplier as a constant or as a function of the average daily traffic (ADT). Kerri et al. (1985) also suggested that the number of vehicles during a storm be a satisfactory independent variable for estimating the loads of selective pollutants.

Schueler (1987) generalized a simple method based on regression correlations to estimate stormwater runoff pollutant loads for urban areas including road surfaces. He proposed that the annual pollutant loads from different urban land uses can be given as:

$$W = (0.227)P_e AC \qquad (3.1)$$

where, W = annual load in pounds (lb); A = drainage area in acres (ac); C = pollutant concentration in milligrams per liter (mg/L); 0.227 = unit conversion factor; and P_e = annual effective rainfall in inches (in), which is given by:

$$P_e = PP_j R_v \qquad (3.2)$$

$$R_v = 0.05 + 0.9 I_a \qquad (3.3)$$

where, P = annual rainfall (in); P_j = fraction of annual rainfall events that produce runoff (usually 0.9); R_v = runoff coefficient; and I_a = impervious fraction (%).

By assembling and analyzing the monitoring data from 993 individual storm events at thirty-two highway runoff sites in eleven states of the United States, Driscoll et al. (1990) adopted a statistical technique to develop a set of predictive models to estimate pollutant discharges from highway runoff. The procedure includes initial estimates of a runoff flow rate and the volume based on local rainfall properties and runoff coefficients, determination of the site median concentration for a particular pollutant of interest, and final computation of the annual or seasonal mass loads. The site median concentrations ($SMCs$) of highway runoff pollutants were observed to be linearly correlated to ADT, expressed as:

$$SMC = a * ADT + b \tag{3.4}$$

where, SMC = the site median concentration of a pollutant in mg/L; ADT = average daily traffic in 1000 vehicles per day; and a, b = the coefficients given in Table 3.2 for those pollutants that show a statistically significant correlation in their analyses.

Table 3.2: Regression coefficients for SMC estimation in Driscoll et al.(1990)'s model

Pollutant	a	b	R-squared
Volatile suspended solids (VSS)	0.385	11.	42%
Total Kjeldahl nitrogen (TKN)	0.01	1.06	25%
Chemical oxygen demand (COD)	0.874	47.	40%
Total organic carbon (TOC)	0.233	5.	42%
Zn	0.003	0.07	70%

These established highway runoff WQ regression models are simple and easy for use. As shown in their predictive equations, however, a major shortage is that only few factors had been taken into account to analyze and predict highway stormwater runoff quantity and quality. One factor is the runoff coefficient and another is traffic volume, either the traffic volume during storm events or average daily traffic. Neither approach included variables such as physical, land-use, climatic characteristics, nor was the uncertainty of the predicted pollutant load formulated and analyzed in the process of regression modeling. In terms of these two aspects, a significant step was made by Driver and Tasker (1990), which has great influence on the later studies. By adopting a more comprehensive multiple linear regression (MLR) procedure to analyze all the urban storm-runoff data available then from U.S. Geological Servey (USGS) and USEPA urban storm-runoff data bases, Driver and Tasker (1990) developed four sets of seventy-five linear regression equations for three statistically different regions delineated by mean annual rainfall. Among them, thirty-four equations were developed for estimating storm runoff constituent loads and storm runoff volumes, thirty-one were for storm runoff mean concentrations of constituents, and ten for mean seasonal or mean annual constituent loads. All the equations in their MLR model take the form of

$$logY = \beta_0 + \beta_1 logX_1 + \beta_2 logX_2 + \cdots + \beta_n logX_n \quad (3.5)$$

where, Y = estimated storm-runoff load or volume (response variable); $X_1, X_2, \ldots, X_n$= physical, land-use, or climatic characteristics (explanatory variables); $\beta_0, \beta_1, \beta_2, \ldots, \beta_n$= regression coefficients; and n = number of explanatory variables in the regression model.

The standard error of an estimate was also calculated in all the regression models using the following equation:

$$SE = 100\sqrt{\left(e^{5.302\sigma^2} - 1\right)} \quad (3.6)$$

where, SE = the standard error of an estimate, in percent; and σ^2 = the mean square error in log (base 10) units.

Driver and Tasker (1990) dealt with storm runoff from urban areas in general and did not specifically look into highway runoff pollutant loads in detail. Following the procedure and format similar to those used by Driver and Tasker, Irish et al. (1998) took the MLR analysis for storm water loadings from an expressway in the Austin area of Texas and determined that the pollutant load in highway runoff can be explained by causal variables measured during the rainstorm event, the antecedent dry period (ADP), and the previous storm event. They also found that the loads for each of the constituents in highway runoff are dependent on a unique subset of identified variables and that the processes responsible for the generation, accumulation, and washoff of pollutants are constituents-specific.

The regression model of Irish et al. (1998) provides the event pollutant load for a specific pollutant, expressed as:

$$Y = \beta_0 + (\beta_{s1}X_{s1} + \beta_{s2}X_{s2} + \cdots + \beta_{si}X_{si}) + (\beta_{a1}X_{a1} + \beta_{a2}X_{a2} + \cdots + \beta_{aj}X_{aj}) + (\beta_{p1}X_{p1} + \beta_{p2}X_{p2} + \cdots + \beta_{pk}X_{pk}) + E \quad (3.7)$$

where, Y = the event pollutant load in grams per square meter (g/m2); β = model coefficients; X = model variables; E = an uncertainty term; $s1, s2, \ldots,$ and si = subscripts of variables from the current storm; $a1, a2, \ldots,$ and aj = subscripts of variables from the antecedent dry period; and $p1, p2, \ldots,$ and pk = subscripts of variables from the preceding storm event.

All the constituents predicted, their identified variables, and regression coefficients are given in Table 3.3.

Kayhanian et al. (2007) developed a multiple linear regression (MLR) model as a predictive tool to estimate event mean concentrations (EMCs) of road runoff constituents. Their MLR model takes the form of

$$ln\,(EMC) = \beta_0 + a\beta_1 + b\beta_2 + c\beta_3 + d\beta_4 + e\beta_5 \quad (3.8)$$

where, EMC= event mean concentrations in μg/L for trace metals and mg/L for others; $a, b, c, d,$ and e = model coefficients for five significant independent variables; β_0 = the coefficient as a constant; $\beta_1 = \ln(\text{TER})$. TER denotes the total event rainfall in millimeters (mm); $\beta_2 = \ln(\text{ADP})$. ADP denotes antecedent dry period in days; $\beta_3 = (\text{SCR})^{\frac{1}{2}}$. SCR denotes seasonal cumulative rainfall (SCR), mm; $\beta_4 = \ln(\text{DA})$. DA denotes drainage area in ha; and $\beta_5 = \text{AADT} \times 10^{-6}$. AADT denotes average annual daily traffic in vehicles/day. The values for all the coefficients are given in Table 3.4.

Table 3.3: Coefficients of Irish et al.(1998)'s regression model

Constituent	N	S	R^2	β_0	T_{DOS}	V	I	VDS	T_{ADP}	ATC	T_{PS}	V_{PS}	I_{PS}
TSS	402	0.5482	0.93	0.2556	–	0.3068	2.0181	–	0.0037	–	–	–	-2.9865
VSS	401	0.0630	0.93	-0.0186	–	0.0348	0.1649	–	0.0005	–	–	0.0069	-0.6721
COD	420	0.1169	0.95	-0.0613	0.0007	0.0773	0.7785	–	-0.0041	6.0E-6	–	–	–
BOD5	398	0.0145	0.86	-0.0081	–	0.0035	0.0619	1.1E-5	–	1.5E-7	–	–	–
O&G	263	0.0054	0.94	-0.0004	–	0.0030	–	1.0E-5	–	–	–	–	–
P	411	0.0005	0.90	-0.0005	3.3E-6	0.0002	0.0032	–	–	5.1E-9	–	–	–
$NO3^-$	351	0.0010	0.95	-0.0015	–	0.0006	0.0086	–	2.3E-5	–	–	–	–
Fe	399	0.0084	0.92	-0.0028	–	0.0042	0.0282	–	–	4.9E-9	-3.2E-6	0.0003	-0.0241
Zn	399	0.0007	0.92	0.0002	2.5E-6	0.0001	–	–	–	–	–	–	-0.0023
Pb	319	0.0004	0.68	0.0008	–	6.5E-5	-0.0020	8.0E-8	–	–	–	–	–
Cu	398	8.1E-5	0.90	1.9E-5	3.8E-6	2.4E-5	–	-2.4E-7	–	–	–	–	–

Note:

a) Terms/acronyms: N = the number of observation; S = standard deviation error (g/m^2); R^2 = correlation coefficient; β_0 = the constant term in the equation (g/m^2); T_{DOS} = total duration of storm (minutes); V = the total volume of flow per unit area of watershed during the storm (L/m^2); I = intensity = V/T_{DOS} (L/m^2-min); VDS = average number of vehicles traveling through the storm in a single lane (vehicles/lane); T_{ADP} = total duration of the antecedent dry period (hours); ATC = average number of vehicles during the antecedent dry period in a single lane (vehicles/lane); T_{PS} = the total duration of the preceding storm (minutes); V_{PS} = the total volume of flow per unit area of watershed (L/m^2) during the preceding storm event; I_{PS} = Intensity of the preceding storm = V_{PS}/T_{PS} (L/m^2-min).

b) "–" indicates variable is not significant or was excluded from model for co-linearity problems.

c) Positive or negative coefficients indicate a tendency to cause an increase or decrease in the pollutant load, respectively.

Table 3.4: Coefficients of Kayhanian et al.(2007)'s MLR model

Constituent, y	y form	Data size	$R^{2\ a}$	SE [b]	β_0	Significant independent parameters [c,d]				
						β_1	β_2	β_3	β_4	β_5
Aggregates										
TSS	ln (y)	575	0.25	1.01	4.28	-0.124	0.102	-0.099	–	4.934
TDS	ln (y)	572	0.29	0.73	4.73	-0.309	0.126	-0.050	–	2.582
DOC	ln (y)	590	0.41	0.61	4.11	-0.404	0.123	-0.129	–	–
TOC	ln (y)	583	0.14	1.09	5.23	-0.209	0.129	-0.154	–	–
Metals (total)										
Cu	ln (y)	582	0.52	0.72	2.90	-0.161	0.163	-0.079	–	6.823
Pb	ln (y)	586	0.36	1.18	2.72	–	–	-0.102	–	9.650
Ni	ln (y)	557	0.22	0.67	2.51	-0.196	0.141	-0.075	-0.155	1.013
Zn	ln (y)	579	0.51	0.76	4.83	-0.227	0.143	-0.084	–	6.747
Metals (dissolved)										
Cu	ln (y)	581	0.51	0.62	2.92	-0.290	0.185	-0.102	–	3.679
Pb	ln (y)	376	0.08	1.15	2.04	-0.248	–	-0.101	–	0.007
Ni	ln (y)	474	0.27	0.57	2.73	-0.270	0.068	-0.107	-0.094	–
Zn	ln (y)	577	0.31	0.79	4.74	-0.343	0.164	-0.112	–	1.676
Nutrients										
NO3-N	ln (y)	529	0.37	0.38	1.30	-0.417	0.092	-0.090	–	2.870
P, total	ln (y)	520	0.10	0.78	-1.2	-0.143	0.128	-0.051	–	0.900
TKN	ln (y)	537	0.38	0.66	1.7	-0.343	0.102	-0.128	–	1.535

[a] SE = root mean square error.
[b] Threshold of statistical significance is $p < 0.05$.
[c] "–" indicates variable is not significant or was excluded from model for co-linearity problems.
[d] Positive or negative coefficients indicate a tendency to cause an increase or decrease in the pollutant concentration, respectively.

The MLR models developed by Irish et al. (1998) and Kayhanian et al. (2007) represent a great progress in highway storm runoff modeling to determine pollutant loads. However, as Wu and Allan (2010b) pointed out that the processes behind the creation of these models usually involve requiring a large set of highway stormwater runoff monitoring data and performing rigorous statistical hypothesis tests to identify the relevant explanatory variables among a whole set of plausible variables for each specific pollutant constituent. It poses a great challenge to practitioners in an attempt to obtain a satisfactory volume of data from an extensive monitoring program and implement the tedious process modeling methodology to quantify site-specific pollutant loading (SSPL) for highway runoff. Based on their long-term investigation and studies in several highway stormwater projects with support of NC DOT and federal government agencies, Wu and Allan (2010b) assembled causal variables into three categories (hydrology, atmospheric deposition, and roadway traffic conditions) and developed a SSPL model with five levels of modeling options in terms of the availability of these variables. This five-level SSPL model is shown in Eq. 3.9 – Eq. 3.13.

Level I: Hydrology

$$L = a(ADD)^b(I_{AV})^c(P_5)^d(R_v)^e \tag{3.9}$$

Level II: Hydrology + Bulk deposition

$$L = a(ADD)^b(I_{AV})^c(P_5)^d(R_v)^e(Y_B)^f \tag{3.10}$$

Level III: Hydrology + VDS

$$L = a(ADD)^b(I_{AV})^c(P_5)^d(R_v)^e(VDS)^f \tag{3.11}$$

Level IV: Hydrology + VDD

$$L = a(ADD)^b(I_{AV})^c(P_5)^d(R_v)^e(VDD)^f \tag{3.12}$$

Level V: Hydrology + VDS + VDD

$$L = a(ADD)^b(I_{AV})^c(P_5)^d(R_v)^e(VDS)^f(VDD)^g \tag{3.13}$$

where, L = constituent event load, mg/m2; ADD = antecedent dry days; I_{AV} = average rainfall intensity, mm/hr; P_5= 5-minute peak intensity of rainfall, mm/hr; R_v = runoff coefficient; Y_B = bulk deposition, mg/m^2; VDD = volume of traffic during the storm, vehicles/day; VDS = volume of traffic and during ADD, vehicles/day; and a, b, ..., and g = model coefficients.

In summary, all the regression models introduced above are commonly developed on the basis of highway stormwater field monitoring and lab testing data. Depending on the availability of the data gathered locally, regionally, or nationwide, the types and the volume of data analyzed for modeling vary greatly from model to model. The number or types of pollutants investigated and analysis in depth of relations between response variable (runoff or pollutants) and explanatory variables are also determined by the availability of both data volume and data details. Even for the large set of databases assembled from throughout the nation, the analyses are also limited by the inconsistency in the databases because the purposes of collecting these data usually change to somehow from time to time, and from location to location. Generally, the complexity of models and the set of explanatory variables incorporated into the model development increase over time as more detailed field monitoring data are available. As a result, some regression models are quite simple and/or capable of predicting the load only for a few of highway runoff constituents (Chui et al. 1982, Kerri et al. 1985, Driver and Tasker 1990); some are more comprehensive and capable of estimating the load for the common constituents of highway stormwater runoff (Irish et al. 1998, Kayhanian et al. 2007). Moreover, because land-use, climate, and fashions and types of human activities change widely across the country from location to location, some models are suitable to be used for single sites (Wu and Allan 2010b); some can be used regionally or statewide (Irish et al. 1998, Wu et al. 1998, Kayhanian et al. 2007); and some can be used nationwide (Schueler 1987, Driscoll et al. 1990, Driver and Tasker 1990), depending on the data analyzed for the model construction.

3.3.2 Simulation models of/ for highway stormwater runoff

Currently, numerous models have been developed to simulate stormwater runoff quantity and quality from urban and non-urban land uses. In EPA's TMDL *Model Evaluation and Research Needs*, more than 60 available watershed and receiving water models have been rated in terms of their capabilities or applicability (USEPA 2005b). Among them, twenty-six models are land-use or physically-based such as (Annualized) Agricultural Nonpoint Source Pollution Model (AGNPS/AnnAGNPS); Better Assessment Science Integrating Point and Nonpoint Sources (BASINS); Hydrological Simulation Program – FORTRAN (HSPF); Loading Simulation Program in C++ (LSPC); Model for Urban Stormwater Improvement Conceptualization (MUSIC); Soil and Water Assessment Tool (SWAT); Storm Water Management Model (SWMM); WARMF; and others. Theoretically, all these 26 physically-based models could be adopted to simulate highway stormwater quantity and quality. However, only a few of them are now widely used by other than just the model developers or researchers for highway stormwater runoff simulation, including HSPF, STORM, and SWMM.

Furthermore, these commonly used models, including the FHWA Urban Highway Storm Drainage Model (FHWA) which is specifically developed for highway sites, generally simulate the buildup of pollutants during dry periods, followed by washoff during storms. This was first implemented in the original SWMM, even though the functional form of the build-up and washoff equations varies from model to model. Hence, the following discussion will be focused on SWMM, instead of reviewing each of these models individually.

SWMM was first developed during 1969 to 1971. Since then, it has undergone several major upgrades. The current version SWMM 5 operates within Windows. It is a dynamic rainfall-runoff simulation model used for both a single event and a long-term continuous simulation of runoff quantity and quality over the entire range of an urban catchment, including surface areas, the drainage system, and storage/treatment facilities.

In SWMM, runoff is generated from rainfall and routed using an overland flow model - the non-linear "reservoir" method; pollutant loads are simulated using buildup-washoff models; and flow and water quality routing are performed using one of the following three options: steady flow routing, kinematic wave routing, and dynamic wave routing.

1. Overland flow model.

In SWMM, the drainage area of a road segment is treated as a sub-catchment surface, or the nonlinear "reservoir" as sketched in Figure 3.1. "The capacity of this reservoir is the maximum depression storage, which is the maximum surface storage provided by ponding, surface wetting, and interception. Surface runoff …, Q, occurs only when the depth of water in the reservoir exceeds the maximum depression storage, d_p(Rossman 2009)", which is given using Manning's equation as shown in Eq. 3.14.

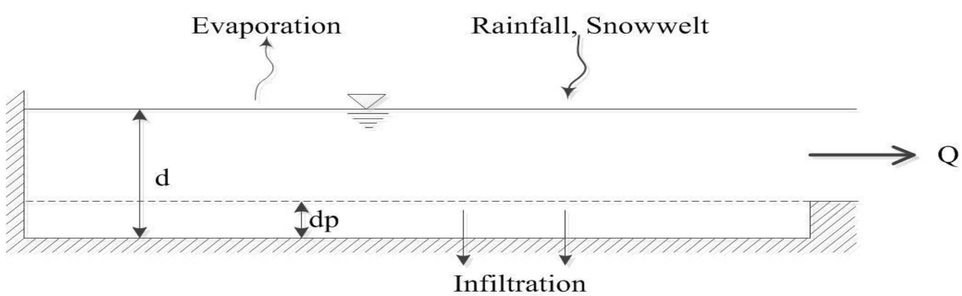


Figure 3.1: Conceptual view of surface runoff

$$Q = \frac{B}{n}\left(d - d_p\right)^{1.67} S^{0.5} \qquad (3.14)$$

where, Q = outflow rate (m3/s); B = sub-catchment width (m); n = Manning's roughness coefficient; d = water depth (m); d_p = depth of depression storage (m); and S = sub-catchment slope (m/m).

2. Buildup model.

In SWMM, it is assumed that a supply of pollutants builds up on the road land surface during dry weather preceding a storm due to the effects of such processes as traffic operation, dry fallout, wind erosion, and street sweeping. The amounts of built-up pollutants are considered as a function of the number of preceding dry weather days and estimated by either Power Function, or Exponential Function, or Saturation Function.

In the *Power Function*, the pollutant buildup (W_B in mass per unit area or unit curb length) accumulates proportionally to the preceding dry time (t in days) raised to some power, until a maximum limit is reached, expressed as:

$$W_B = Min(W_{Bmax}, k_B t^{\alpha}) \qquad (3.15)$$

where, W_{Bmax} = maximum buildup possible (in mass per unit area or unit curb length); k_B = buildup rate constant (in mass per unit area or unit curb length per day); and α =time exponent.

In the *Exponential Function*, the pollutant buildup follows an exponential growth curve that approaches a maximum limit asymptotically, expressed as:

$$W_B = W_{Bmax}(1 - e^{-k_B t}) \qquad (3.16)$$

where, W_{Bmax} = maximum buildup possible (in mass per unit area or unit curb length) and k_B = buildup rate constant (1/days).

In the *Saturation Function*, the pollutant buildup begins at a linear rate that continuously declines over time until a saturation value is achieved, expressed as:

$$W_B = \frac{W_{Bmax} t}{t_{\frac{1}{2}Bmax} + t} \qquad (3.17)$$

where, W_{Bmax} = maximum buildup possible (in mass per unit area or unit curb length) and $t_{\frac{1}{2}Bmax}$ = half-saturation constant (days to reach half of the maximum buildup).

In each of these three buildup functions, once the pollutant build-up reaches the maximum limit (e.g., 2.4 kg/ha for solids), additional build-up is not allowed, which is assumed to be wind re-suspended or driven off the surface.

3. Washoff model.

During a storm event the built-up pollutants are washed off highway land use surfaces into the drainage system. SWMM provides three options to calculate the amounts of pollutant washoff: Exponential Washoff; Rating Curve Washoff; and Event Mean Concentration (EMC).

In the *Exponential Washoff* function, the washoff load (W_{off} in mass per hour) is proportional to the product of runoff raised to some power and the amount of buildup remaining, expressed as:

$$W_{off} = k_{off} q^{\beta} W_B \tag{3.18}$$

where, k_{off} = washoff coefficient; β = washoff exponent; q = runoff rate per unit area (inches/hour or mm/hour); and W_B = total pollutant buildup in mass units.

In the *Rating Curve Washoff* method, the rate of washoff (W_{off}in mass per second) is proportional to the runoff rate raised to some power, expressed as:

$$W_{off} = k_{off} Q^{\beta} \tag{3.19}$$

where, k_{off} = washoff coefficient; β = washoff exponent; and Q = runoff rate in user-defined flow units.

In the *EMC* method, the rate of washoff is given as:

$$W_{off} = CQ \tag{3.20}$$

where, C = event mean concentration in mass per unit volume of runoff; and Q = runoff rate in volume per unit time.

The EMC method can be considered as a special case of Rating Curve Washoff where the exponent β in Eq. 3.19 is equal to 1.0 and the coefficient k_{off} represents the EMC of a pollutant.

As shown in Eq. 3.19 and Eq. 3.20, if the Rating Curve option or EMC option is adopted, it is not necessary to model any pollutant buildup in SWMM. The question is, according to SWMM developers, that the total pollutant loads during a storm event are still limited by the buildup available, based on the buildup-washoff relationship in mass balance. In other words, it is assumed in SWMM that the "buildup is continuously depleted as washoff proceeds, and washoff ceases when there is no more buildup available (Rossman 2009)". However, this may not be true due to the running traffic during a storm event which can be an "additional" key source of pollutants.

Basically, the other three models (HSPF, STORM, and FHWA) simulate the quantity and quality of stormwater runoff from urban areas, including highway surfaces, by using the same or similar buildup and washoff algorithms as SWMM does, but are less flexible than SWMM where more options have been provided.

In addition to SWMM, HSPF, STORM, and FHWA, the N.C. Department of Environment and Natural Resources has lately adopted WARMF – a simulation model designed to support the watershed approach and TMDL calculations – to develop the *Falls Lake Watershed Analysis Risk Management Framework* by predicting nutrient loads from both point sources and nonpoint sources (NC DENR 2009). The pollutant accumulation and wash-off from urban areas in WARMF was also adapted from the SWMM. Furthermore, highways were delineated as a separate category of land use in

Falls Lake WARMF Development. As such, this case is reviewed as a baseline model for estimating highway stormwater nutrient TMDLs in this research.

By comparing to regression models, simulation models can be summarized as follows (Driscoll et al. 1990):

- Simulation models provide a more physically-based predictive mechanism. When calibrated, they are more easily altered to examine the effects of land use and meteorological changes and various abatement practices (BMPs).
- Simulation models provide a spatial and temporal distribution which is not available in regression models. Their spatial capacity makes it a reality to track water quality back to different pollutant sources and establish the spatial linkage between the both. Their continuous simulation capacity makes it a reality to generate a time history of pollutant loads from which a frequency analysis may then be conducted. This allows an analysis on the basis of pollutant characteristics rather than on rainfall or runoff characteristics.
- Simulation models usually consist of a series of simulation equations. These equations must be calibrated by using the same least squares method to fit ordinary regression relationships to the sit-specific measured runoff quantity and quality data as does the regression model development. In this point, simulation models can be viewed as “very complex regression equations”.

3.4 Uncertainty issue in stormwater modeling and TMDL development

Each of either regression models or simulation models discussed previously can be considered as a simplification of reality that is constructed to gain insights into select attributes of the system of highway/urban stormwater runoff generation, transport, and fate. Some of these models and others have been widely used as an efficient and cost-saving alternative to field monitoring for tracking pollution in the environment, developing stormwater TMDLs, and assessing the effectiveness of the stormwater control measures (SCMs, also known as best management practices or BMPs). However, a major concern with application of these models is the uncertainty in their simulated results. This is because the uncertainty of model results is not only inevitable, but also has important policy, regulatory, and management implications.

Uncertainty is defined as the estimated amount by which an observed or calculated value may depart from the true value (Lapedes 1978). There is always a degree of uncertainty associated with almost all predictive water quality and TMDL models due mainly to: (1) spatial and temporal variability of environmental and ecological systems; (2) model simplifying approaches and assumptions; and (3) "lack of knowledge about models, parameters, constants, data, and beliefs" (USEPA 2009). Specifically, for a TMDL model, its output uncertainty may result from input variability, model algorithms, model calibration data, and scale (Shirmohammadi et al. 2006).

However, how to quantify the uncertainty in simulated outputs of TMDL models and further incorporate it into the process of TMDL development and implementation has not been well resolved. Although the standard error of an estimate or the variance and an uncertainty term have been introduced in regression equations to account for the uncertainty as shown in Eq. 3.6 and Eq. 3.7 above, almost all water quality models available for TMDL development have failed to document the uncertainties in their simulated results. Thus, in the current TMDL process, uncertainty is considered under the component of margin of safety (MOS), which is usually an arbitrary load allocated along with both the waste load allocation for point sources (WLA) and the load allocation for nonpoint sources (LA) to represent the TMDL for a waterbody as:

$$TMDL = \sum WLA + \sum LA + MOS \quad (3.21)$$

To better inform decisions for environmental protection by adopting TMDL simulation models, the National Research Council Committee recommended that "EPA should end the practice of arbitrary selection of the MOS and instead require uncertainty analysis as the basis for MOS determination" (NRC 2001). EPA also requires that the uncertainty associated with model simulation results should be evaluated and documented (USEPA 2009). This is because "… estimation of TMDL forecast uncertainty should not be a requirement merely because the margin of safety requires it. Rather, uncertainty should be computed because it results in better decisions. In the short run, this can happen when the TMDL assessment is based on considerations of risk. In the long run, adaptive implementation should improve the TMDL program, and effective use of adaptive implementation is facilitated with uncertainty analysis. Regardless of time frame, the TMDL program will be better served with complete estimates of uncertainty than with arbitrary hedging factors that simply fulfill an administrative requirement" (Reckhow 2003).

In this aspect, a great stride is made by Shirmohammadi et al. In their comprehensive study, *Uncertainty in TMDL Models*, Shirmohammadi et al. (2006) investigated the potential sources of uncertainty in simulated outputs of TMDL models, reviewed five common methods of uncertainty evaluation: first-order approximation, mean value first-order reliability method, Monte Carlo, Latin hypercube sampling with constrained Monte Carlo, and generalized likelihood uncertainty estimation, and used the latter three methods to estimate the uncertainty in the established Soil and Water Assessment Tool (SWAT) model's output due to input variability in the TMDL assessment phase of different watersheds located in three different states. Their study shows that "determination and presentation of model outputs with associated probabilities for each simulation output can improve management decisions related to TMDL allocation and implementation. Including explicit qualification of uncertainty due to different sources in the TMDL process would provide more complete information for decision makers and other stakeholders." They also suggested that if uncertainty is directly considered in the estimates of the WLA and the LA, then the MOS is not necessary. In their study, however, how to explicitly or directly quantify the associated uncertainty with the WLA and the LA estimates in the TMDL modeling process still remains unsolved.

CHAPTER 4: WARMF – A BASELINE MODELING METHODOLOGY FOR HIGHWAY STORMWATER TMDL ESTIMATION

Watershed Analysis Risk Management Framework (WARMF) is a physical land-use based decision support system (DSS) designed by the Electric Power Research Institute (EPRI) to support the watershed approach and TMDL calculation. N.C. Department of Environment and Natural Resources (NC DENR) adopted it to develop the Falls Lake watershed analysis risk management framework. In the project, the watershed-scale highway network was first treated as a separate land use category and its nutrient loadings were separately tracked with the help of N.C. Department of Transportation (NCDOT). This chapter is intended to briefly introduce the WARMF model, review the approach to estimating NCDOT highway storm runoff nutrient TMDLs in the *Falls Lake WARMF Development* (NC DENR 2009), and discuss its advantages and shortages.

4.1 WARMF description

As shown in Figure 4.1, WARMF consists of the following five linked modules (Chen et al., 2001):

- The Engineering module, which is the base or core of the whole system, contains several well-established models and system framework setup to simulate the hydrology and water quality for the different landscapes of a river basin.
- The Data module, which provides windows/places for inputting time series data, such as meteorology, air quality, water quality, point source discharge, river flow, reservoir flow release data as well as calibration data.

- The Knowledge module, which is a utility for model developers and stakeholders to store important documents, such as reservoir operation rules, water quality standards, rate coefficients, and other items for the watershed management decision-making.
- The Consensus module, which provides a 7-step road map to guide stakeholders to a consensus on a watershed management plan, following the EPA's guidelines of the watershed approach.
- The TMDL module, which provides a step-by-step procedure for stakeholders to calculate TMDLs for nonpoint source loads under different control levels of point source loads or vice versa.

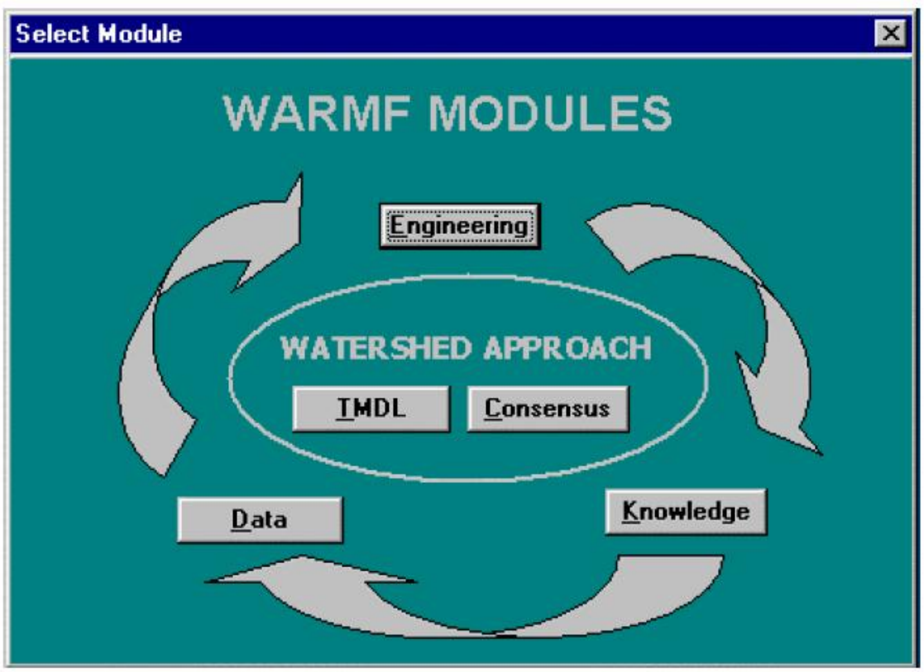


Figure 4.1: The Five Modules of WARMF

WARMF has incorporated several established models into its system. The embedded Integrated Lake-Watershed Acidification Study (ILWAS) model (Chen et al., 1983; Gherini et al., 1985) divides a watershed into a network of land catchments (including canopy and soil layers), stream segments, and lake layers. The algorithms for sediment erosion and pollutant transport from farm lands and other land uses are adapted from ANSWERS (Beasley and Huggins, 1991; Beasley et al., 1980) and the universal soil loss equation (Meyer and Wischmeier, 1969). The algorithms for pollutant accumulation and wash-off from urban areas are adapted from the Storm Water Management Model (SWMM) (USEPA, 1992). The mass balance equations are adopted from ILWAS (Chen et al., 1983; Gherini et al., 1985) and WASP5 (Ambrose et al., 1991) for the simulated parameters including flow, temperature, pH, nutrients (nitrogen and phosphorus species), total suspended sediment (TSS), biological oxygen demand (BOD), dissolved oxygen (DO), fecal coliform bacteria, and chlorophyll-a.

WARMF uses physically based processes and algorithms as well as the continuously stirred tank reactor (CSTR) model to simulate hydrology and water quality within an entire watershed. The land surface of the watershed is characterized by different categories of land use / land cover including forest, agriculture, urban, and others. Instead of empirical methods such as the Soil Conservation Service (SCS) runoff method, a dynamic water balance is performed through the processes of canopy interception, snow pack accumulation and snow melt, infiltration through soil layers, evapotranspiration from soil, ex-filtration of ground water to stream segments, kinematic wave routing of stream flows, and flow routing of the terminal reservoir. Such detailed simulations track the flow paths of precipitation from canopy, through soil layers and streams to lakes. Along each flow path, the mass balance and chemical equilibrium calculations are performed (Chen et al., 2001). Pollutants are routed with water in throughfall, infiltration, soil adsorption, exfiltration, and overland flow. The sources of point and nonpoint loads are routed through the system with the mass so that the source of nonpoint loading can be traced back to land use and location.

4.2 Modeling methodology for highways in WARMF

WARMF as a land use-based modeling system provides an opportunity for integrating highways into the process of TMDL calculation. In developing the Falls Lake watershed analysis management risk framework for nutrient management as well as nutrient TMDL calculation, N.C. Department of Environment and Natural Resources (NC DENR, 2009), in cooperation with NCDOT, first integrated the road network right of way (ROW) with the 2001 National Land Cover Data (NLCD) as an additional land class.

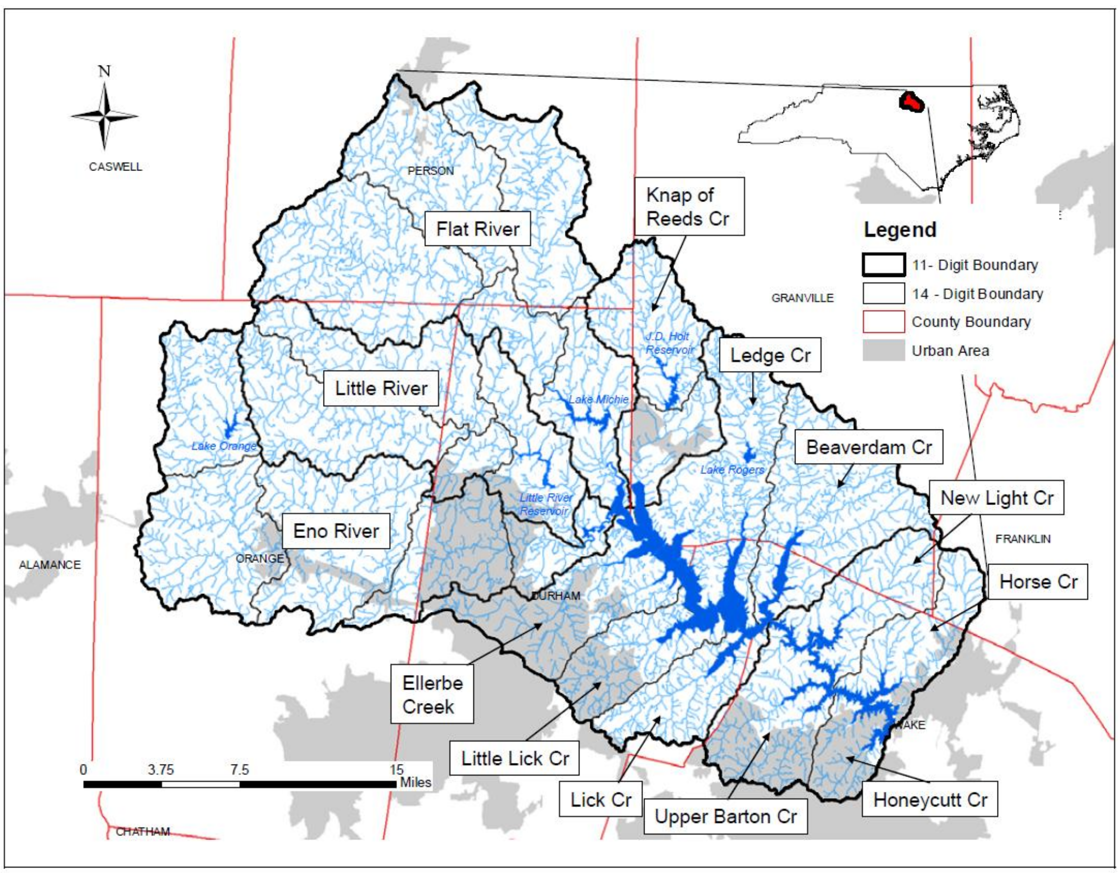


Figure 4.2: Location of the Falls Lake Watershed

In the study area, Falls Lake Watershed, roads account for 2.4% of the total land use. As shown in Table 4.1, in the five calibrated subwatersheds, highway land use accounts for 2.2% on average, ranging from 1.0% to 4.2% in each subwatershed.

Table 4.1: Land use/land cover in five calibrated subwatersheds

(in acre)	Knap of Reeds Creek	Flat River	Little River	Eno River	Ellerbe Creek	Total	Percentage
Forest	18,463	60,803	38,171	53,623	7,146	178,206	56.0%
Shrub/Grass	2,126	7,195	3,501	4,394	1,233	18,449	5.8%
Agriculture	3,982	28,239	17,578	15,830	1,657	67,286	21.1%
Developed	2,370	5,099	4,662	15,342	10,317	37,790	11.9%
NCDOT	*287*	*1,732*	*1,294*	*2,681*	*976*	*6,970*	*2.2%*
NCDOT, %	*1.0%*	*1.6%*	*1.9%*	*2.9%*	*4.2%*	*2.2%*	
Barren	124	173	42	71	24	434	0.1%
Wetland	955	1,219	1,194	1,265	1,408	6,041	1.9%
Water	502	927	676	810	369	3,284	1.0%
Total	28,809	105,387	67,118	94,016	23,130	318,460	
Percentage	9.0%	33.1%	21.1%	29.5%	7.3%		100%

The methods for calculating the runoff and nutrient pollutant contributions from highways follow the same procedure and algorithms as do for other categories of land use/land cover in the WARMF (Chen et al., 2001). The major difference is that a set of different system coefficients are assigned for the highway land use based on its characteristics as summarized in Table 4.2, Table 4.3, and Table 4.4. Also, a set of different fertilizer application rates are assigned for the highway land use in each catchment based on their locations (Table 4.5).

Table 4.2: Coefficients of system parameters for DOT land use (I)

System Parameters		NCDOT	System Parameters		NCDOT
Open in Water		0.85	Active respiration	1/d	0.000000062
Rainfall detachment factor		0.03	Maintenance respiration	1/d	0.000000035
Flow detachment factor		0.9	Dry collection efficiency		0.6
Fraction impervious		0.5	Wet collection efficiency		0.9
Interception storage	cm	0.05	Leaf weight/area	g/cm^2	0.004
Long-term growth	1/yr	1	Canopy height	m	16
leaf growth factor		1	Stomatal resistance	s/cm	0.95
Productivity	$kg/m^2/yr$	0.5			

Table 4.3: Coefficients of system parameters for DOT land use (II)

System parameters	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Cropping factor	0.17	0.17	0.17	0.17	0.17	0.17	0.17	0.17	0.17	0.17	0.17	0.17
Leaf area index	0.6	0.6	0.9	1.5	2.5	2.9	3.2	3.2	2.5	1.6	1	0.7
Litter fall rate, $kg/m^2/mo$	0.0003	0.0003	0.0003	0.0003	0.0029	0.0039	0.0039	0.0039	0.0039	0.0322	0.0012	0.0012
Exudation rate, /d	0.00001	0.00001	0.00001	0.00002	0.00002	0.00002	0.00003	0.00004	0.00004	0.00004	0.00003	0.00001

Table 4.4: Coefficients of system parameters for DOT land use (III)

System parameters	NH4 - N	Ca	Mg	K	Na	SO4 - S	NO3 - N	Cl	PO4 - P	Alk.
	mg/g	mg/g	mg/g	mg/g	mg/g	mg/g	mg/g	mg/g	mg/g	mg/g CaCO4
Leaf composition	13.5	4.7	0.96	5	0.04	1.4	0	0.011	1.1	0
Trunk composition	0.73	0.75	0.15	0.35	0.009	0.2	0	0.003	0.06	0

Table 4.5: Fertilizer application rates for highway land use

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
	Subcatchment 29 in Eno River Subwatershed (kg/ha)											
NH4 - N	0.003	0.022	0.022	0.022	0.022	0.003	0.003	0.003	0.020	0.020	0.011	0.011
K	0.025	0.072	0.072	0.072	0.072	0.025	0.025	0.025	0.123	0.123	0.100	0.100
NO3 - N	0.003	0.022	0.022	0.022	0.022	0.003	0.003	0.003	0.020	0.020	0.011	0.011
PO4 - P	0.013	0.038	0.038	0.038	0.038	0.013	0.013	0.013	0.065	0.065	0.053	0.053
Alk. CaCO3	0.011	0.031	0.031	0.031	0.031	0.011	0.011	0.011	0.052	0.052	0.042	0.042
	Subcatchment 39 in Eno River Subwatershed (kg/ha)											
NH4 - N	0.001	0.006	0.006	0.006	0.006	0.001	0.001	0.001	0.007	0.007	0.005	0.005
K	0.011	0.021	0.021	0.021	0.021	0.011	0.011	0.011	0.049	0.049	0.044	0.044
NO3 - N	0.001	0.006	0.006	0.006	0.006	0.001	0.001	0.001	0.007	0.007	0.005	0.005
PO4 - P	0.006	0.011	0.011	0.011	0.011	0.006	0.006	0.006	0.026	0.026	0.023	0.023
Alk. CaCO3	0.004	0.009	0.009	0.009	0.009	0.004	0.004	0.004	0.021	0.021	0.019	0.019

4.3 Results and discussion

The results of calculation for daily loads of pollutants, i.e., total nitrogen (TN) and total phosphorus (TP) from each subwatershed and each pollutant source are summarized in Table 4.6 and Table 4.7. For TN, the total source contribution rate from five calibrated subwatersheds and the total delivered load to Falls Lake are 1161 kg/day and 825 kg/day, respectively. For TP, the total source contribution rate and the total delivered load are 141 kg/day and 72 kg/day, respectively.

Comparing the delivered load and/to the source contribution among different subwatersheds, it is found that the smallest Ellerbe Creek subwatershed that accounts for approximately 7% of the total land cover contributes 26% TN and 27% TP to Falls Lake;

a second small subwatershed, Knap of Reeds Creek with 9% of the total land cover, contributes 17% TN and 23% TP; however, the largest Flat River subwatershed with 33% of the total land cover only contributes 25% TN and 31% TP (Table 4.6 and Figure 4.3). This is mainly because both Ellerbe Creek Watershed including part of Durham and Knap of Reeds Creek Watershed have been more heavily urbanized with more point sources and also have short delivery distances to the lake (Figure 4.2).

Comparing the loading rates among different pollutant sources and land use/land cover, it is found that agricultural land use and point sources (e.g., waste water treatment plants) are two main contributors of nutrient pollutants in Falls Lake. For TN, agriculture with 21% of the total land use and point sources contribute 27% and 24% of the total load to the lake, respectively; other major pollutant sources include forest (16%), septic systems (14%), and developed/urban areas (13%).

Table 4.6: Pollutant loads from subwatersheds

Subwatershed	Land Cover		TN				TP			
			Source Contribution		Delivered		Source Contribution		Delivered	
	acre	%	kg/d	%	kg/d	%	kg/d	%	kg/d	%
Knap of Reeds Creek	28,809	9.0%	186.2	16.0%	140.3	17.0%	18.2	12.9%	16.6	23.0%
Flat River	105,387	33.1%	395.0	34.0%	206.3	25.0%	69.2	49.0%	22.3	31.0%
Little River	67,118	21.1%	172.1	14.8%	107.3	13.0%	17.2	12.2%	5.0	7.0%
Eno River	94,016	29.5%	183.3	15.8%	156.8	19.0%	16.5	11.7%	8.6	12.0%
Ellerbe Creek	23,130	7.3%	224.2	19.3%	214.5	26.0%	20.3	14.4%	19.4	27.0%
Total	318,460	100%	1160.8	100%	825.0	100%	141.3	100%	72.0	100%

Table 4.7: Pollutant loads from different pollutant sources

Land Cover or Sources			TN				TP			
			Source Contribution		Delivered		Source Contribution		Delivered	
	acre	%	kg/d	%	kg/d	%	kg/d	%	kg/d	%
Forest	178,206	56.0%	196.7	16.9%	132.0	16.0%	1.7	1.2%	0.7	1.0%
Shrub/Grass	18,449	5.8%	29.6	2.5%	16.5	2.0%	0.2	0.1%	0.1	0.1%
Agriculture	67,286	21.1%	381.0	32.8%	222.8	27.0%	93.8	66.4%	30.2	42.0%
Developed	37,790	11.9%	138.6	11.9%	107.3	13.0%	4.3	3.0%	3.6	5.0%
NC DOT	*6,970*	*2.2%*	*10.1*	*0.9%*	*8.3*	*1.0%*	*1.3*	*0.9%*	*0.9*	*1.2%*
Wetlands	6,041	1.9%	4.9	0.4%	4.1	0.5%	0.1	0.1%	0.1	0.1%
Other NPS	3,718	1.1%	10.5	0.9%	16.5	2.0%	0.5	0.3%	3.6	5.0%
Septic	NA	NA	171.4	14.8%	115.5	14.0%	11.6	8.2%	6.5	9.0%
PS	NA	NA	202.8	17.5%	198.0	24.0%	27.9	19.8%	26.6	37.0%
Air Deposition	NA	NA	15.2	1.3%	9.9	1.2%	0.0	0.0%	0.0	0.0%
Total	318,460	100%	1160.8	100%	830.8	100%	141.3	100%	72.3	100%

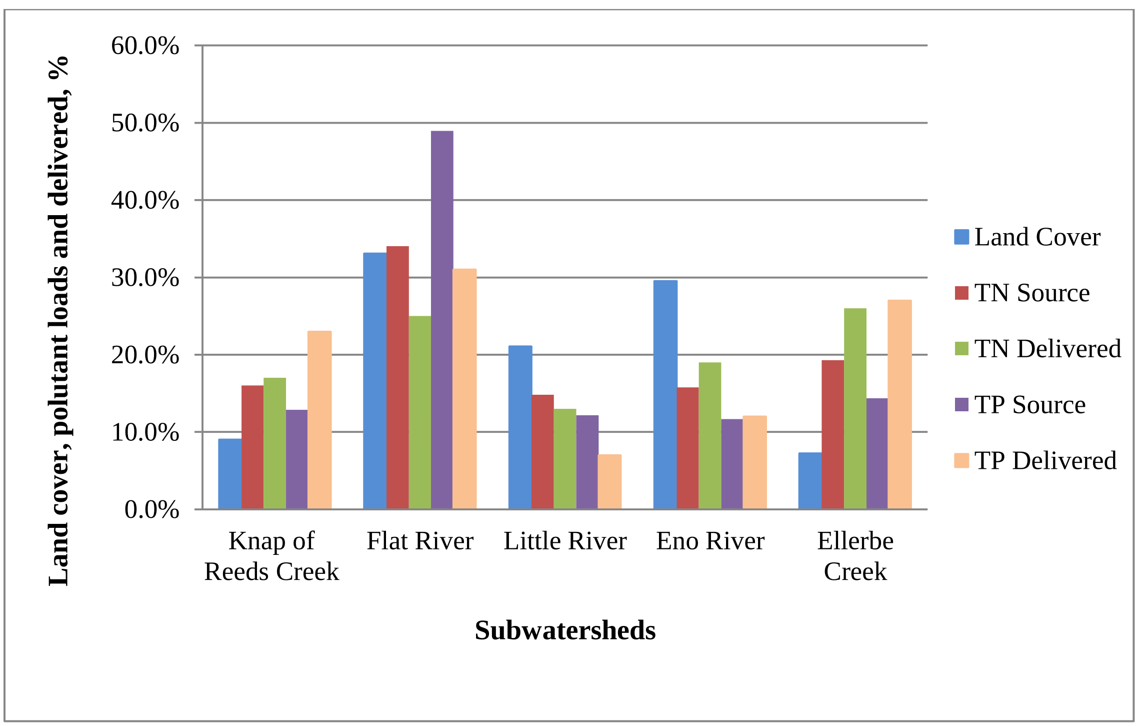


Figure 4.3: Comparison of pollutant loads by subwatersheds

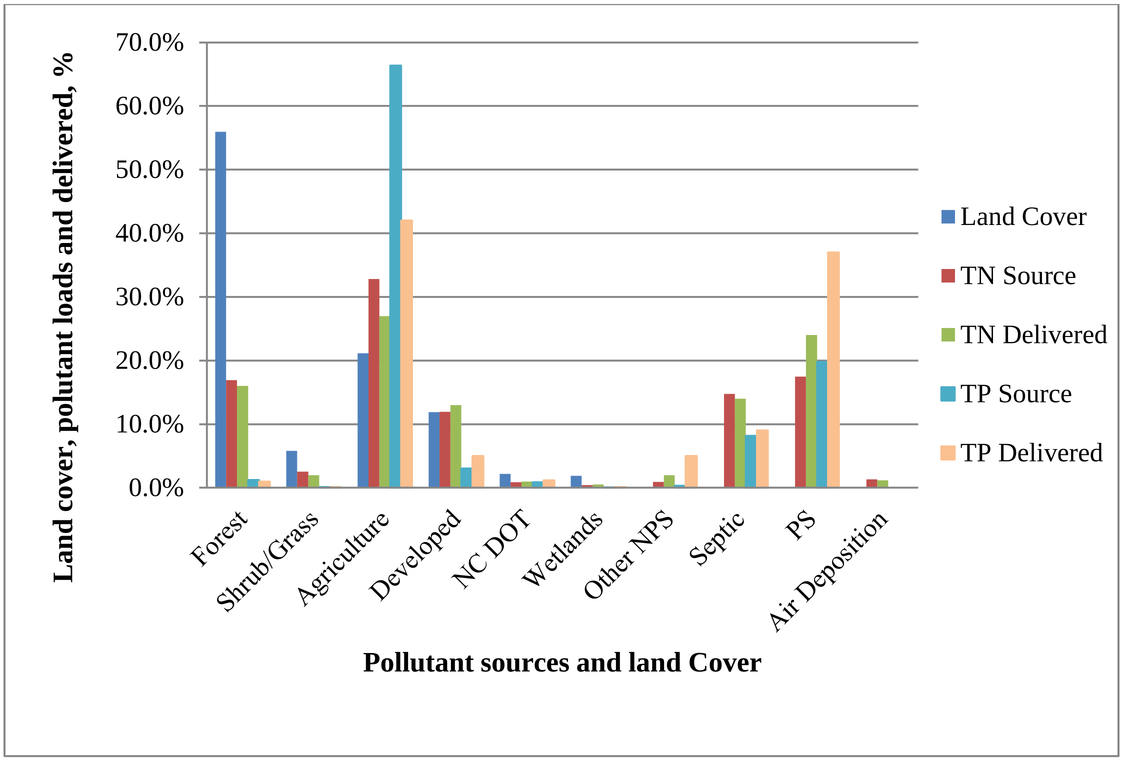


Figure 4.4: Comparison of pollutant loads by different pollutant sources

For TP, agriculture and point sources contribute 42% and 37%, respectively; other major sources are septic systems (9%) and developed/urban areas (5%). As shown in Table 4.7 and 4.8, the road ROW with 2.2% of the total land use/land cover only contributes 1.0% of TN and 1.2% of TP loading to the lake. Their corresponding source loadings are 10.1 kg/d (2.951 lb/ac.yr) of TN and 1.3 kg/d (0.147 lb/ac.yr) of TP, accounting for 0.9% of the total source loadings, respectively.

Table 4.8: Nonpoint source pollutant loads from different land use/land cover

LU/LC	Forest	Shrub/Grass	Agriculture	Developed	*NC DOT*	Wetlands
Unit	lb/ac.yr	lb/ac.yr	lb/ac.yr	lb/ac.yr	*lb/ac.yr*	lb/ac.yr
TN	0.888	1.291	4.556	2.951	*1.166*	0.653
TP	0.008	0.007	1.121	0.091	*0.147*	0.016

As stated previously, WARMF is a physically based DSS to support the watershed approach and TMDL calculation. Especially, that the road ROW is creatively integrated in WARMF as a separate category of land use/land cover and further into the process of TMDL calculation and watershed-scale decision making provides an opportunity to see the position of highways in the whole picture of pollutant loadings. It has been noted that, however, the highway ROW land use is not only different from forest and agricultural land use, also different from normal urban and other developed areas. The highway system has its own unique characteristics. It has limited area of land use along the way including paved road surface, compacted shoulders, and roadside pervious areas or corridors. It is linear, diffuse, and widespread, usually spans hundreds and sometimes thousands of miles in a watershed, and traverses streams, rivers, and the lake. A number of studies show that the source strength of road/traffic-generated pollutants, the pattern of precipitation, the spacing of road runoff drainage outlets, the terrain and type of adjacent land uses, and the connectivity of roads to established drainage lines and to the stream system are crucial for water quality preservation (Wu et al., 1998; Wu and Allan, 2001; Wu and Allan, 2004; Kayhanian et al., 2007; Takken et al., 2008; Eastaugh et al., 2008). Moreover, water pollution can only occur when road runoff and its associated pollutants are delivered to the drainage network or waterbodies (i.e., streams, rivers, or lake). In the other words, the road-to-stream connectivity as well as the characteristics of road runoff pathways is the most important. But, this is not well reflected in WARMF. In short, from highway hydrology and water quality points of view, WARMF has the following major shortcomings:

- The road network ROW is considered as a general class of land use/land cover in WARMF and its unique characteristics such as the road-to-stream connectivity and different road runoff flow paths have not been taken into consideration.

- The pollutants released from the traffic are not considered in WARMF, which likely is the most important source based on several studies (Irish et al., 1998; Wu et al., 1998; Wu and Allan, 2001; Kayhanian et al., 2007).
- The observed water quality data of road runoff are neither used to calculate the pollutant loads, nor used to calibrate the model so that it is hard to tell if the resulting pollutant loads estimated by WARMF are close enough to the reality and also their uncertainties are unknown.

To solve these issues, a "volume to break through (Vbt)" based WQ model will be developed as an alternative to estimating the TMDL component for highways in the next chapter.

CHAPTER 5: PVbtWQM – AN ALTERNATIVE WATERSHED-SCALED MODEL AND ITS ALGORITHMS DEVELOPED FOR ESTIMATING HIGHWAY STORMWATER TMDLS

This chapter consists of six sections. It is intended to develop a new comprehensive watershed-scaled road-to-stream hydrologic connectivity and water quality model. In the first three sections, the concept of "volume-to-breakthrough (Vbt)" and a probabilistic Vbt model (PVbtM) are briefly introduced; the type of road runoff flow pathways is investigated and classified; and two Vbt field experiments are examined. In the beginning of Section 4, the road-to-stream hydrologic connectivity is further defined, and then the rest of this section is contributed to deriving algorithms for evaluating the watershed-scaled road-to-stream hydrologic connectivity. The last two sections present all the algorithms developed for the probabilistic Vbt water quality model (PVbtWQM) to estimate highway stormwater pollutant loads, TMDLs, and their associated uncertainties.

5.1 Background

The probabilistic Vbt modeling concept was initially proposed by Hairsine *et al*. (2002) to obtain the volume of runoff required to enter an area before the discharge is observed at the downslope boundary of that area. This required volume is defined as the volume to break through which accounts for the water loss due to infiltration through overland flow, depression storage, and water in transit between the upper and lower boundary of a drainage area. Subsequently, several Australian researchers have elaborated and applied this concept to quantify stormwater runoff and its associated pollutants from roads (Lane *et al*. 2006; Takken *et al*. 2008; Eastaugh *et al*. 2008; Thompson *et al*. 2009). The initial PVbtM and its extensions are based on a key concept of the "road-to-stream hydrologic connectivity" that was defined as the volume of road runoff reaching the stream network either at direct road/stream crossings, from incised flow paths (gullies) between road drain outlets and the stream, or diffusely via overland flow from road surfaces across slopes (Wemple *et al*. 1996; Hairsine *et al*. 2002; Bracken *et al*. 2004; Eastaugh *et al*., 2008). Thus, this model is also called the probabilistic road-to-stream connectivity model.

The experimental data collected by Croke *et al*. (1999) from three forested watersheds in southeast Australia across a range of soil types, forest age classes, and rainfall intensities were used by Hairsine *et al*. (2002) to validate PVbtM. The researchers employed a mean volume of overland flow required for a flow plume to reach 5 m from the road edge (V_{bt5}) and its variance (σ^2_{vbt5}) to predict the mean volume of overflow at a certain distance from a roadway drain and its associated uncertainty. The work by Lane *et al*. (2006) has confirmed the validity of PVbtM in a different forest environment in the Upper Tyers watershed, Victoria, Australia. The model was used to determine appropriate drainage spacing distances for forestry roads for reducing the delivery of road-generated runoff to the stream network. Takken *et al*. (2008) adopted the Vbt method and hydrologic connectivity analysis to evaluate the risk of delivering road-generated runoff via three different types of runoff flow-paths (stream crossings, gullied pathways, and diffused pathways) in three forestry watersheds in Victoria and New South Wales, Australia. Their results show that the degree of connectivity from a road to a stream depends on such factors as watershed topography, road placement, drain spacing along the road network, and road and drainage density.

The aforementioned studies are mostly focused on the delivery of runoff and the associated sediment from road segments to streams over single sites other than on evaluating the road-to-stream hydrologic connectivity and pollutant delivery for an entire road network at a large watershed scale. For the purpose of highway stormwater TMDL assessment, it is necessary and expected to focus on not only evaluating the watershed-scaled road-to-stream hydrologic connectivity, but also estimating delivered pollutant loads by storm runoff from an entire road network. The hydrological aspect of connectivity has been undertaken by Eastaugh *et al*. (2008) and Thompson *et al*. (2009). In Eastaugh *et al*.'s study (2008), the context of assessing different road decommissioning and relocation works in the Lower Cotter watershed, Canberra, Australia, was used to further develop the PVbtM. A procedure was provided to quantify the hydrologic connectivity for individual road segments and the road network as a whole by explicitly considering both the uncertainty of connectivity through specification of confidence limits and the potential impacts of road segments that may or may not be hydrologically connected to the stream network. In Thompson *et al*.'s study (2009), a road runoff and sediment connectivity assessment tool, named as ROADCAT, was developed as a decision support system (DSS) for unsealed roads by integrating gully threshold model, road runoff model, and the PVbtM model into one ArcGIS program to assess the extent of runoff and sediment connectivity from roads to streams at watershed scales. But the sediment connectivity assessment portion of this tool is still under development and improvement (personal communication with Dr. Chris Thompson).

Overall, PVbtM was developed for unsealed road conditions in the forestry environment. Emphasis of the studies is mainly placed on the hydrological aspect. The water quality aspect, however, still remains to be explored. This chapter is intended to develop a new WQ model for highway TMDL assessment by modifying the PVbtM and adding a water quality component, and the new model is thereby named the PVbtWQM model. The first step for the formulation of PVbtWQM is to define different flow pathways of road runoff in terms of the hydro-spatial relationship between a road and the stream network.

5.2 Classification of types of the road runoff flow pathways

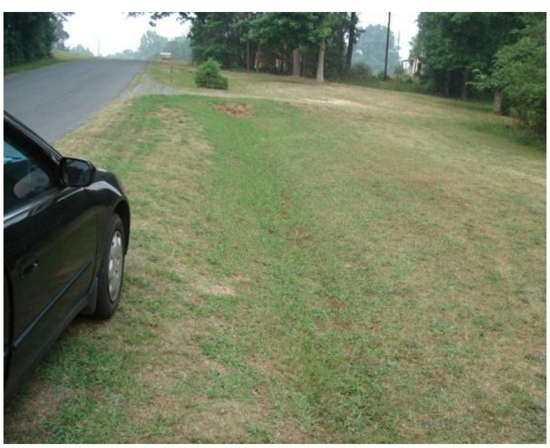
Given that the discharge of stormwater runoff and its associated pollutants are inevitable from road land uses, the different types of flow pathways may contribute a big difference in the quantity and quality of road runoff delivering to receiving waterbodies.

Based on the field investigation author performed of the road surface runoff drainage scenarios in both Jordan Lake and Falls Lake watersheds in the Piedmont region of North Carolina, five types of road runoff flow pathways in a typical urban watershed can be classified (Figure 5.1):

a) Road segments with curbs directly connected with drainage lines and/or channels, mostly occurring in urban areas.
b) Road segments with vegetated ditches directly connected with drainage lines and/or channels.
c) Road segments without curbs or vegetated ditches directly connected with streams or channels at road/stream crossings.
d) Road segments with vegetated ditches and/or gullies, and at the end of ditches or gullied paths the runoff drains to a flat area or hill slopes with grass and/or stands of trees.


a) Road with curbs connected with drains b) Road with ditches connected with a drain


c) Road/stream crossings: bridge or culvert under the crossing




d) Road with ditches flowing diffusely e) Road without ditches flowing diffusely

Figure 5.1: Five categories of highway runoff flow paths

e) Road segments without vegetated ditches. The runoff directly flows diffusely over a flat area or hill slopes.

In terms of the hydrologic connectivity, these five cases can be further grouped into two general categories: (1) directly connected flow pathways including cases a), b), and c); (2) diffuse overland flow pathways including cases d) and e). In Category 1, the road runoff is concentrated in a short period of time and directly finds its way via a pipe or a channel to a stream without a minimal loss, which may impair the receiving waterbody on both quantity and quality in a quick and intensive fashion. In Category 2, the road runoff flows slowly and diffusively over land surfaces, experiences significant losses by surface storage and infiltration, and is also filtered and taken up by the on-site vegetation. It is much more environmental friendly. Therefore, it is necessary to take these conditions into consideration when the runoff from the entire road network in a watershed is evaluated. To accomplish this, the first step of analysis is to determine the road-to-stream connectivity using the modified PVbtM model.

5.3 Obtainment of the values of Vbt parameters

According to Hairsine *et al*. (2002), the PVbtM model is derived from the mean volume of runoff required to break through a 5-meter length of the overland flow plume (V_{bt5}) and its variance (σ^2_{Vbt5}). At present, there are two types of field experiment independently performed by Croke *et al*. (1999) and Lane *et al*. (2006) for obtaining these two key parameters as shown in Figure 5.2. The major difference between the both is that Croke *et al*. (1999) used the CSIRO's large, field-based rainfall simulator with 10 'Spraying Systems' sprinklers mounted so as to spray upwards on top of 3 m tall risers to simulate actual rainfall (Figure 5.2 (a)); Lane *et al*. (2006) used a 2400-liter tank refilled from water truck or stream and releasing water at the point of a culvert pipe to simulate actual road drainage (Figure 5.2 (b)).

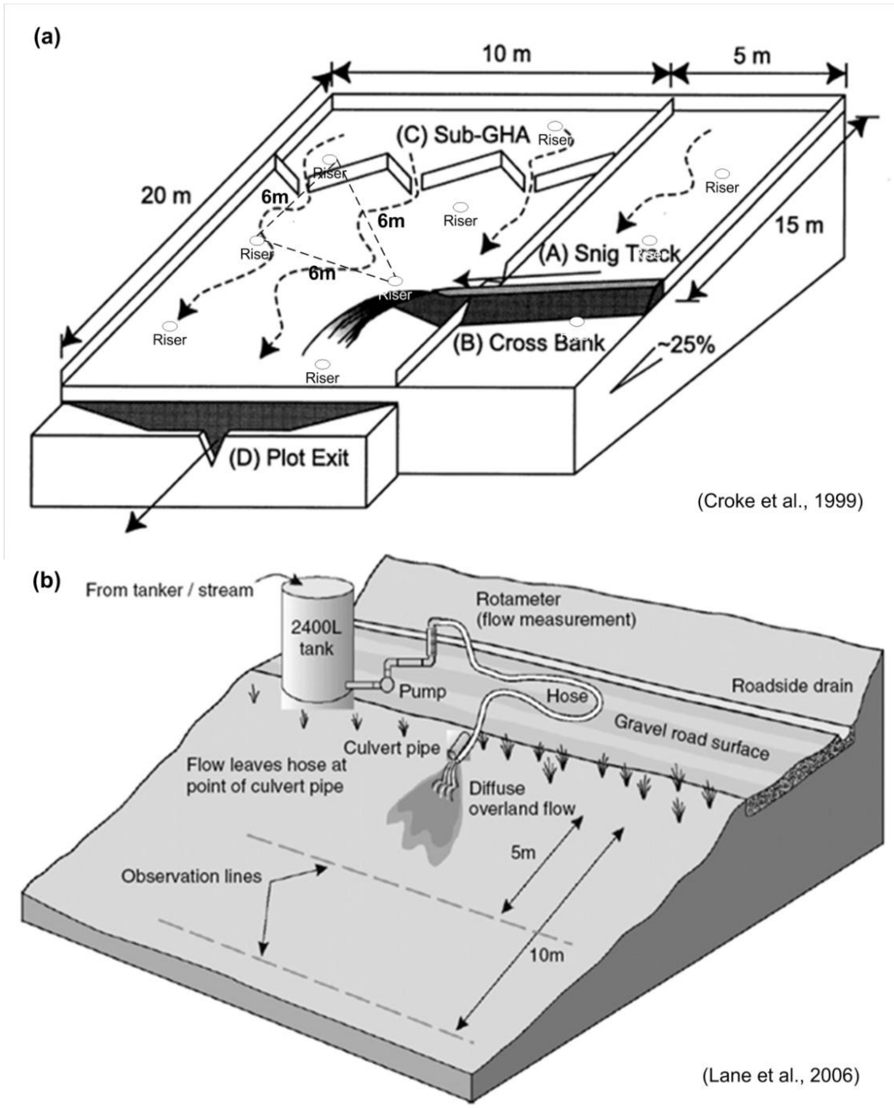


Figure 5.2: Two types of field setup for Vbt experiments

The results of these two field experiments on the V_{bt5} are given in Appendix A. Croke *et al.*'s experiment yielded a result of $V_{bt5} = 336$ liters with the variance $\sigma^2_{vbt5} = 35{,}600$ (or $V_{bt5} = 336 \pm 189$ liters); Lane *et al.*'s experiment yielded a result of $V_{bt5} = 543$ liters with $\sigma^2_{vbt5} = 545{,}481$ (or $V_{bt5} = 543 \pm 793$ liters). It seems that there is a big difference between these two sets of values. By revisiting the original data of two experiments, however, it is found that in Lane *et al*.'s data, there is one extreme value of V_{bt5} (3360 liters) which was included to do the calculation. This value is approximately 6.1 times of the interquartile range (IQR = 452 liters) greater than the upper quartile (603 liters), which should be considered to be an outlier and deleted according to Kreyszig (2006). Without this outlier, Lane *et al*.'s experiment will result in the mean $V_{bt5} = 364$ liters with $\sigma^2_{vbt5} = 82{,}841$ (or $V_{bt5} = 364 \pm 288$ liters). The results of F-test and T-test show in Table 5.1 and 5.2 that these two means of V_{bt5} are not significantly different, but the variances are.

Table 5.1: F-Test: Two-Sample for Variances

	Vbt5, liters	*Vbt5, liters*
Mean	364	336
Variance	82841	35607
Observations	17	20
df	16	19
F	2.327	
P(F<=f) one-tail	**0.041**	
F Critical one-tail	2.215	

Table 5.2: t-Test: Two-Sample Assuming Unequal Variances

	Vbt5, liters	*Vbt5, liters*
Mean	364	336
Variance	82841	35607
Observations	17	20
Hypothesized Mean Difference	0	
df	27	
t Stat	0.337	
P(T<=t) one-tail	**0.370**	
t Critical one-tail	1.703	
P(T<=t) two-tail	0.739	
t Critical two-tail	2.052	

For our model development and algorithms derivation, the first set of values will be temporarily adopted, i.e., $V_{bt5} = 336$ liters with $\sigma^2_{vbt5} = 35{,}600$. These parameters are changeable. If actual values under local conditions are available, they should be applied instead. If not available, these values should be adjusted to local conditions. How to transfer them to a target watershed will be discussed in more details in the next chapter.

According to Hairsine et al. (2002), the V_{bt5} and its variance can be utilized to predict the mean length of the overland flow plume (l_{pred}) and the variance (σ_l^2) as:

$$l_{pred} = 5\frac{V_{out}}{V_{bt5}} = \frac{V_{out}}{67.2} \qquad (V_{bt5} = 336\ liters) \qquad (5.1)$$

$$\sigma_l^2 = \frac{25\sigma_{vbt5}^2 V_{out}^2}{V_{bt5}^4} = (6.98 \times 10^{-5})V_{out}^2 \qquad (\sigma_{vbt5}^2 = 35{,}600) \qquad (5.2)$$

where l_{pred} is in meters and V_{out} is the volume of runoff leaving the drainage outlet or a road edge in liters, flowing over the land.

Also, the mean volume (V_x) of overland flow to pass any point a distance (x) downslope of the outlet and its variance ($\sigma_{V_x}^2$) can be given by:

$$V_x = V_{out} - \frac{x}{5}V_{bt5} \qquad (0 \le V_x \le V_{out}) \qquad (5.3)$$

Or,

$$V_x = V_{out} - 67.2x \qquad (V_{bt5} = 336\ liters) \qquad (5.4)$$

$$\sigma_{V_x}^2 = \frac{x^2}{25}\sigma_{vbt5}^2 = 1424x^2 \qquad (\sigma_{vbt5}^2 = 35{,}600) \qquad (5.5)$$

Or,

$$\sigma_{V_x} = \pm 37.74x \qquad (5.6)$$

where V_{out} is the volume of road-derived runoff leaving the outlet or road edge; both V_x and V_{out} are in liters; and x is the length of a plume or distance downslope of the outlet/road edge, in meters.

From the above proposal, therefore, for a given road segment with a length of the diffuse overland flow pathway from its drainage outlet or a road edge to a stream (X_0 in meters), if $X_0 < l_{pred}$, the runoff reaching the stream (V_{X_0}) and its associated variance ($\sigma^2_{V_X}$) can be estimated as:

$$V_{X_0} = V_{out} - \frac{X_0}{5} V_{bt5} = V_{out} - 67.2X_0 \qquad (V_{bt5} = 336\ liters) \tag{5.7}$$

$$\sigma^2_{V_X} = \frac{X_0^2}{25} \sigma^2_{vbt5} = 1424X_0^2 \qquad (\sigma^2_{vbt5} = 35{,}600) \tag{5.8}$$

5.4 Development of watershed scaled road-to-stream hydrological model

This section will describe the statistical algorithms to predict the mean value of the road-generated runoff reaching streams and its uncertainty for both the sliced land use pieces of individual road segments and the whole land use of an entire road network in a watershed, based on whether a road segment is directly or diffusely connected to the stream network. To do so, the road-to-stream hydrologic connectivity is redefined and Eastaugh *et al*.'s methodology (2008) is improved as well.

As introduced at the beginning of this chapter, the hydrologic connectivity of road-to-stream has there been defined as "the volume of road runoff reaching the stream network". This definition is actually arguable because it cannot explicitly reflect the extent to which a road connects hydrologically with the stream network. More meaningfully, the road-to-stream hydrologic connectivity should be defined as a ratio of the volume of road runoff reaching the stream network to the volume originally generated from the road land use, expressed by:

$$\psi = \frac{V_{X_0}}{V_{out}} \tag{5.9}$$

Substitute Eq. 5.7 into Eq. 5.9, ψ can also be given as:

$$\psi = \frac{V_{out} - 67.2X_0}{V_{out}} \tag{5.10}$$

where, V_{out}, V_{X_0}, and X_0 are defined as previously; ψ and Ψ are here adopted to denote the hydrologic connectivity for an individual road segment and an entire road network, respectively.

It is noted from Eq. 5.10 that when the volume of road runoff (V_{out}) increases under an increased precipitation, the road-to-stream connectivity (ψ) will increase because the length of the flow pathway from a road to the stream (X_0) usually keeps unchanged, or vice versa. It is also known that the reasonable value of ψ ranges from 0 to 1, not exclusively, i.e., $\psi = [0{,}1]$. Furthermore, according to ψ values (i.e., the extent of road-to-stream connectivity), all individual road segments can be classified into the following three categories:

$$\psi = \begin{cases} 1 & V_{X_0} = V_{out} & all\ runoff\ flows\ to\ streams \\ (0{,}1) & 0 < V_{X_0} < V_{out} & partial\ runoff\ reaches\ streams \\ 0 & V_{X_0} = 0 & no\ runoff\ arrives\ to\ streams \end{cases} \tag{5.11}$$

By defining the road-to-stream hydrologic connectivity (ψ) according to Eq. 5.11, no matter whether a road segment is connected to the stream network directly or diffusely, the volume of road runoff reaching streams (V_{X_0}) can be generally given as:

$$V_{X_0} = \psi V_{out} \tag{5.12}$$

Moreover, different from Eastaugh *et al.*'s proposal (2008) where the area of road surface was only dealt with, the entire land use of roads including paved road surface and its surrounding pervious areas is herein treated as a whole to be evaluated. As a result, the road surface area cannot be used as a surrogate for the volume of runoff generated from the road land use as Eastaugh *et al*. did. Instead, the volume of road runoff reaching the stream network for individual road segments or the entire road network is first calculated by using the PVbtM model proposed by Hairsine et al. (2002), and then the road-to-stream connectivity and its associated uncertainty will be evaluated.

5.4.1 Predicting the runoff reaching streams for individual road segments

1. For directly connected road segments.

For a single road segment that has a direct connection to the stream network via a concentrated flow path through a pipe and a ditch/channel, or the overland flow path at a road/stream crossing, an assumption of 100% connectivity is likely to be a good approximation in most instances because of a minimal loss of runoff in the pipe, a low infiltration rate through the indurated sub-surface sediment layer on the bottom of a ditch, or a small loss of overland flow along slopes in a very short period of time at the cut-and-fill road/stream crossing, i.e., $\psi = 1$, all the flow leaving the segment (V_{out}) is assumed to reach the stream. Therefore, for a directly connected road segment,

$$V_{X_d} = V_{out} \qquad (\psi = 1) \qquad (5.13)$$

where, both V_{X_d} and V_{out} are given in L; d indicates the “directed connected flow path”.

2. For diffusely connected road segments.

For a single road segment that has a diffuse overland flow path, as described previously (referring to Eq. 5.7, 5.10, and 5.12), the mean volume of road runoff reaching the stream is estimated as:

$$V_{X_{df}} = V_{out} - 67.2X_0 = \psi V_{out} \qquad (0 < \psi < 1) \qquad (5.14)$$

$$V_{X_{df}} = 0 \qquad (l_{pred} < X_0 \ or \ \psi = 0) \qquad (5.15)$$

where, $V_{X_{df}}$ and V_{out} are given in L; df indicates the “diffuse overland flow”; X_0 is the actual length of the diffuse overland flow path from a road drainage outlet to the stream network and l_{pred} is the predicted length along that path, both given as in meters.

In the meantime, when either the flow is expected to reach a stream or not, its associated uncertainties should be taken into account. For the flow expected to reach a stream, i.e., $V_{X_0} \geq 0$ and $0 \leq \psi < 1$, its uncertainty, ε_X, can be given as:

$$\varepsilon_X = \pm z\sigma_{V_{X_0}} = \pm z(37.74)X_0 \qquad (0 \leq \psi < 1) \qquad (5.16)$$

Or,

$$\varepsilon_X' = \pm z\frac{\sigma_{V_{X_0}}}{V_{X_0}} = \pm z\frac{37.74X_0}{V_{out}-67.2X_0} \qquad (0 \leq \psi < 1) \qquad (5.17)$$

where, ε_X is the maximum absolute uncertainty (relative to X_0) expressed in the same units as in V_{X_0}(in liters); ε_X' refers to the fractional uncertainty or the maximum percent uncertainty of V_{X_0}; and z is a factor chosen to reflect the desired level of confidence. For instance, a z value of 1.645 would yield a 90% confidence interval around the mean value.

It is noted that the absolute uncertainty given by Eq. 5.16 actually is a maximum value of uncertainty which can be reached when $V_{X_0} = 0$ (i.e., $V_{out} = 67.2X_0$) for a certain road segment. After this value is reached, when road generated runoff (V_{out}) increases, the absolute uncertainty will not change. The fractional uncertainty, however, will decrease as shown in Eq. 5.16. In other words, as V_{out}increases, the certainty of V_{X_0}will be increased when $V_{out} > 67.2X_0$, i.e., $\psi > 0$.

Now, our interest is that from a statistical point of view, for the road segments with diffuse flow paths where the runoff is not expected to reach the stream network, there might be a portion of V_{out} which could reach the stream. Thus, it is necessary to consider this scenario in order to determine an overall uncertainty estimate for a multi-segmental or an entire road network in a watershed.

There are two possibilities which will occur when the runoff is not expected to reach the stream. One possibility occurs when $V_{X_0} = 0$, i.e., $V_{out} = 67.2X_0$ and ψ is exactly equal to zero. In this case, the uncertainty associated with V_{X_0} can be directly determined by Eq. 5.16. The other occurs when $V_{out} < 67.2X_0$. At this moment, what is interested is the extent to which the propagation of errors influences the final uncertainty. In Eq. 5.16, if X_0 is substituted by x which indicates the flow distance from road drainage outlet to any point approaching the stream network, the uncertainty associated with the V_x at that point can be given as:

$$\varepsilon_x = \pm z(37.74)x \tag{5.18}$$

Furthermore, when the given V_{out} is exhausted, a maximum value of ε (relative to V_{out}) will be reached, expressed as:

$$\varepsilon_l = \pm z(37.74)l_{pred} \qquad (V_{out} < 67.2X_0) \tag{5.19}$$

Substituting Eq. 5.1 $l_{pred} = \frac{V_{out}}{67.2}$ into the above equation, ε_{max} is also given as:

$$\varepsilon_l = \pm z(0.5616)V_{out} \qquad (V_{out} < 67.2X_0) \tag{5.20}$$

After that, the uncertainty will decrease as the solid line shows in Figure 5.3, assuming that the uncertainty reduces in the same slope as made in the equation above. Thus, the resulting uncertainty, ε_X, can be derived as:

$$\begin{aligned} \varepsilon_X &= \pm z[2\varepsilon_l - (37.74)X_0] \\ &= \pm z[(2)(0.5616)V_{out} - (37.74)X_0] \\ &= \pm z(1.123V_{out} - 37.74X_0) \end{aligned} \tag{5.21}$$

Therefore, the volume of flow reaching the stream network from a single road segment and its associated uncertainty can then summarized as follows:

- $V_{X_d} = V_{out}$ for a directly connected segment when $\psi = 1$;
- $V_{X_{df}} = (V_{out} - 67.2X_0) \pm z(37.74)X_0$ for a diffusely connected segment when $0 < \psi < 1$;
- $V_{X_{df}} = 0 + z(37.74)X_0$ for a diffusely connected segment when $\psi = 0$;
- $V_{X_{df}} = 0 + z(1.123V_{out} - 37.74X_0)$ for a diffusely connected segment with $\frac{1}{2}X_0 < l_{pred} < X_0$ (or shortly expressed as $\psi < 0$ for the sake of convenience); for those segments where $l_{pred} \leq \frac{1}{2}X_0$, the values of $V_{X_{df}}$ should be taken as zero.

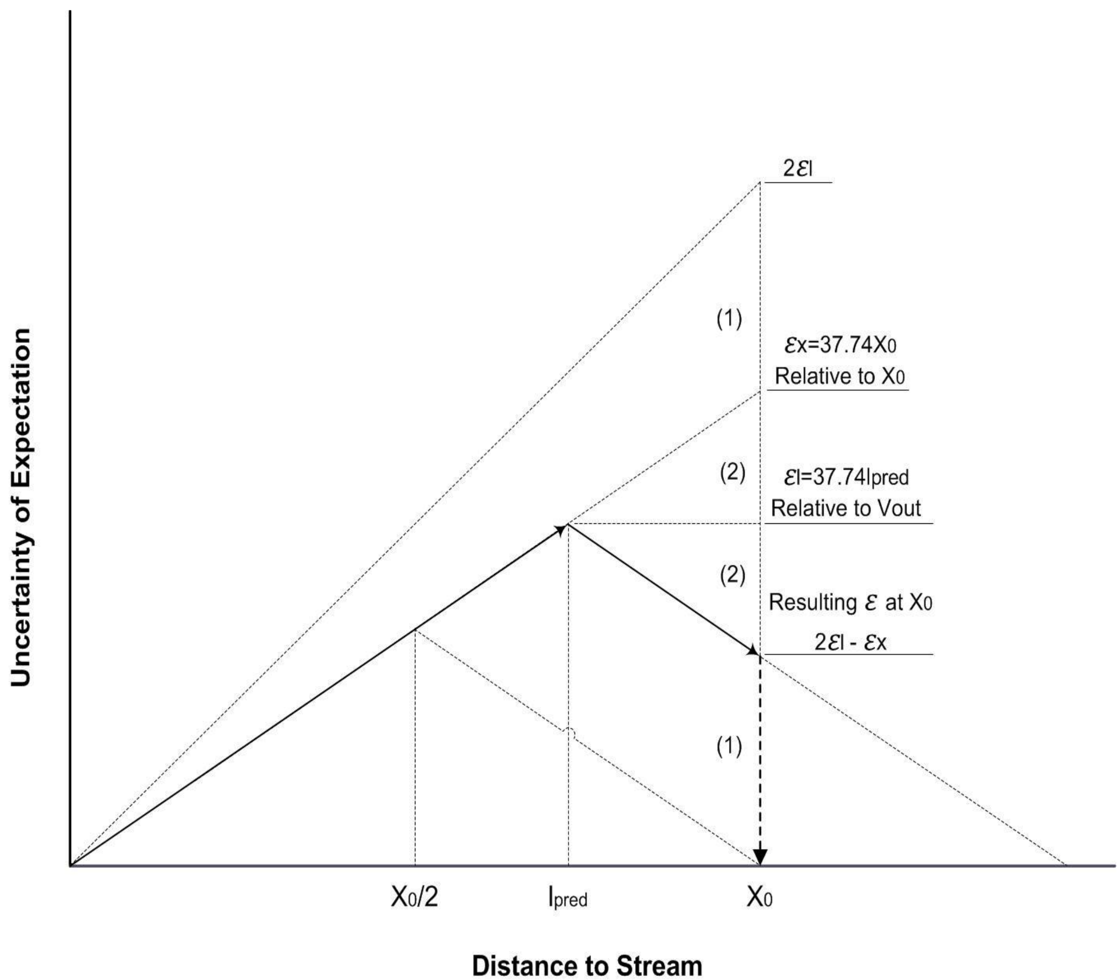


Figure 5.3: Conceptual representation of the changes in uncertainty of the VBT flow volume predictions with distance along the flow path

5.4.2 Total runoff reaching streams for the entire road network

1. Total runoff without uncertainty.

Without considering the uncertainty, the total mean volume of road runoff from the entire road network in a watershed can be given by combining Eq. 5.13 and Eq. 5.14 as:

$$V_{X_T} = \sum_{\psi=1} V_{X_i} + \sum_{0<\psi<1} V_{X_i}$$

$$= \sum_{\psi=1} V_{out_i} + \sum_{0<\psi<1} \left(V_{out_i} - 67.2 X_{0_i}\right) \quad (5.22)$$

where, all the amounts of runoff are given in liters; X_0 in meters; d and df indicate direct and diffuse flow paths, respectively; and i indicates individual segments of a road.

2. Total runoff with uncertainty.

For directly connected road segments, all the runoff generated from each of them is assumed to reach its receiving stream, and its associated uncertainty, ε_{d_i}, is taken as zero. Apparently, this is a conservative assumption because the V_{out} itself is a function of such parameters as the amount of precipitation, the area of road land use, soil types, and others. All of them are generally obtained from the field measurement that inescapably yields certain errors.

For diffusely connected road segments, the overall uncertainty can be estimated in two different ways, named them as un-weighted and weighted methods for description convenience.

a. Overall uncertainty estimated by the un-weighted method.

The overall absolute uncertainty of the sum of a bunch of variables can be obtained by directly summing up the uncertainty of each variable (Serway and Jewett 2004). For example, the predicted volume of runoff reaching stream and its absolute uncertainty for

Road Segment A are 400 L and ±25 L, those for Road Segment B are 600 L and ±35 L, the total volume and overall uncertainty for both should be (1000 ± 60) L. If the overall uncertainty is given in percentage, this result can also be expressed as (1000 ± 6%). Based on this, the total predicted volume of runoff reaching stream and its overall absolute uncertainty for the entire road network can be given as:

$$V_{X_T} = \left[\sum_{\psi=1} V_{out_i} + \sum_{0<\psi<1}\left(V_{out_i} - 67.2X_{0_i}\right)\right] + E \qquad (5.23)$$

where, E denotes the overall uncertainty, given by:

$$E = \pm z\left[\sum_{0\leq\psi<1}\left(37.74X_{0_i}\right) + \sum_{\psi<0}\left(1.123V_{out_{df_i}} - 37.74X_{0_i}\right)\right] \qquad (5.24)$$

b. Overall uncertainty estimated by the weighted method.

Statistically, the overall uncertainty of the total volume of flows can be also obtained by summing their individual uncertainties in terms of variances weighted according to the proportion of runoff from each road segment relative to the total amount of runoff from the entire road network, V_T. In such way, the summation of the uncertainty for the segments where $0 \leq \psi < 1$ can be given as:

$$E = \pm z\sqrt{\sum\left[\left(\frac{V_{out_i}}{V_T}\right)^2 \sigma^2_{V_{X_i}}\right]} = \pm z\sqrt{\sum\left[\left(\frac{V_{out_i}}{V_T}\right)^2 \left(1424X^2_{0_i}\right)\right]} \qquad (5.25)$$

The summation of the uncertainty for the segments where $\psi < 0$ can be given as:

$$E = \pm z\sqrt{\sum\left[\left(\frac{V_{out_i}}{V_T}\right)^2 \left(1.261V^2_{out_i} - 1424X^2_{0_i}\right)\right]} \qquad (5.26)$$

Combining Eq. 5.25 and Eq. 5.26, the total variance in the predicted runoff of the entire road network, σ^2_T, can be given by:

$$\sigma^2_T = \sum_{0\leq\psi<1}\left[\left(\frac{V_{out_i}}{V_T}\right)^2 \left(1424X^2_{0_i}\right)\right] + \sum_{\psi<0}\left[\left(\frac{V_{out_i}}{V_T}\right)^2 \left(1.261V^2_{out_i} - 1424X^2_{0_i}\right)\right] \qquad (5.27)$$

The total predicted runoff and uncertainty of a road or road network in a watershed can then be given as:

$$V_{X_T} = \sum_{\psi=1} V_{out_i} + \sum_{0<\psi<1}\left(V_{out_i} - 67.2X_{0_i}\right) \pm z\sqrt{\sigma_T^2} \quad (5.28)$$

Dividing this expression by the total volume of road runoff V_T provides an overall road-to-stream connectivity in the watershed, expressed as:

$$\Psi = \frac{V_{X_T}}{V_T} \quad (5.29)$$

5.5 Development of the probabilistic Vbt water quality model (PVbtWQM)

Generally speaking, the source load of a pollutant (W) entrained in the road-derived runoff leaving the road edge or a drain outlet during a storm event can be given as the product of the total volume of runoff (V) and the mean concentration of that pollutant in the runoff (C_V), expressed by:

$$W = V\, C_V \quad (5.30)$$

Conservatively assuming that pollutant concentration is independent on runoff volume, the variance of the pollutant load (σ_w^2) due to both field measurement and experimental errors can be given by:

$$\sigma_w^2 = (V^2 + \sigma_v^2)(C_V^2 + \sigma_c^2) - (V^2)(C_V^2) \quad (5.31)$$

Then, the uncertainty of the pollutant load (E_w) can be defined as:

$$E_w = \pm z\sigma_w \quad (5.32)$$

where z is a factor chosen to reflect the desired level of confidence. For instance, a z value of 1.645 would yield a 90% confidence interval around the mean value.

Substituting runoff volume with flow rate (Q) and the mean concentration with instantaneous concentration in the above three equations, the loading rate of a pollutant

(W_t), its variance ($\sigma^2_{W_t}$), and the uncertainty (E_{W_t}) can be given as:

$$W_t = QC_Q \quad (5.33)$$

$$\sigma^2_{W_t} = (Q^2 + \sigma^2_Q)(C^2_Q + \sigma^2_C) - (Q^2)(C^2_Q) \quad (5.34)$$

$$E_{W_t} = \pm z\sigma_{W_t} \quad (5.35)$$

5.5.1 Pollutant load of runoff from individual road segments

According to the runoff drainage pattern and hydrologic connectivity of a road segment to a stream, calculations of the pollutant load and its uncertainty for a road segment can be classified into the following four different cases.

Case I: for a directly connected road segment where $\psi = 1$, all the runoff leaving the drainage outlet is assumed to fully reach a channel or a stream, its pollutant load ($W\ in\ kg$) and variance ($\sigma^2_W\ in\ kg^2$) can be given as follows:

$$W = (10^{-6})V_{out}C_{out} \quad (5.36)$$

$$\sigma^2_W = (10^{-12})(V_{out})^2(\sigma^2_C) \quad (5.37)$$

where V_{out} is the volume of runoff leaving the drainage outlet in liters; C_{out} is pollutant concentration in the runoff in mg/L; and the constants $10^{-6}$and 10^{-12} are unit conversion factors.

The uncertainty of this pollutant load is given as:

$$\varepsilon_W = \pm z\sigma_W = \pm z(10^{-6})V_{out}\sigma_C \quad (5.38)$$

Case II: for a diffusely connected road segment where $0 < \psi < 1$, its pollutant load ($W\ in\ kg$) and variance ($\sigma^2_W in\ kg^2$) can be given as:

$$W = (10^{-6})V_X C_X = (10^{-6})(V_{out} - 67.2X_0)C_X \quad (5.39)$$

$$\sigma^2_W = (10^{-12})\{(V^2_X + \sigma^2_{V_X})(C^2_X + \sigma^2_C) - (V^2_X)(C^2_X)\}$$

$$= (10^{-12})\{[(V_{out} - 67.2X_0)^2 + 1424X_0^2](C_X^2 + \sigma_C^2) - (V_{out} - 67.2X_0)^2 C_X^2\} \quad (5.40)$$

where V_X is the volume of runoff reaching the stream in liters; V_{out} is the volume of runoff leaving the road edge in liters; C_X is pollutant concentration in the runoff reaching the stream in mg/L; X_0 is the length of flow pathway from road to stream in meters, and the other parameters are defined as previously.

The uncertainty of this pollutant load is given as:

$$\varepsilon_W = \pm z(10^{-6})\sqrt{[(V_{out} - 67.2X_0)^2 + 1424X_0^2](C_X^2 + \sigma_C^2) - (V_{out} - 67.2X_0)^2 C_X^2} \quad (5.41)$$

Case III: for a diffusely connected road segment where $\psi = 0$ (i.e., $l_{pred} = X_0$), the pollutant load is equal to zero (i.e., $W = 0$) because no runoff reaches a stream (i.e., $V_X = 0$). However, the uncertainty of pollutant load caused by the uncertainty propagation of runoff should be taken into consideration. The uncertainty of runoff where $\psi = 0$ is $\pm z(37.74)X_0$. Thus, the uncertainty of pollutant load can be given as:

$$\varepsilon_W = \pm z(10^{-6})(37.74)X_0\sigma_C \quad (5.42)$$

Case IV: for a diffusely connected road segment where $\psi < 0$ and $\frac{X_0}{2} < l_{pred} < X_0$, the uncertainty of runoff is $\pm z(1.123V_{out} - 37.74X_0)$. Similarly, the uncertainty of pollutant load is given as:

$$\varepsilon_W = \pm z(10^{-6})(1.123V_{out} - 37.74X_0)\sigma_C \quad (5.43)$$

For a diffusely connected road segment where $l_{pred} \leq \frac{1}{2}X_0$, the uncertainty of pollutant load should be taken as zero.

Replacing the runoff volume and its pollutant EMC with the flow rate of runoff and its instantaneous concentration of the pollutant in Eq. 5.36 through Eq. 5.43, the pollutant load rate and its uncertainty will be obtained.

5.5.2 Event pollutant loads of runoff from an entire road network

1. Event pollutant load without uncertainty.

The total pollutant load from the entire road network in a watershed during a storm event without considering the uncertainty can be straightforwardly given by combining Eq. 5.36 and Eq. 5.39, expressed as:

$$W_{Te} = (10^{-6})\left\{\sum_{\psi=1}(V_{out}C_{out}) + \sum_{0<\psi<1}[(V_{out} - 67.2X_0)C_X]\right\} \quad (5.44)$$

where W_{Te} is the pollutant load of an event in kg; the former item is the sum of pollutant loads from directly connected road segments and the later item is the sum from diffusely connected road segments.

Replacing flow volume with flow rate and mean concentration with instantaneous concentration, the total rate of pollutant load, W_{Te_t}, from the entire road network can be given as:

$$W_{Te\_t} = (10^{-6})\left\{\sum_{\psi=1}\int_0^D(V_{out}C_{out}) + \sum_{0<\psi<1}\int_0^D[(V_{out} - 67.2X_0)C_X]\right\} \quad (5.45)$$

where, D denotes flow duration of road runoff.

2. Event pollutant load with uncertainty.

There are two different ways to estimate the uncertainty of the event load of a pollutant, similar to those in estimating the overall uncertainty of road runoff.

a. Uncertainty of event pollutant load estimated by the un-weighted method.

Using the un-weighted method, the overall uncertainty of the event load of a pollutant from the entire road network can be obtained by directly sum up the uncertainties of pollutant loads from individual road segments, expressed as:

$$E_{We} =$$

$$\pm z(10^{-6})\left\{\sum_{\psi=1}(V_{out}\sigma_C) + \right.$$

$$\sum_{0<\psi<1}\sqrt{[(V_{out}-67.2X_0)^2+1424X_0^2](C_X^2+\sigma_C^2)-(V_{out}-67.2X_0)^2C_X^2}+$$
$$\sum_{\psi=0}(37.74X_0\sigma_C)+\sum_{\psi<0}[(1.123V_{out}-37.74X_0)\sigma_C]\Big\} \quad (5.46)$$

b. Uncertainty of event pollutant load estimated by the weighted method.

Using the weighted method, the overall uncertainty of the event load of a pollutant from the entire road network can be obtained by summing their individual uncertainties of pollutant loads from road segments in terms of variances weighted according to the proportion of pollutant source loads from each road segment (W) relative to the total amount of pollutant source load from the entire road network (W_{Te}). In such way, the overall uncertainty of the event load of that pollutant can be given as:

$$E_{We}=\pm z(10^{-6})\Big\{\sum_{\psi=1}\left(\frac{W}{W_{Te}}\right)^2(V_{out})^2(\sigma_C^2)+\sum_{0<\psi<1}\left(\frac{W}{W_{Te}}\right)^2[((V_{out}-67.2X_0)^2+$$
$$1424X_0^2)(C_X^2+\sigma_C^2)-(V_{out}-67.2X_0)^2(C_X^2)]+\Big\{\sum_{\psi=0}\left(\frac{W}{W_{Te}}\right)^2(37.74X_0\sigma_C)^2+$$
$$\Big\{\sum_{\psi<0}\left(\frac{W}{W_{Te}}\right)^2((1.123V_{out}-37.74X_0)\sigma_C)^2\Big\}^{\frac{1}{2}} \quad (5.47)$$

where, pollutant loads (W_{Te} and W) are in kg; the volumes of runoff in L; concentrations of the pollutant in mg/L; X_0 in meters; and z is a factor reflecting a level of confidence.

Combining Eq. 5.44 and Eq. 5.46 or Eq. 5.47 provides the total pollutant load with uncertainty from an entire road network.

5.6 Estimating highway stormwater pollutant TMDLs and their uncertainties

Previously discussed is how to estimate the event load of a pollutant in the storm runoff from the land use of an entire road network. Over a year, this type of loads occurs intermittently. For the purpose of TMDL development, however, it is usually required that the load or loading of a pollutant be expressed in a continuous fashion with the unit of mass per a unit time, for instance, kilograms/day or pounds/day. Therefore, it is necessary to further estimate the equivalent continuous loading, based on intermittent pollutant loads. To do so, Thomann and Mueller (1987) proposed that a long-term average loading rate W_A can be estimated from

$$W_A = \frac{W_R D}{\Delta} \tag{5.48}$$

where, W_R is the mean load per event; D is the average duration of storms; and Δ is the average time between storms.

This algorithm has been long adopted by many water quality researchers for estimating the long-term average loading rates of pollutants entrained in urban stormwater runoff, based on their hydrological and water quality data that are obtained from field monitoring of limited numbers of events over a certain period of time, usually in one or two years.

Another alternative approach is that if pollutant loads from each event in a long period of time (e.g., one year or several years) can be estimated, the average loading rate can be obtained through dividing the total pollutant loads of all the events by that period of time. This approach is adopted in most water quality continuous simulation models, such as WARMF, SWAT, and others, and so does the PVbtWQM model. Furthermore, considering that precipitation data are usually available on hourly rainfall or daily totals, the PVbtWQM model is designed to simulate storms on a daily basis. As such, the average loading rate of a pollutant entrained in highway storm runoff from the entire road network in a watershed, which can be considered to be the TMDL of the pollutant, can be given as,

$$TMDL = \frac{\sum W_{Te}}{N} \tag{5.49}$$

where W_{Te} is the total event load or daily load in kg during wet weather, depending on the type of rainfall data used, by event or by day; N is the total number of days simulated, including the time of both dry weather and wet weather; TMDL is given in kg/day.

The uncertainty of the TMDL is given as

$$E_{TMDL} = \pm z\left(SD + \frac{\sum|E_{We}|}{N}\right) \qquad (5.50)$$

Or,

$$E_{TMDL} = \pm z\left(SD + \frac{\sum\left(\frac{W_{Te}}{\sum W_{Te}}\right)|E_{We}|}{N}\right) \qquad (5.51)$$

where, the first term, SD, is the standard deviation associated with the daily averaged value and the second term is the propagated uncertainty associated with the calculated event-based loadings. All the other parameters are defined as previously.

In the following Chapter 7, the manipulation of the PVbtWQM model and its algorithms will be described in detail by applying them to the Lake Orange watershed in North Carolina.

CHAPTER 6: MANIPULATING THE PVbtWQM MODEL TO ESTIMATE HIGHWAY STORMWATER NUTRIENT TMDLS

In Chapter 5 all the algorithms for PVbtWQM are developed to quantify watershed-scale highway stormwater runoff, pollutant loads, and their associated uncertainties. This chapter is intended to apply the PVbtWQM model to the Lake Orange (LO) watershed in North Carolina and demonstrate how to manipulate it for estimating the nutrient TMDLs of stormwater runoff from the entire road network land use in the watershed. Prior to description of the procedure of model manipulation, the characteristics of the Lake Orange watershed will be first introduced, and then the preparation of model inputs discussed in depth. In the end of the chapter presented will be the model simulation results of highway stormwater TMDLs of nutrients including total nitrogen (TN) and total phosphors (TP).

6.1 Characteristics of the Lake Orange watershed

The Lake Orange watershed (HU030202010301) is located in Orange County of North Carolina (Figure 6.1). This 26.74-mi^2 (17,114-acre) watershed is portion of the Eno River watershed (HU0302020103) – one of three major headwater watersheds of the Falls Lake watershed (HU03020201), which is the north portion of the Neuse River Basin at the northeastern Piedmont region. Falls Lake is a man-made reservoir constructed during 1978 – 1981 for the purposes of flood protection, water supply, water quality control, and recreation. In1983, the Falls Lake watershed was classified by the NC Environmental Management Commission (EMC) as Nutrient Sensitive Waters

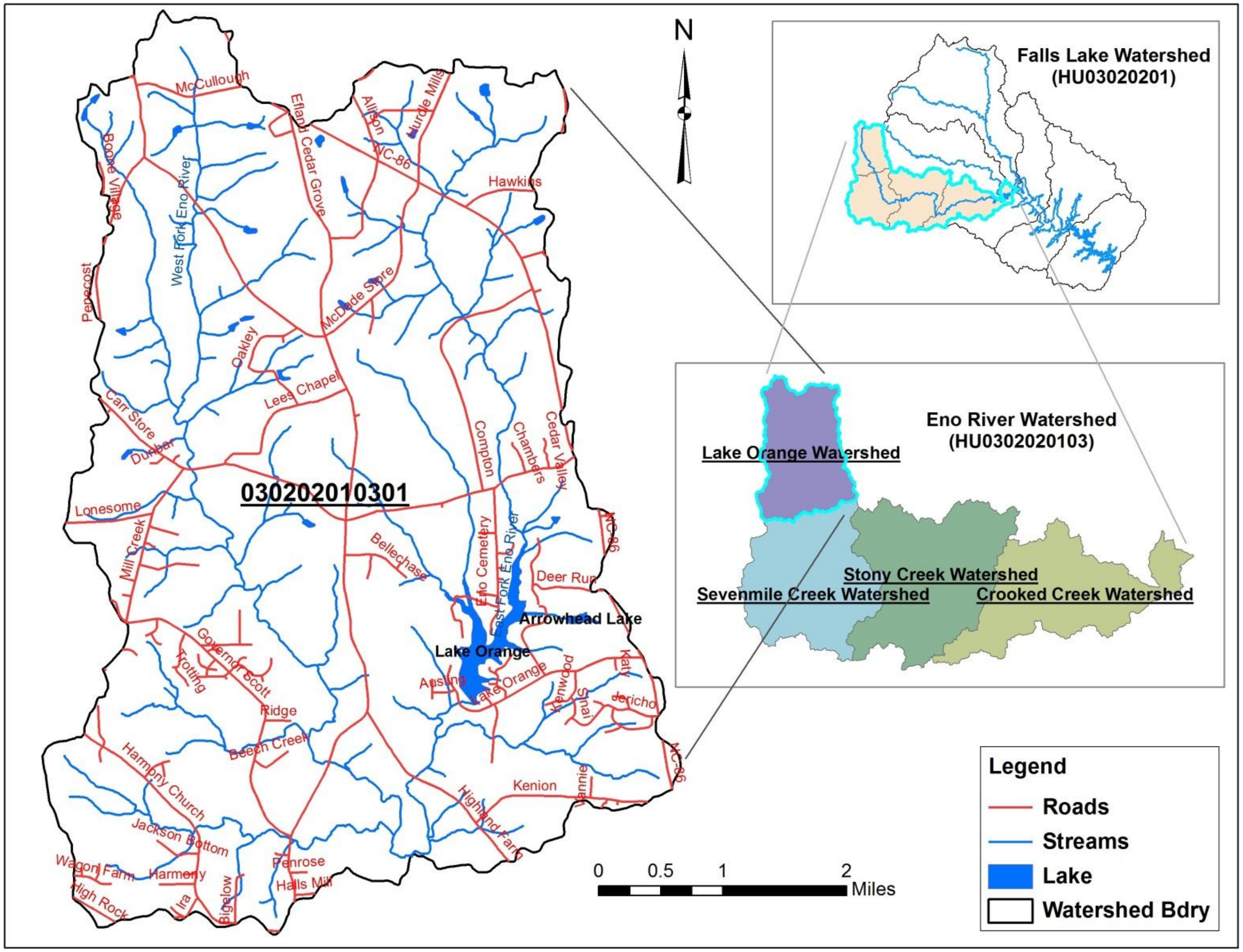


Figure 6.1: Location of the LO watershed

(NCDENR 1998). The lake was listed on NC's Draft 2008 303(d) list as impaired for chlorophyll a and turbidity (NCDENR 2009).

6.1.1 Climate

The Lake Orange watershed has the warm, humid climate that is typical of the southeastern United States. Specific monthly temperature and precipitation are listed in Table 6.1 and illustrated in Figure 6.2. The average temperature is 43.3 ℉ in the winter and 73.9 ℉ in summer. The average daily minimum temperature is 28.2 ℉, and the average daily maximum temperature is 83.8 ℉. The average annual total precipitation is 48.04 inches per year at Durham City, typical for the Lake Orange watershed. Of which, about 28.41 inches (59%) usually falls in April through October. In winter the precipitation is usually light snow and showers, and in other seasons it is either light, prolonged rain or quick, hard showers. The precipitation is rather uniformly distributed during the year. The humidity varies from 45 % in March and April to about 90 % in the late summer.

Table 6.1: Monthly temperature and precipitation at the ER watershed

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Maximum Temperature, ℉	49.2	53.4	62.1	71.3	78.6	85.0	88.6	86.8	81.0	71.4	62.0	52.7
Minimum Temperature, ℉	27.8	29.5	37.0	45.8	55.6	65.4	70.1	67.9	60.3	46.6	37.4	30.4
Mean Temperature, ℉	38.5	41.5	49.6	58.6	67.1	75.2	79.4	77.4	70.7	59.0	49.7	41.6
Highest Mean Temperature, ℉	49.0	48.4	55.8	63.0	72.3	78.9	83.8	81.4	74.0	65.0	57.8	49.2
Lowest Mean Temperature, ℉	28.2	33.9	44.5	54.9	62.7	72.0	74.4	73.7	66.8	52.3	42.5	32.1
Precipitation, inches	4.4	3.7	4.7	3.4	4.6	4.0	4.0	4.4	4.4	3.7	3.4	3.4

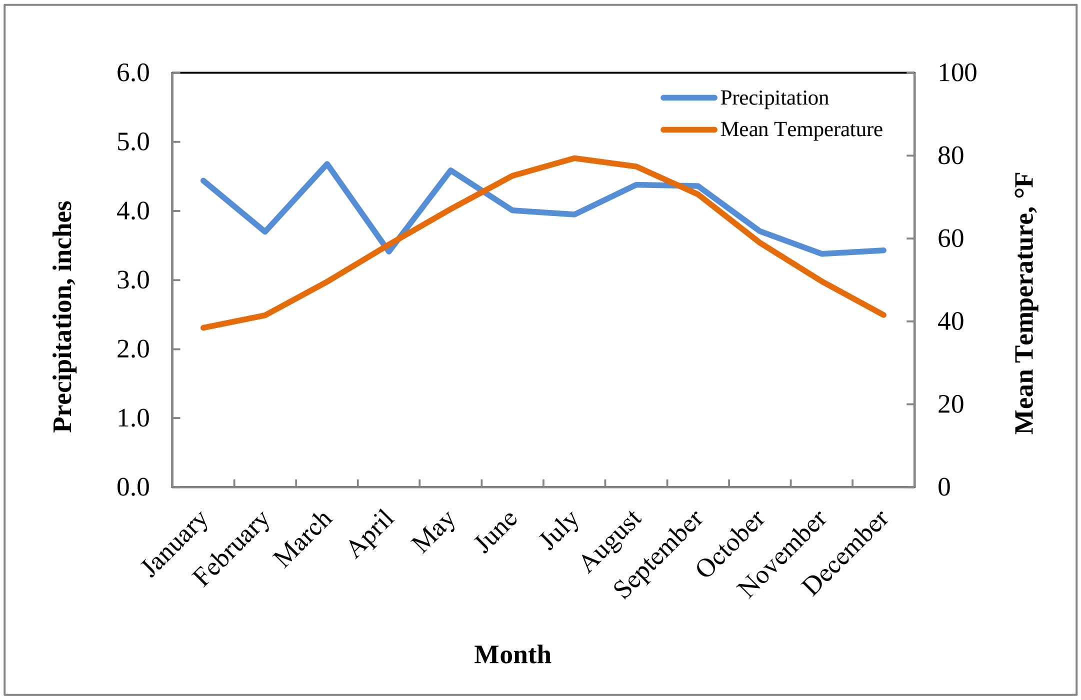


Figure 6.2: Monthly temperature and precipitation at the Lake Orange watershed

6.1.2 Soil types and land use

According to the *Soil Survey Geographic (SSURGO) database for Orange County, North Carolina* (NRCS 2010), the Lake Orange watershed is covered with twenty-five types of eighteen soil series and water bodies such as streams, rivers, ponds, and the lake. Their spatial distribution is illustrated in Figure 6.3, and the acreage of each type of soil is given in Table 6.2. Among these soil series, six dominate ones account for 14,917 acres which is 87.2% of the total area of the watershed, including Georgeville soils 6,296 acres (36.8%); Helena and Helena-Sedgefield 3,080 acres (18.0%); Appling 2,294 acres (13.4%); Herndon 1,609 acres (9.4%); Chewacla 880 acres (5.1%); and Tatum 757 acres (4.4%). All the soil types also can be generally further grouped into the following three soil associations:

a) Nason-Herndon-Helena-Georgeville-Appling association (9,014 acres/ 52.7%);

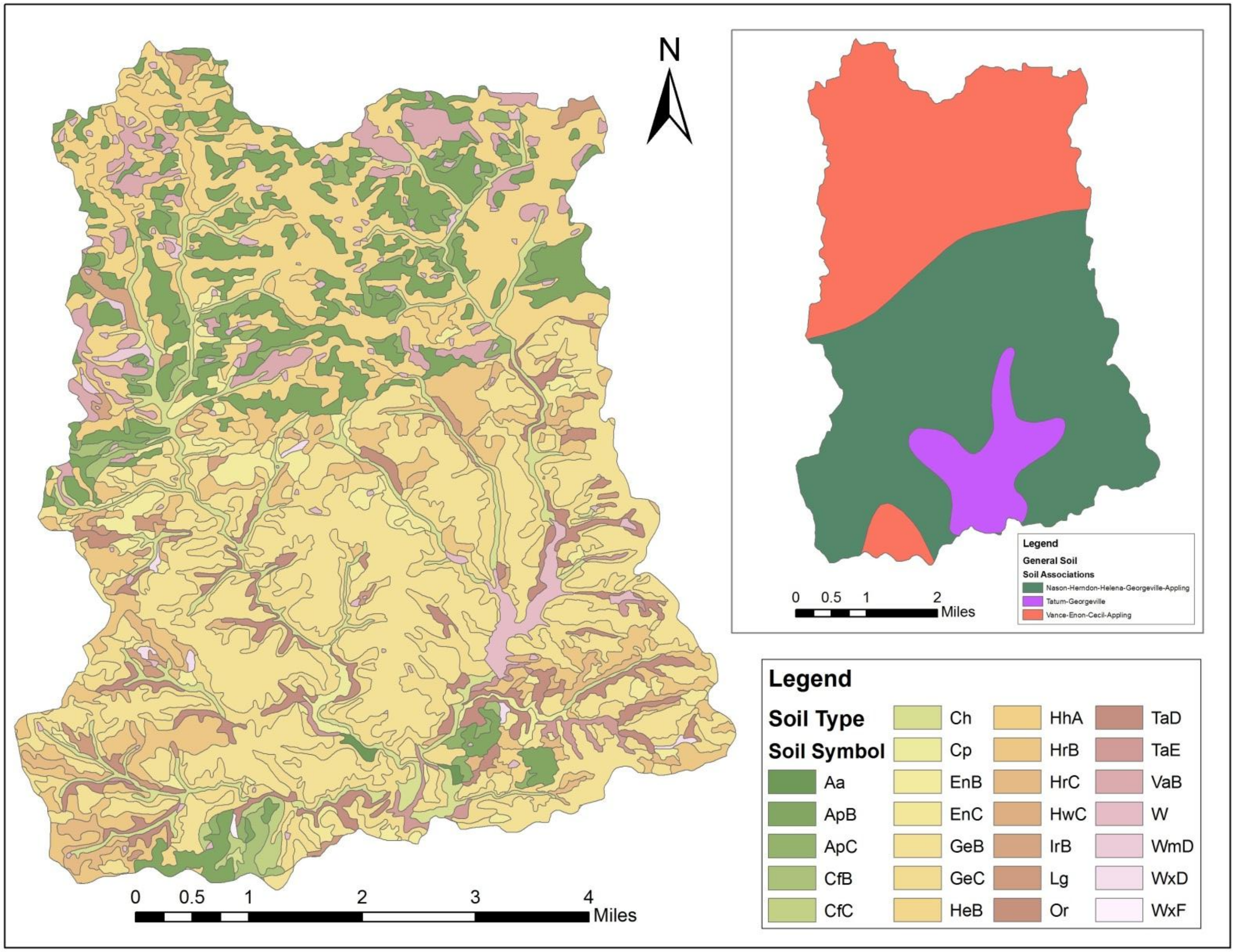


Figure 6.3: Soil map of the LO watershed

Table 6.2: Acreage of different soil types in the Lake Orange watershed

Map Symbol	Soil Name	Area (acre)	Percent (%)	Rank
Aa	Altavista fine sandy loam, 0 - 3 % slopes	23	0.14	24
ApB	Appling sandy loam, 2 - 6 % slopes	1928	11.26	4
ApC	Appling sandy loam, 6 - 10 % slopes	366	2.14	12
CfB	Cecil fine sandy loam, 2 - 6 % slopes	102	0.59	19
CfC	Cecil fine sandy loam, 6 - 10 % slopes	84	0.49	20
Ch	Chewacla loam	880	5.14	6
Cp	Congaree fine sandy loam	69	0.40	21
EnB	Enon loam, 2 - 6 % slopes	406	2.38	10
EnC	Enon loam, 6 - 10 % slopes	226	1.32	14
GeB	Georgeville silt loam, 2 - 6 % slopes	4289	25.07	1
GeC	Georgeville silt loam, 6 - 10 % slopes	2007	11.73	3
HeB	Helena sandy loam, 2 - 8 % slopes	2557	14.94	2
HhA	Helena-Sedgefield sandy loams, 0 - 2 % slopes	523	3.05	9
HrB	Herndon silt loam, 2 - 6 % slopes	1232	7.20	5
HrC	Herndon silt loam, 6 - 10 % slopes	377	2.21	11
HwC	Hiwassee clay loam, 6 - 10 % slopes	5	0.03	25
IrB	Iredell gravelly loam, 1 - 4 % slopes	105	0.61	18
Lg	Lignum silt loam, 0 - 3 % slopes	126	0.74	16
Or	Orange silt loam, 0 - 3 % slopes	109	0.64	17
TaD	Tatum silt loam, 8 - 15 % slopes	623	3.64	7
TaE	Tatum silt loam, 15 - 25 % slopes	134	0.79	15
VaB	Vance sandy loam, 2 - 8 % slopes	557	3.25	8
W	Water	296	1.73	13
WmD	Wedowee sandy loam, 8 - 15 % slopes	44	0.25	22
WxD	Wilkes gravelly loam, 8 - 15 % slopes	37	0.22	23
WxF	Wilkes gravelly loam, 15 - 45 % slopes	5	0.03	26

b) Vance-Enon-Cecil-Appling association (6,684 acres/39.1%); and

c) Tatum-Georgeville association (1,414 acres/8.3%).

For each soil type or series, its definition and property description in depth are referred to the manuscript *Soil Survey of Orange County, North Carolina* (NRCS 1977).

After integrating NC DOT land use with the 2001 National Land Cover Dataset (NLCD2001), the land use/land cover (LULC) in the Lake Orange watershed is as follows: deciduous, evergreen, and mixed forest, 8,811 acres (51.5%); pasture and cultivated crops, 5,851 acres (34.2%); urban developed other than NC DOT road land use, 885 acres (5.2%); shrub and grassland, 748 (4.4%); NC DOT land use, 231 acres (1.3%); wetlands, 150 acres (0.9%); and water, 427 acres (2.5%)(Table 6.3 and Figure 2.4).

The NLCD2001 raster data is requested to download from the U.S. Geological Survey (USGS) web site (http://seamless.usgs.gov/); and NC DOT land use data is prepared with ArcGIS tools in terms of road characteristic attributes in the digital file Road Characteristics Arcs that are available from the NC DOT web site (http://www.ncdot.org/it/gis/DataDistribution/DOTData/). The in-depth description of the approaches to preparing NLCD and NC DOT LULC dada, and integrating the both are provided in Appendix C.

Table 6.3: Acreage of land use/land cover in the Lake Orange watershed

Code	Class name of land cover*	Area (acre)	Percent (%)	Rank
11	Open Water	427	2.50	5
21	Developed, Open Space	755	4.41	4
22	Developed, Low Intensity	126	0.74	12
23	Developed, Medium Intensity	4	0.02	14
29**	NC DOT	231	1.35	10
31	Barren Land (Rock/Sand/Clay)	11	0.06	13
41	Deciduous Forest	7,677	44.86	1
42	Evergreen Forest	796	4.65	3
43	Mixed Forest	339	1.98	7
52	Shrub/Scrub	337	1.97	8
71	Grassland/Herbaceous	412	2.40	6
81	Pasture/Hay	5,570	32.55	2
82	Cultivated Crops	281	1.64	9
90	Woody Wetlands	150	0.88	11
Total		17,114	100	14

* The definitions for each class excluding NC DOT are referred to Appendix D.

**Includes the land use of Interstates, US routes, NC routes, secondary routes, and ramps.

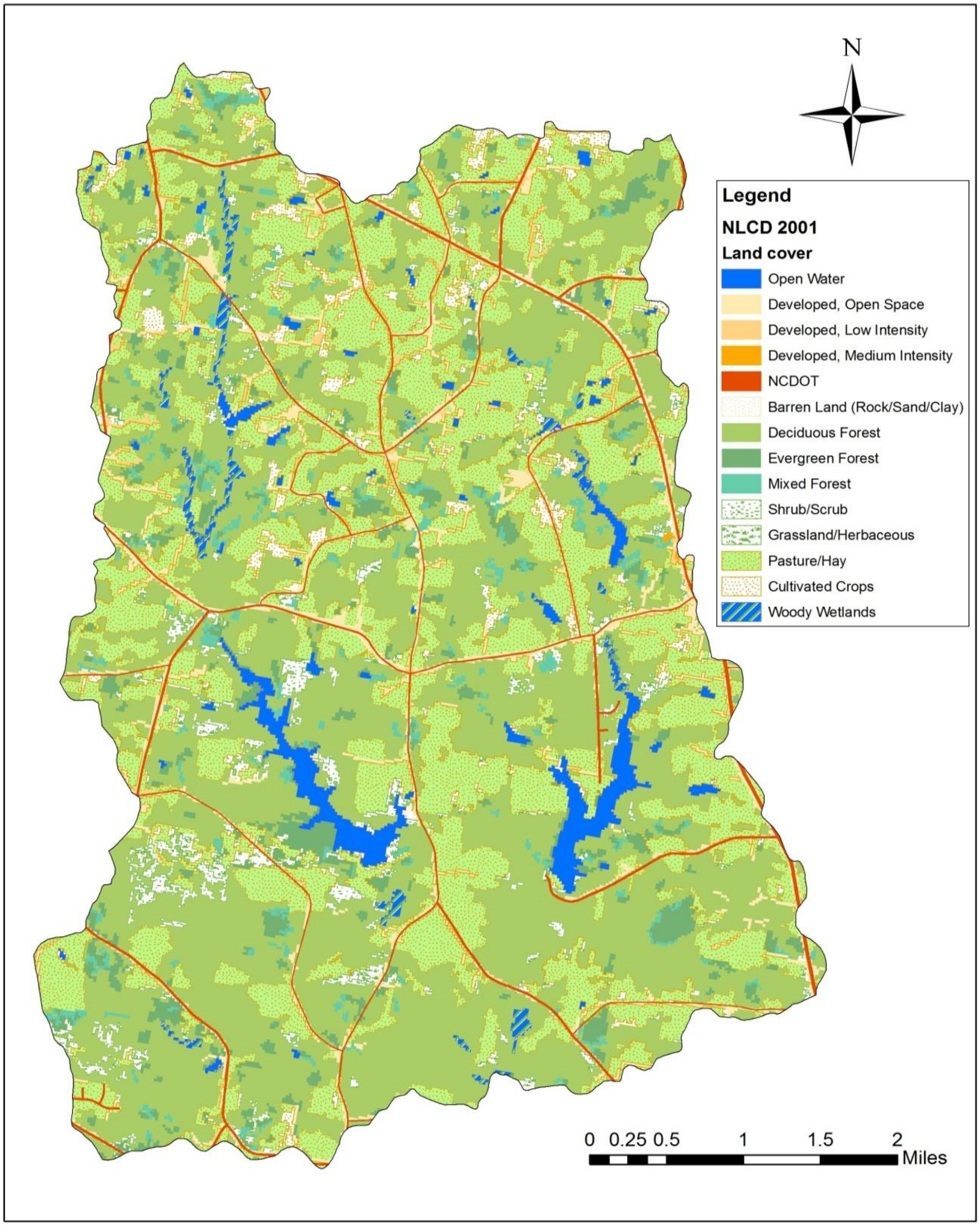


Figure 6.4: Land cover/land use of the Lake Orange watershed

6.1.3 Topography and stream density

As illustrated in Figure 6.6, the Lake Orange watershed shows a W-shaped landform, higher in the middle with two rivers, one of each side, East Fork Eno River and West Fork Eno River, which run from north to south through the watershed and converge at the outlet of watershed to start the Eno River. The difference of elevation in the watershed is approximately 194.6 feet, ranging from 561.5 feet to 756.1 feet above the sea level. Most slopes are gently sloping and vary from 0 to 47.4 degrees (or 1.087), with a mean value of slope 2.9 degrees (or 0.051). The land-surface terrain is relatively flat. Fifty percent of land surface has a slope less than 4 degrees and 90% has a slope less than 9 degrees (Figure 6.5).

The drainage systems in the watershed are well developed. The total length of “streams” extracted from the National Hydrography Dataset (NHD) is approximately 73.9 mi (118.9 km) and the stream density is about 2.76 mi/mi^2 (1.72 km/km^2). The longest river is West Fork Eno River (8.6 mi or 13.9 km); and the second is East Fork Eno River (7.8 mi or 12.5 km) which is the source water of Lake Orange.

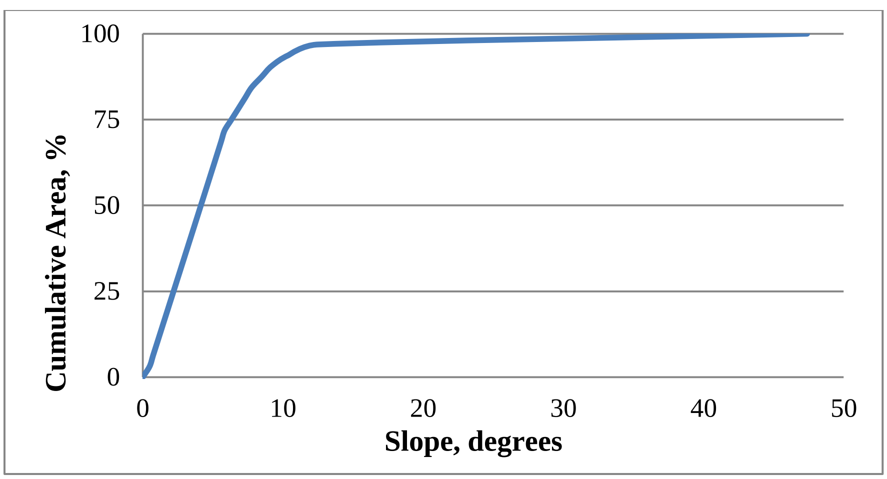
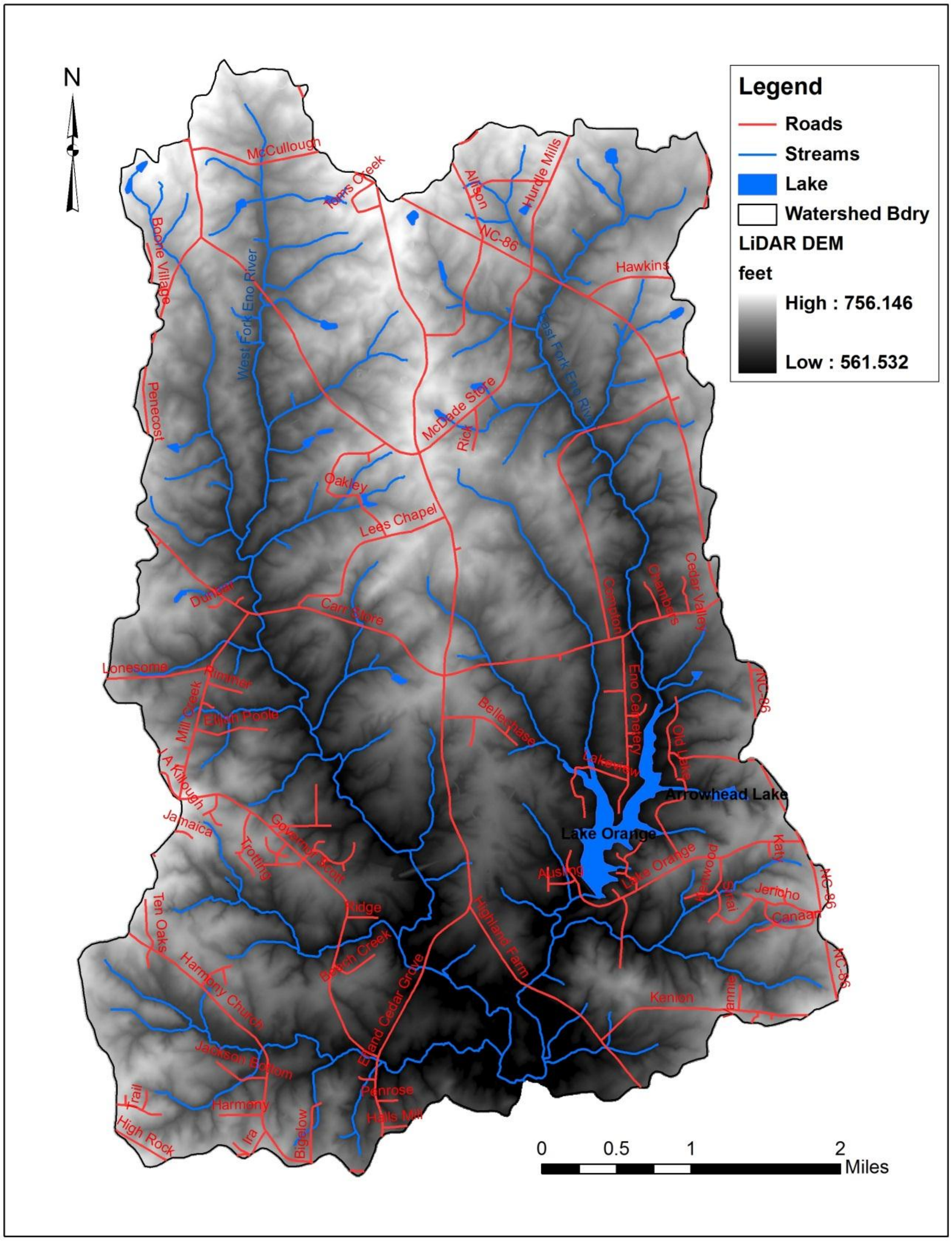


Figure 6.5: Cumulative area with slope in the Lake Orange watershed



(Data sources: USGS National Hydrography Dataset (NHD) and NCDOT GIS Data Layers)

Figure 6.6: DEM of the Eno River watershed

6.1.4 Road density

According to NCDOT's Integrated Statewide Road Network (ISRN) Layer (Version II), the total length of all the roads in the Lake Orange watershed is approximately 64.5 miles (103.8 km) and the road density is about 2.41 mi/mi^2 (1.50 km/km^2). The length of NCDOT maintained roads, however, is only 46.9 miles (75.4 km) and the density is 1.75 mi/mi^2 (1.09 km/km^2), based on the 1st Quarter 2011 Release of the Road Characteristics Layer by NC DOT. As shown in Figure 6.6, most roads are situated at the uplands or "ridges" of the watershed.

6.2 Procedure of manipulating the PVbtWQM model

The whole PVbtWQM model consists of the following three components: a) hydrological or HC component for storm runoff estimation and HC evaluation; b) event-based WQ simulation component for calculating TN and TP loads; and c) TMDL component for estimating TN and TP loading rates. Each of these components has its own set of unique functions. All the algorithms for performing these three sets of functions have been populated and programmed in the separate spreadsheets of Microsoft Excel (Appendix G).

Based on the model's functionality and the current availability of its required input data, the general procedure for manipulating this model to estimate highway storm runoff pollutant TMDLs is illustrated step by step in Figure 6.7, including eight sequential steps as follows:

Step 1: Delineating catchments of highway storm water and measuring lengths of overland flow pathways of road runoff by performing the highway storm runoff drainage analysis through field surveying, terrain preprocessing, or the both in combination.

Step 2: Preparing highway land use/land cover according to road characteristic attributes of the existing road centerline GIS shape file and estimating the drainage area and its impervious proportion for each of the road segments defined in Step 1.

Step 3: Estimating the amounts of runoff which are originally generated from the land use of each road segment.

Step 4: Obtaining the values of the Vbt5 parameter by performing field experiments, or adapting the values from literature under local climatic and hydrogeological conditions.

Step 5: Calculating the volume of road runoff reaching the stream network and evaluating the road-to-stream hydrologic connectivity for either individual road segments or the entire road network in a watershed by using the hydrological component.

Step 6: Estimating event mean concentrations and their uncertainties of pollutants for the runoff from different road segments by using multiple regression equations that are established on the base of field monitoring of highway stormwater runoff.

Step 7: Performing the event-based simulation to calculate pollutant loads and their uncertainties for individual storm events from the entire road network land use in a watershed by using the WQ component.

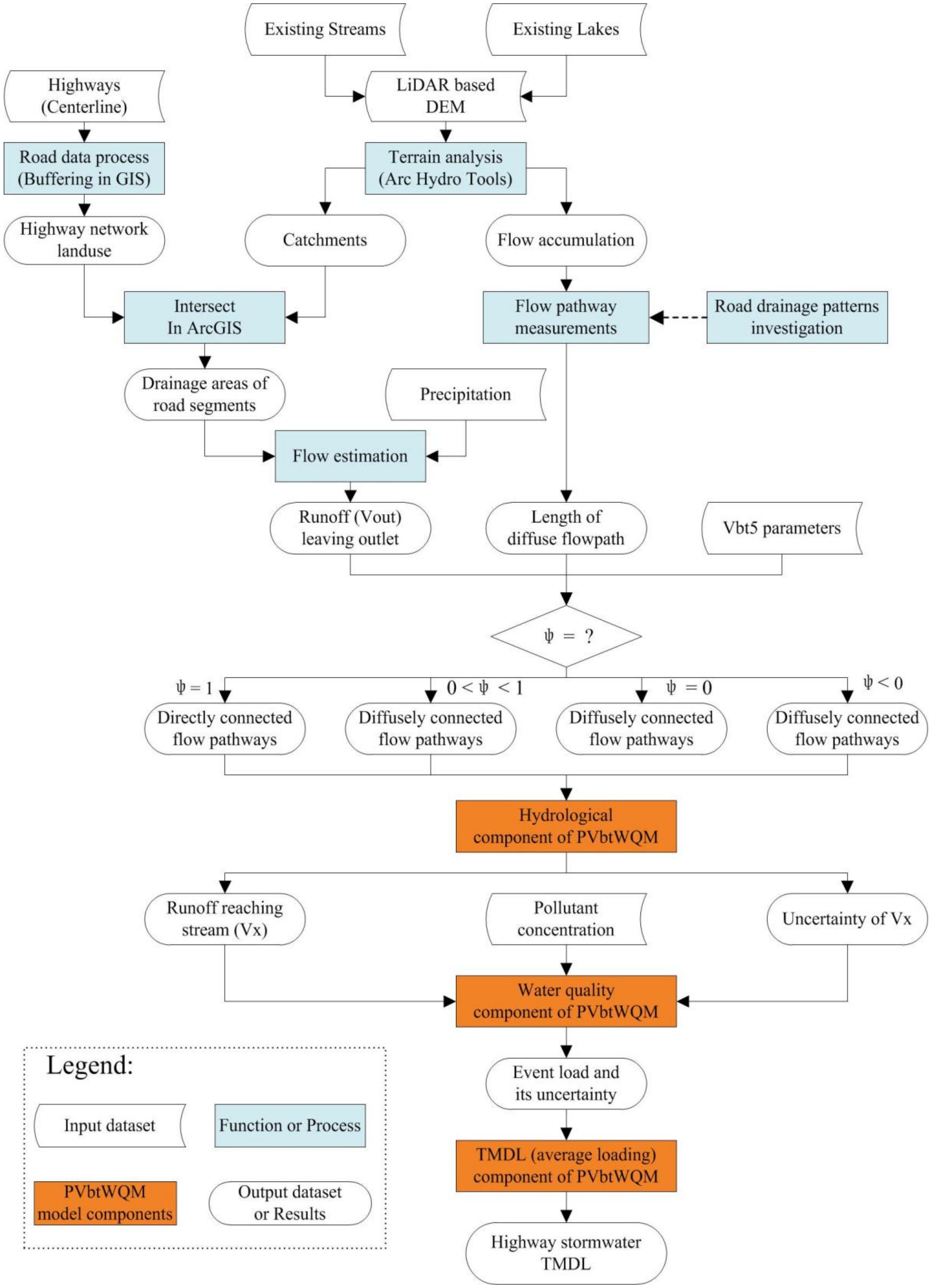


Figure 6.7: Procedure of manipulating the PVbtWQM model

Step 8: Continuously simulating the storm events to estimate storm runoff pollutant TMDLs and their uncertainties from the entire highway network land use in the watershed by using the TMDL component.

This eight-step procedure can be divided into two parts. The first part, including Steps 1 to 4 and 6, is intended to prepare a variety of important model inputs; and the second part, including Steps 5, 7, and 8, is the model's three core components. Each of these components will be fully demonstrated in both the modeling results of Section 6.4 and the entire process of model programming. For the steps in the first part, Step 2 related to highway land use processing has been briefly described in Section 6.3.2 and Appendix C; the rest of the steps concerning input data preparation methods will be described in depth in the next section.

6.3 Preparation of model inputs

Considering that it is a recently emerging task for state transportation agencies to quantify watershed-scale storm runoff pollutant loads from highways for the purpose of compliance with TMDL implementation requirements, at present there are few ready-to-go data for doing this job in the existing highway stormwater data repositories. As a result, most of the inputs fed into no matter what model is used for TMDL development have to be prepared ahead. The main inputs to the PVbtWQM model include precipitation, drainage area and imperviousness coverage of individual road segments, drainage pattern information and lengths of overland flow pathways, Vbt5 values, traffic volumes, and pollutant concentrations in the road runoff at different locations. In the Lake Orange watershed to be simulated, except for the daily rainfall data which has been estimated by Andy McDaniel of NC DOT and retrieved from the *Falls Lake WARMF*

Development (referring to Apendix B), all the others need to be prepared from the following currently available data sources:

- Orange County high resolution LiDAR-based DEM with a grid spacing of 20 by 20 feet;
- HU0302 high resolution Watershed Boundary Dataset (WBD) and National Hydrography Dataset (NHD, also known as NHDinGEO), containing rivers and streams (i.e., NHD Flow line), lakes and big ponds (NHD Waterbody), and 12-digit watershed boundary data;
- Road Characteristics Arcs GIS layer (road centerline shape file); and
- NC DOT highway storm runoff WQ data collected from the field monitoring research projects that were funded by Federal and NC State government agencies.

To do so, terrain preprocessing is the first essential step and also one of the most important steps in data preparation.

6.3.1 Terrain preprocessing

For the Lake Orange watershed, a comprehensive terrain preprocessing is performed by using the Arc Hydro tools (Version 1.3) with ArcGIS (Version 9.3) on the LiDAR-based DEM mentioned above due to its known drainage patterns (i.e., known streams and lakes). The Arc Hydro tools are available for free download on the ESRI web site (http://support.esri.com/en/downloads/datamodel/detail/15). The role of the preprocessing is conducting drainage analysis to derive raster data sets on flow direction, flow accumulation, stream definition, stream segmentation, and watershed delineation. These data are then used to develop a vector representation of catchments and drainage lines. The preprocessing workflow is illustrated in Figure 6.8. The input data and results for each of the functions used in the process are demonstrated in Appendix E. All these functions or steps are explained here and performed sequentially as follows.

1. Fill Sinks. Sinks (depressions, pits) are the areas into which the water flows but does not exit as surface flow. In DEMs, most of the sinks are artificial and are artifacts of DEM construction. There are also real sinks. This function fills the sinks in a grid, and insures that all the sinks in the original terrain are filled and that all the water in the drainage basin is routed into the stream system. The function will generate the "filled DEM" with no sinks in it.
2. DEM Reconditioning. This function "burns" the known streams onto the DEM. Before executing this function, the know stream layer to be imposed onto the DEM should be "cleaned" (Djokic, 2008). The burning process implemented in the Arc Hydro tools follows the AGREE method (Hellweger 1997). The process might take several iterations to get acceptable results (by changing the three input parameters).
3. Fill Sinks. Filling the sinks again makes sure to eliminate any potential depressions introduced by the burning process.
4. Flow Direction. The flow direction function generates a grid that defines for each cell the steepest descent direction based on the eight neighboring cells (D8 method). Flow direction grid should have only eight distinct values (1, 2, 4, 8, 16, 32, 64, and 128). If not, this is an indication that the sinks were not filled successfully.
5. Adjust Flow Direction in Lakes. This function modifies an existing flow direction grid. The input into the function should be the flow direction grid that had the streams already burned in. If the stream layer is not available, then the synthetic streams can be used.

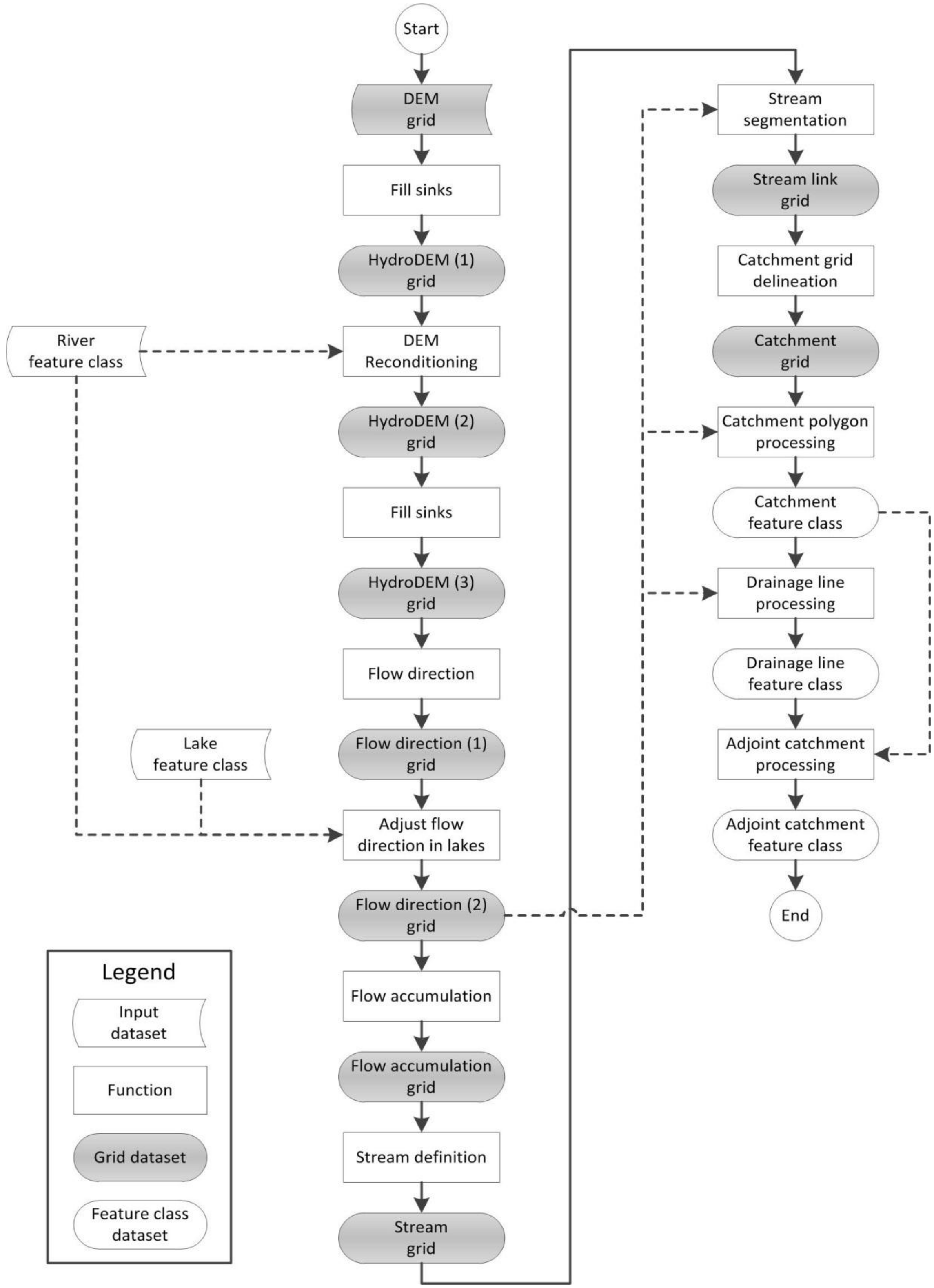


Figure 6.8: Terrain preprocessing workflow for imposing the known drainage patterns and flow direction within lakes

6. Flow accumulation. The flow accumulation step generates a grid that contains a number of upstream cells that drain through each cell.
7. Stream Definition. This function identifies those cells that are “streams” (also referred to as “synthetic streams”), based on a user specified stream threshold. The default value of stream threshold is 1% of the maximum flow accumulation value, which is 18,768 cells (697,457 m^2) for the DEM of the Lake Orange watershed. For the purpose of road drainage analysis of this watershed, a 400-cell (14,865 m^2) stream threshold is selected by multiple trials.
8. Stream Segmentation. This function uniquely numbers stream segments (links) between the confluences. Make sure that the “Sink Link Grid” and “Sink Watershed Grid” entries in the form are set to “Null” to ensure that the whole DEM is processed.
9. Catchment Grid Delineation. This step identifies drainage areas that drain to each stream link.
10. Catchment Polygon Processing. The catchment polygon processing step defines catchments in vector format.
11. Drainage Line Processing. The drainage line processing step defines stream segments in vector format.
12. Adjoint Catchment Processing. The adjoint catchment processing step determines the cumulative area upstream from a catchment (in vector format).

6.3.2 Measurement of diffuse flow pathways

In the PVbtWQM model, lengths of diffuse flow pathways are one of the most important parameters. There are two ways to get these values: a) surveying in the field;

and b) measuring on the map. Although field surveying is more accurate, it is time consuming and costly. Furthermore, some forest areas may be inaccessible on sometime of the year. A combination of the "Flow Path Tracing" function in the Arc Hydro tools and the "Measure" tool in ArcGIS provides an efficient alternative to field surveying to investigate the drainage patterns for a road segment, define the types of flow pathways, and measure the lengths of diffuse flow pathways, based on the derivatives from the previously-described terrain preprocessing, such as *Flow Direction, Catchment, and Drainage Line*. The investigation and measurement are conducted catchment by catchment and a road segment by a road segment as illustrated in Figure 6.9. The steps are as follows:

- After terrain preprocessing has been performed, add road centerline vector data into ArcMap, also the integrated NLCD and high resolution image for topographical and land use references. Make sure all the newly added data display on the fly in the same coordinate system as the DEM.
- Zoom in to the road segment(s) in a catchment and use the "Interactive Flow Path Tracing" function in the Arc Hydro tools to investigate the road runoff drainage pattern and define the type of flow pathways.
- Further divide the road segment into smaller segments, based on the drainage pattern.
- Define the flow pathway for each diffusely connected segment by using "Flow Path Tracing" tool, and measure their lengths. This step may need several trials and make some judgments. For the directly connected road segments, the lengths of their flow pathways are assumed to be zero.

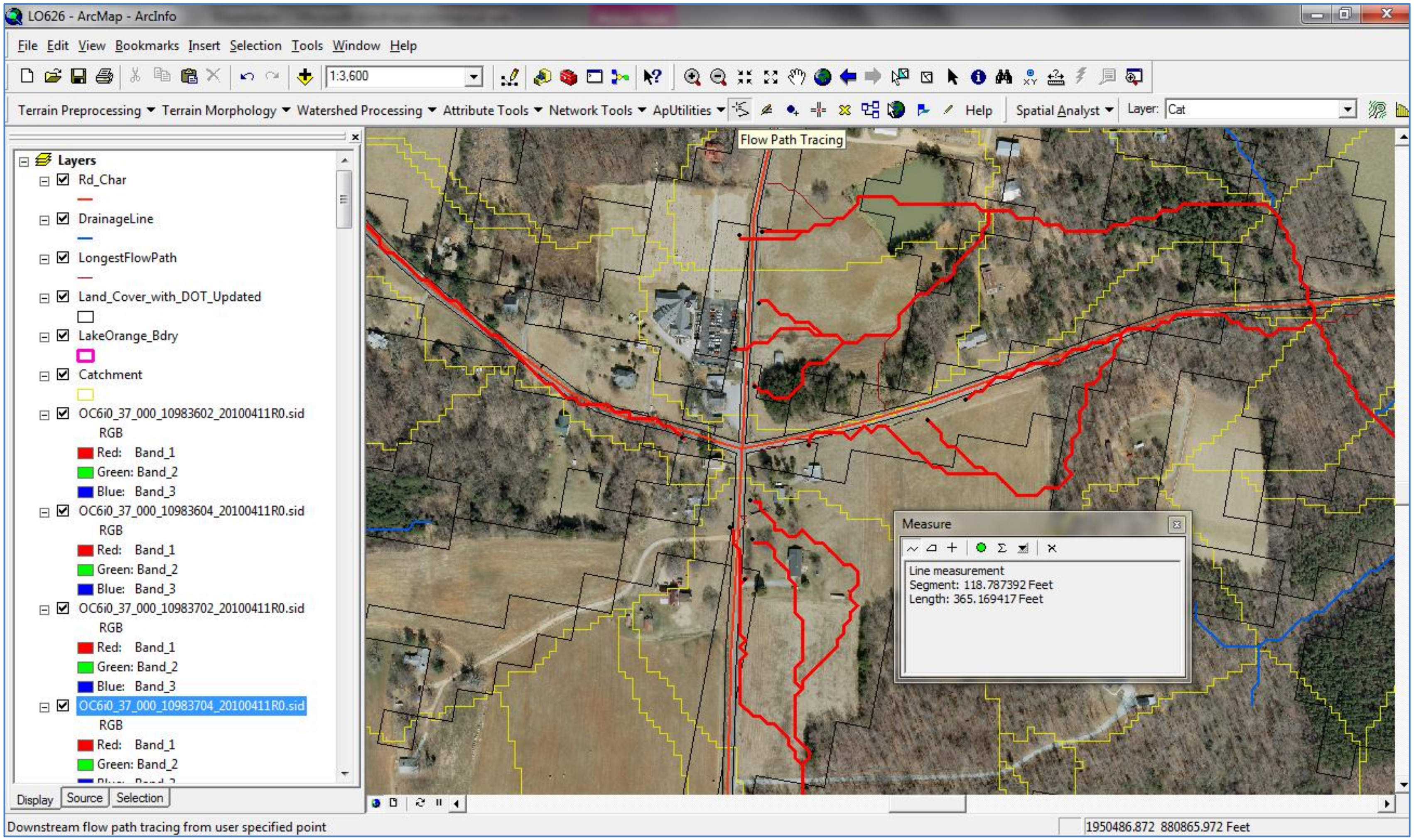


Figure 6.9: Illustration of measuring lengths of diffuse flow pathways with tools “Flow Path Tracing” and “Measure” at the intersection of SR-1004, SR-1352, and SR-1357

After the length of the flow pathway from each smaller road segment has been determined, its impervious paved area and total drainage area are also measured. All these measurements for the roads are given in Appendix F. In the Lake Orange watershed, 23.1% of the total road land use (or 23.6% of the total impervious pavement area) drains through the directly connected path, and 76.9% (or 76.4% impervious area) through the diffuse flow path. Figure 6.10 shows the relationship between the length of road runoff flow pathways and cumulative percent of drainage area in the Lake Orange watershed.

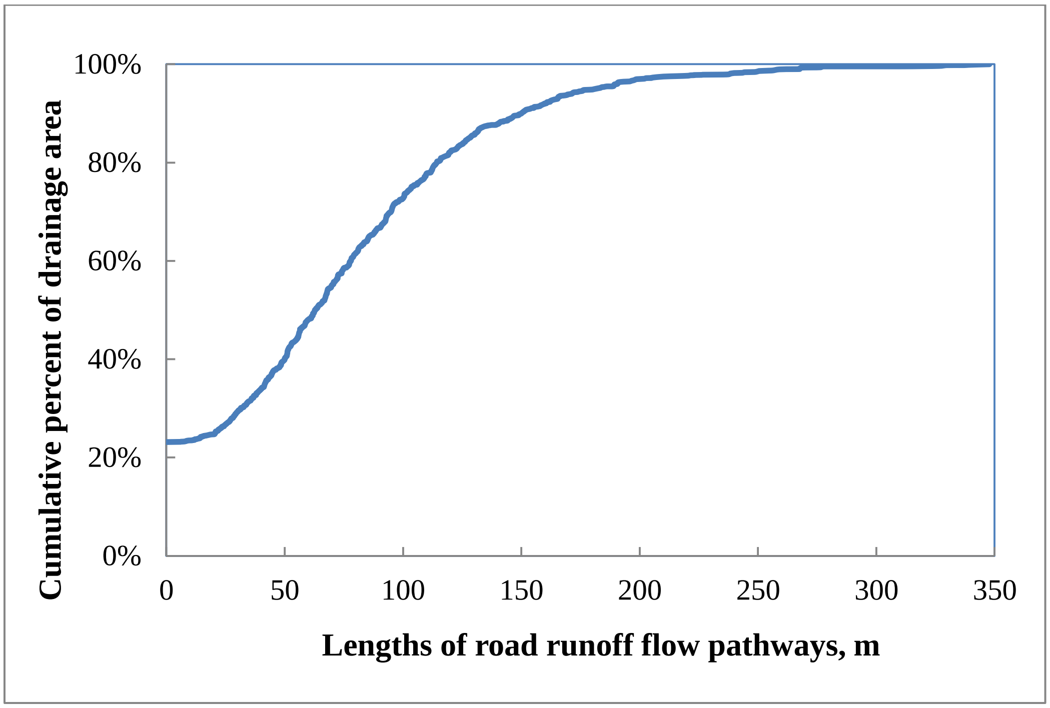


Figure 6.10: Relationship between flow-path length and cumulative drainage area in the Lake Orange watershed

6.3.3 Estimation of road-generated runoff

In general, the storm runoff derived from road land use including the paved impervious road surfaces and surrounding pervious areas can be given as,

$$V_{out} = AP_e \tag{6.1}$$

where V_{out} is the volume of road derived runoff in liters; A is the area of road land use in m^2; and P_e is the depth of excess precipitation or direct runoff in mm. Based on the availability of data, P_e can be given by one of the following three methods.

a. The SCS method:

$$P_e = \frac{(P - 0.2S)^2}{P + 0.8S} \tag{6.2}$$

where P is precipitation in inches; S is potential maximum retention or storage in inches, which is given by,

$$S = \frac{1000}{CN} - 10 \tag{6.3}$$

where CN is a runoff curve number that is a function of land use, antecedent soil moisture, and other factors affecting runoff and retention in a watershed. The curve number is a dimentionless number defined such that $0 \le CN \le 100$.

b. The conceptual- empirical infiltration-excess runoff method:

$$P_e = (R - I)t \tag{6.4}$$

where R is rainfall intensity in mm/hr; I is the average infiltration rate on road land use in mm/hr; and t is a period of raining time in hours.

c. The simple method:

According to Schueler (1987),

$$P_e = PR_v \tag{6.5}$$

where P is precipitation in mm and R_v is runoff coefficient.

In the simple method, the runoff coefficient is calculated based on impervious cover in a catchment, which can be given by:

$$R_v = 0.05 + 0.9I_a \tag{6.6}$$

where I_a = Impervious fraction.

In the PVbtWQM model, the simple method is adopted to estimate the amount of storm runoff generated from individual road segments in the Lake Orange watershed. But, the R_v equation (Eq. 6.6) is adapted as shown in Figure 6.11, based on several NCDOT highway stormwater research projects (Wu and Allan, 1998, 2001, and 2010; also referring to Table 6.4 for the data). That is, the runoff coefficient in the Piedmont Region road environment of North Carolina is given as:

$$R_v = 0.0621 + 0.0062 I_a \tag{6.7}$$

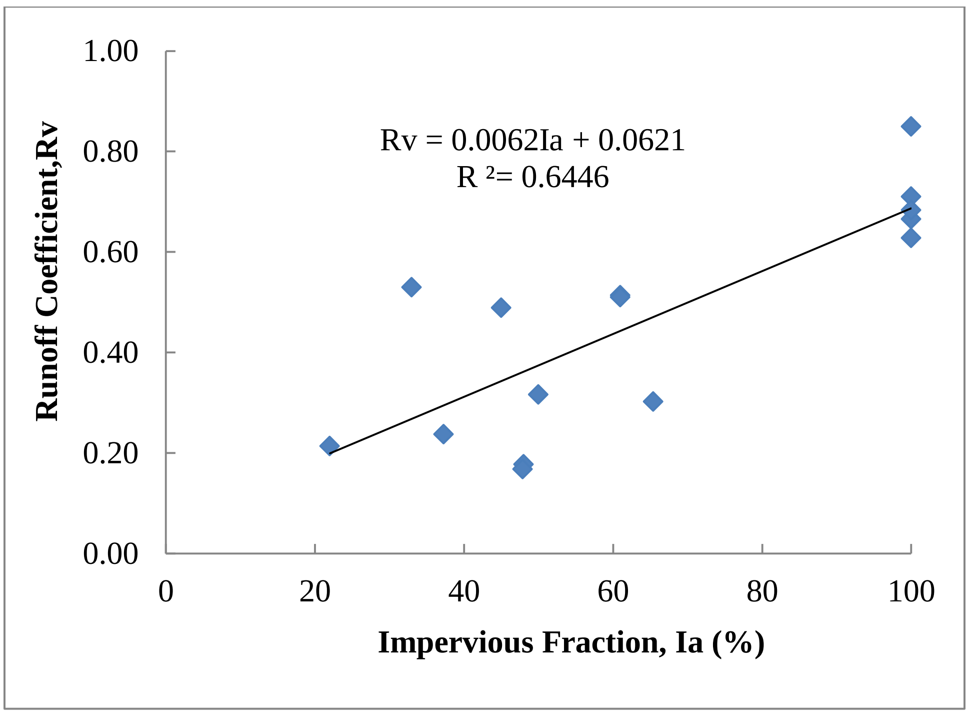


Figure 6.11: Illustration of relationship between runoff coefficient and road ROW impervious fraction in the Piedmont Region of North Carolina

Combining Eq. 6-1, 6-5, and 6-7, the road-generated runoff can be given as:

$$V_{out} = AP(0.0621 + 0.0062 I_a) \tag{6.8}$$

where, V_{out} is given in liters; A in m^2; P in mm; and I_a is here given in percentage (%).

6.3.4 Vbt5 determination

Currently there are no typical values of the Vbt5 parameter available in the United States. According to two existing field studies in Australia on the "volume-to-breakthrough" concept described in Section 5.3 of Chapter 5, Croke *et al*.'s experiment yielded a result of $V_{bt5} = 336 \pm 189\,\text{liters}$; and Lane *et al*.'s experiment yielded a result of $V_{bt5} = 364 \pm 288\,\text{liters}$. Both experiments were performed in the forest environment but at different regions. Their mean values have no significant difference statistically, but the variances have. Moreover, both mean values have a large uncertainty, that is, $336 \pm 56\%$ and $364 \pm 79\%$, respectively. The experiment data in the existing studies are limited and does not show that the Vbt5 parameter has a strong relationship with the surface slope. There is no any established statistical relationship between the Vbt5 and other relevant explanatory variables, either.

In the hydrologic point of view, however, the volume to break through can be considered equivalent to the initial abstraction (Ia) given in the SCS method as:

$$I_a = 0.2S \tag{6.8}$$

where the potential maximum retention or storage, S is given by Eq. 6.3. Considering that the Lake Orange watershed is a lower developed area and has well-drained top soils with a mild mean slope of 0.052 ± 0.038 (or 3.0 ± 2.2 degrees), and that the land uses of diffuse flow pathways are primarily located in the forested area and grassland, the averaged Ia can be estimated as 278 liters in an area of 5-m^2 which is the averaged area of the overland flow plumes obtained from Croke et al's experiement (Hairsine et al., 2002) (Table 6.4). According to this, the value of V_{bt5}, 252 liters with 142 liters of uncertainty, is used in the model.

Table 6.4: Vbt adjustment by initial abstraction in SCS method

Woods (Forest)			Pasture (Grassland)		
Hydrologic Condition	Soil Group		Hydrologic Condition	Soil Group	
	A	B		A	B
Fair	25	55	Fair	39	61
Good	36	60	Good	44	65
Interpolated CN		44	Interpolated CN		52
Storage (in.), S = 1000/CN-10		12.7	Storage (in.), S = 1000/CN-10		9.1
Initial abstraction (in.), Ia = 0.2S		2.5	Initial abstraction (in.), Ia = 0.2S		1.8
Ia by volume (L) in 5 m^2		323	Ia by volume (L) in 5 m^2		232
Average or median Ia of the both (L)					278
75% of Vbt5 (336 L) used					252

* Masch, F. D. (1984). "Hydrology - HEC19". FHWA-1P-84-15. Federal Highway Administration, Office of Implementation, HRT-10, McLean, VA

6.3.5 Estimation of nutrient EMCs

There are two types of nutrient event mean concentrations (EMCs) required by the PVbtWQM model theoretically: a) nutrient EMCs of the runoff that leaves off the road edge or drainage outlet for directly connected road segments; and b) nutrient EMCs of the runoff that reaches streams for the road segments with the diffuse flow pathway. Because most highway stormwater runoff samples are now collected at the edges of roads or at the drainage outlets of road right-of-ways, and there are few samples that have been collected from the end of a diffuse flow pathway, the second type of nutrient EMCs is not available currently. In this case, the first type of nutrient EMCs is used instead, with a very conservative assumption that runoff pollutant concentrations do not change along the diffuse flow pathway.

A summary is provided in Table 6.5 of the site-averaged nutrient EMCs at NC highway stormwater monitoring sites in the Piedmont Region. These data show us that the road stormwater runoff nutrient EMCs varies greatly over the time from location to location. The underlied causes of these changes, however, are not clear. Furthermore, these data were collected in three projects with different research objectives in a long span of time (over 10 years!) and have some inevitable inconsistence or gaps in data collection of explanatory variables. As a result, it is difficult for them to be regressed out some prediction functions for general use in the region of data collection.

In the PVbtWQM model, nutrient EMCs are estimated by adopting the MLR model proposed by Kayhanian et al. (2007). The EMCs of NO_3-N, TKN, and TP in road runoff are respectively given as:

$$C_{NO_3-N} = e^{[1.3-0.417\,ln(TER)+0.092\,ln(ADP)-0.09(SCR)^{\frac{1}{3}}+\frac{2.87(AADT)}{1000000}]} \tag{6.9}$$

$$C_{TKN} = e^{[1.7-0.343\,ln(TER)+0.102\,ln(ADP)-0.128(SCR)^{\frac{1}{3}}+\frac{1.535(AADT)}{1000000}]} \tag{6.10}$$

$$C_{TP} = e^{[-1.2-0.143\,ln(TER)+0.128\,ln(ADP)-0.051(SCR)^{\frac{1}{3}}+\frac{0.9(AADT)}{1000000}]} \tag{6.11}$$

where, EMCs are given in mg/L; TER = total event rainfall in mm; ADP = antecedent dry period in days; SCR = seasonal cumulative rainfall in mm; and AADT = average annual daily traffic in vehicles/day.

The EMC of TN (in mg/L) is estimated by summing up the EMCs of both NO3-N and TKN as:

$$C_{TN} = C_{NO_3-N} + C_{TKN} \tag{6.12}$$

In Kayhanian et al.'s MLR model, how to quantify the uncertainties associated with these estimated EMCs has not been discussed in depth. To solve this issue, a simple method can be proposed by looking into the NCDOT highway stormwater dataset in Table 6.4. As the plots show in Figure 6.12, a strong relationship exists between the site-averaged EMC and its standard deviation for each of these four species. Assuming that there is a linear relationship between the both, their uncertainty (i.e., standard deviation) can be approximately given as:

$$E_{NO_3-N} = \sigma_{NO_3-N} = \pm\left|0.8701C_{NO_3-N} - 0.0252\right| \quad (6.13)$$

$$E_{TKN} = \sigma_{TKN} = \pm|0.5387C_{TKN} - 0.1491| \quad (6.14)$$

$$E_{TN} = \sigma_{TN} = \pm\sqrt{\sigma^2_{NO_3-N} + \sigma^2_{TKN}} \quad (6.15)$$

$$E_{TP} = \sigma_{TP} = \pm|0.9478C_{TP} - 0.0549| \quad (6.16)$$

It is worth pointing out that using Eq. 6.9 – 6.11 to estimate the EMCs of NO3-N, TKN, and TP for individual road segments, their explanatory variable values are supposed to be prepared ahead as follows:

- TER: Considering model comparison, use the same daily rainfall data as those in *Falls Lake WARMF Development*, which is given in Appendix B.
- ADP: Take the average ADP (i.e., 9 days) for the first event in January 2004.
- SCR: Take the average rainfall of 86.4 mm (3.4 inches) in December as an initial value to calculate the SCR for the first season.
- AADT: Retrieve the known values in the NCDOT Road Characteristics Arcs, and estimate this value for the road segments without it according to the known AADT of adjacent road segments. The AADTs for all the road segments in the Lake Orange watershed are given in Appendix F.

All the algorithms of the PVbtWQM model, in combination with various input data preparations described above, have been populated and programmed into the following three sets of spreadsheets:

- HC evaluation Spreadsheets (HC Component). Designed for: (1) estimating the

Table 6.5: Summary of Site-averaged EMCs at North Carolina Roadway Stormwater Monitoring Sites

Site Name	Site Location	DA	Imp.	P (in)		Rv		ADT ($x10^3$)	N	NO_3-N		TKN		TN		TP		Source
		acres	%	Mean	Stdev	Mean	Stdev	Vehicles/day		Mean	Stdev	Mean	Stdev	Mean	Stdev	Mean	Stdev	
Site I	W.T. Harris blvd., bridge deck, Charlotte, NC	0.37	100	0.35	0.17	0.71	0.21	25.0	10	2.25	4.36	1.42	0.76	3.67	4.90	0.43	0.48	Wu & Allan 1998
Site II	N.C. 49 and W.T. Harris Blvd. Overpass Charlotte, NC	0.57	61	0.53	0.26	0.51	0.18	21.5	11	0.22	0.15	1.18	0.47	1.34	0.50	0.52	0.44	Wu & Allan 1998
Site III	I-85 and US-29 connector, Charlotte, NC	1.1	45	1.11	0.69	0.49	0.16	5.5	10	0.14	0.16	1.00	0.34	1.13	0.32	0.47	0.42	Wu & Allan 1998
CLT-1	W.T. Harris blvd., bridge deck, Charlotte, NC	0.37	100	0.67	0.66	0.85	0.07	50.2	27	0.83	0.52	2.37	1.41	3.20	1.88	0.24	0.14	Wu & Allan 2001
CLT-2	N.C. 49 and W.T. Harris Blvd. Overpass Charlotte, NC	0.57	61	0.80	0.49	0.51	0.18	33.4	23	0.56	0.30	2.17	0.70	2.73	0.93	0.34	0.18	Wu & Allan 2001
US-74	US Hwy 74, west of SR 1005 at Broad River and east to west of US 221, Rutherford county	0.86	50	1.06	0.74	0.32	0.24	9.3	26	0.31	0.36	1.32	0.52	1.63	0.65	0.31	0.27	Wu & Allan 2001
WIN	I-40 Bypass Near Winston Salem, Guilford county.	2.16	48	0.89	0.51	0.18	0.18	52.5	25	0.54	0.34	1.29	0.49	1.83	0.42	0.25	0.17	Wu & Allan 2001
GAR	I-40, north of Garner, Wake county	3.46	33	0.89	0.52	0.53	0.77	78.8	25	0.80	1.07	1.05	0.57	1.81	1.29	0.22	0.18	Wu & Allan 2001
MON	US601, near Monroe, Union County	13.46	22	0.66	0.52	0.21	0.12	9.4	24	0.50	0.31	1.55	0.57	2.05	0.71	0.26	0.13	Wu & Allan 2001
JLS-EOP	SR 1943, 3388 Hanks Chapel Rd, Pittsboro, NC	0.024	100	0.71	0.50	0.67	0.16	0.6	26	0.23	0.15	-	-	0.63	0.39	0.12	0.10	Wu & Allan 2010
JLS-Swale	Same as above	0.36	65	0.71	0.50	0.30	0.16	0.6	26	0.05	0.06	-	-	0.50	0.44	0.13	0.10	Wu & Allan 2010
JLN-EOP	SR 1717, 1416 Jack Bennett Rd, Chapel Hill, NC	0.026	100	0.71	0.33	0.68	0.13	2.6	26	0.23	0.15	-	-	0.77	0.44	0.15	0.10	Wu & Allan 2010
JLN-Swale	Same as above	1.11	37	0.71	0.33	0.24	0.12	2.6	26	0.10	0.07	-	-	0.41	0.13	0.39	0.22	Wu & Allan 2010
MIL-EOP	SR 1360, 1398 Brevard Place Rd, Ironton, NC	0.030	100	0.52	0.46	0.63	0.15	1.4	21	0.22	0.12	-	-	0.55	0.23	0.13	0.07	Wu & Allan 2010
MIL-Swale	Same as above	0.24	48	0.52	0.46	0.17	0.15	1.4	21	0.09	0.08	-	-	0.56	0.25	0.12	0.04	Wu & Allan 2010

*DA = Drainag area; Imp. = Imperviousness; P = Precipitation; Rv = Runoff coefficient; ADT = Annual daily traffic; N = the Number of events; and Stdev = Standard deviation.

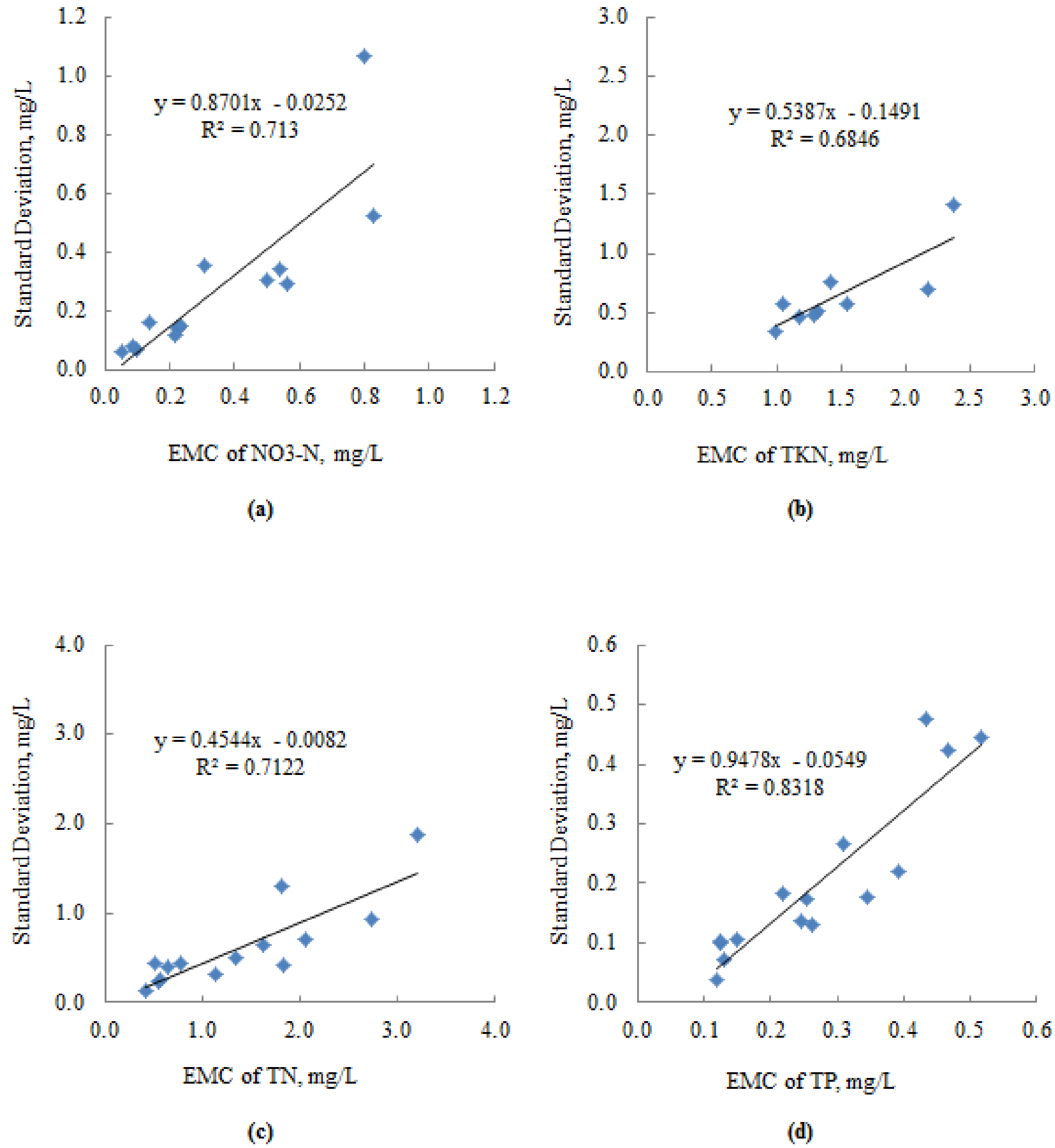


Figure 6.12: Plots of nutrient EMCs in NC highway storm runoff and their standard deviations: (a) NO_3-N; (b) TKN; (c) TN; and (d) TP

amounts of road stormwater runoff and their associated uncertainties from a single event or multiple events; and (2) evaluating the road-to-stream HC (hydrologic connectivity), for individual road segments and the entire road ROW network.

- TN Loading Estimation Spreadsheets (TN Component). Designed for: (1) calculating stormwater runoff TN Loads and their associated uncertainties from a single storm event for both individual road segments and the entire road network in a watershed; and (2) estimating the road stormwater runoff TN TMDL from the Lake Orange watershed through simulating the 4-year daily rainfalls (2004-2007) by using the What-If Analysis function in Microsoft Excel.
- TP Loading Estimation Spreadsheets (TP Component): Using the similar procedure and methods to those in TN loading estimation, (1) calculating stormwater runoff TN Loads and their associated uncertainties from a single storm event for both individual road segments and the entire road ROW network; and (2) estimating the road runoff TN TMDL for the Lake Orange watershed.

6.4 Results – hydrologic connectivity and nutrient loadings from the NCDOT road ROW network to streams in the Lake Orange watershed

TN and TP loadings from the NCDOT road ROWs in the Lake Orange watershed are 0.413 ± 0.001 kg/day (1.426 ± 0.004 lbs/acre.year) and 0.090 ± 0.001 kg/day (0.312 ± 0.002 lbs/acre.year), respectively. Figures 6.13, 6.14, 6.15, and 6.16 illustrate the changes of the overall runoff estimate, road-to-stream connectivity, nutrient concentrations, and nutrient loads over daily precipitation (i.e., on a pseudo-event base) in the watershed during 2004 to 2007. The lake Orange watershed has 233 acres of NCDOT road ROWs land use with 115 acres (49%) impervious pavement.

6.4.1 Road stormwater runoff estimates

Figure 6.13 shows that the estimates of both the overall road-generated runoff and that runoff delivered to streams change with precipitation. Based on the impervious fraction of road ROWs and the linear relation between precipitation and the road-generated runoff (referring to Eq. 6.8), a one-inch rainfall will produce 0.37 inches of road runoff totally. A portion of this runoff (0.14 inches) will be lost during delivery and only 0.23 inches of it reaches streams. The ratio of the delivered runoff to precipitation will increase as the rainfall increases, varying from 0.084 to 0.315 for the events during 2004 to 2007.

6.4.2 Road-to-stream hydrologic connectivity

Figure 6.14 shows that the road-to-stream hydrologic connectivity is dependent on rainfall. It will increase as rainfall increases. The overall hydrologic connectivity of the road network to the stream network in the Lake Orange watershed is 0.32±0.14, ranging from 0.23 to 0.86.

6.4.3 Predicted EMCs and TMDLs of nutrients

Several trials show that the initial equations for predicting EMCs for nitrogen species have to be adjusted due to their extreme over-estimates, 2.19 mg/L for NO3-N and 3.21 mg/L for TKN on the average. By referring to NCDOT highway stormwater runoff WQ data (Table 6.5), these equations have been adjusted as follows:

$$C_{NO_3-N} = e^{[0.05-0.417\,ln(TER)+0.092\,ln(ADP)-0.09(SCR)^{\frac{1}{3}}+\frac{2.87(AADT)}{1000000}]} \qquad (6.9')$$

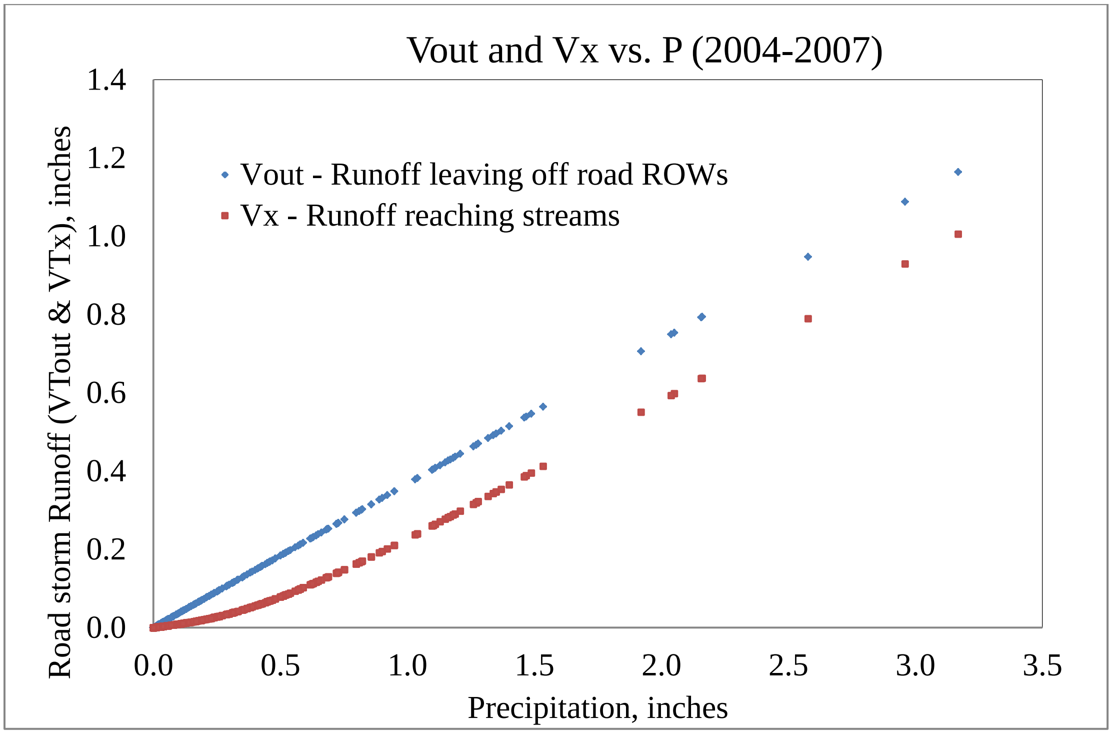


Figure 6.13: Plots of Vout and Vx versus P in the Lake Orange watershed

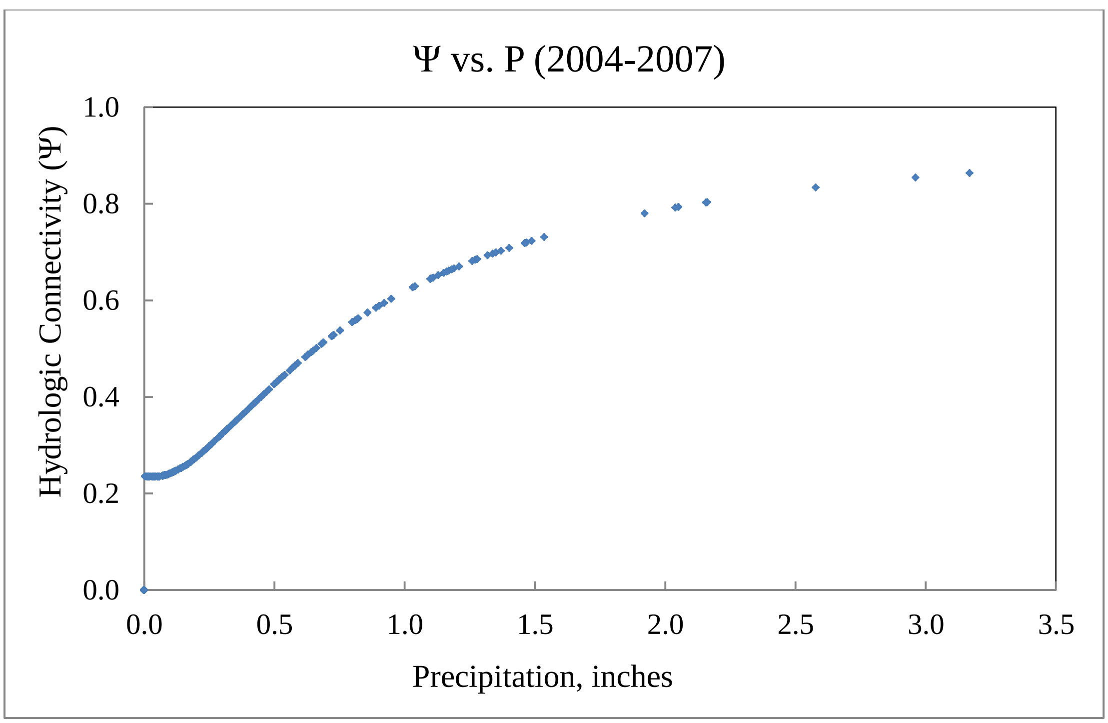


Figure 6.14: Illustration of changing of road-to-stream connectivity over precipitation in the Lake Orange watershed

$$C_{TKN} = e^{\left[0.97 - 0.343\, ln(TER) + 0.102\, ln(ADP) - 0.128 (SCR)^{\frac{1}{3}} + \frac{1.535 (AADT)}{1000000}\right]} \qquad (6.10')$$

The new trained equations yield a moment of 0.71 ± 0.45 mg/L for NO3-N; 1.55 ± 0.81 mg/L for TKN; and a combination of the both for TN as 2.26 ± 1.26 mg/L, as shown in Table 6.6. On the average, the associated propagation uncertainties are 0.97, 1.13, and 2.10 mg/L for No3-N, TKN, and TN, respectively. For phosphorus, the MLR equation is acceptable, which yields a moment of 0.29 ± 0.06 mg/L with an averaged propagation uncertainty of 0.35 mg/L for the 4-year term of simulation. The simulated EMCs of NO3-N, TKN, TP, and their changes over precipitation have been illustrated in Figures 6.15 and 6.16.

Figures 6.15 and 6.16 also illustrate the overall TN and TP loads for individual storm events from the NCDOT road ROW network in the Lake Orange watershed.

Table 6.7 summarizes the total yearly nutrient loads of stormwater runoff from NCDOT highway ROW land use during the period of 2004 and 2007.

For TN, the total source load is 335.2 ± 261.3 kilograms per year, and the total load in the runoff reaching streams is 150.7 ± 148.7 kilograms per year. Their loads from unit

Table 6.6: A summary of nutrient EMCs simulated in the PVbtWQM model

	NO_3-N EMC, mg/L					TKN EMC, mg/L				
	Mean	SD	Median	Max	Min	Mean	SD	Median	Max	Min
2004	0.67	0.40	0.53	1.43	0.14	1.47	0.74	1.25	2.84	0.43
2005	0.69	0.39	0.59	1.43	0.19	1.51	0.71	1.37	2.84	0.54
2006	0.57	0.33	0.53	1.43	0.14	1.30	0.62	1.25	2.84	0.42
2007	0.90	0.58	0.75	2.27	0.16	1.89	1.00	1.67	4.14	0.48
4-Year	0.71	0.45	0.59	2.27	0.14	1.55	0.81	1.37	4.14	0.42
	TN EMC, mg/L					TP EMC, mg/L				
	Mean	SD	Median	Max	Min	Mean	SD	Median	Max	Min
2004	2.14	1.14	1.77	4.27	0.57	0.28	0.06	0.27	0.38	0.17
2005	2.20	1.09	1.96	4.27	0.74	0.28	0.06	0.28	0.38	0.19
2006	1.87	0.94	1.77	4.27	0.56	0.27	0.05	0.27	0.38	0.17
2007	2.79	1.57	2.43	6.41	0.64	0.31	0.07	0.30	0.44	0.18
4-Year	2.26	1.26	1.96	6.41	0.56	0.29	0.06	0.28	0.44	0.17

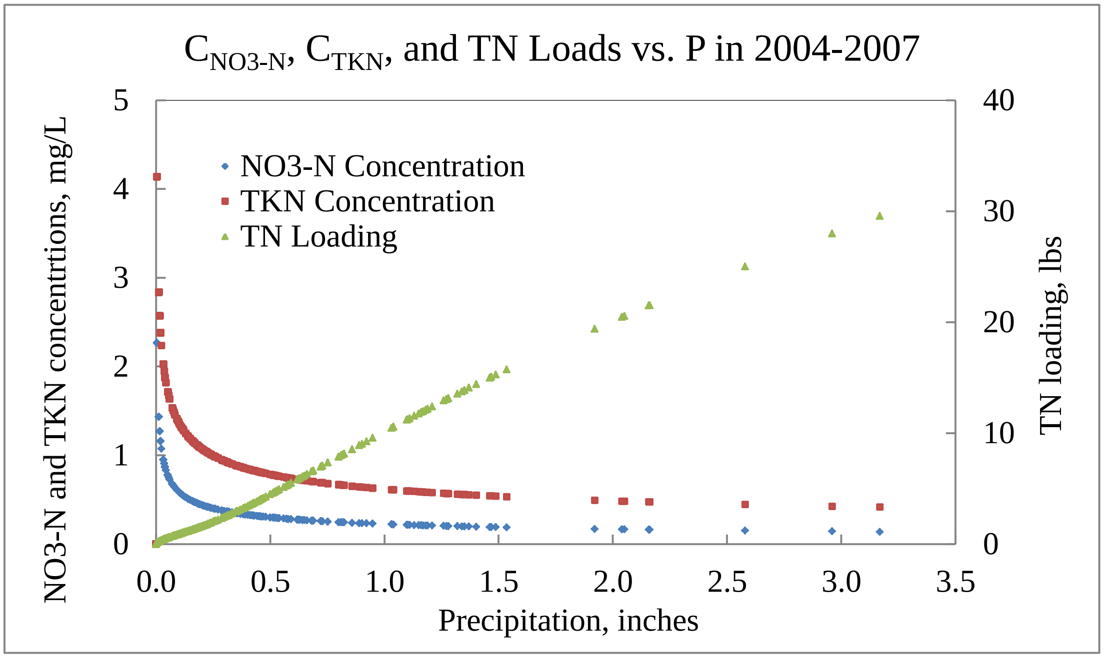


Figure 6.15: Prediction of changes of concentrations of Nitrogen species and TN loads over precipitation from the NCDOT road ROW network in the Lake Orange watershed

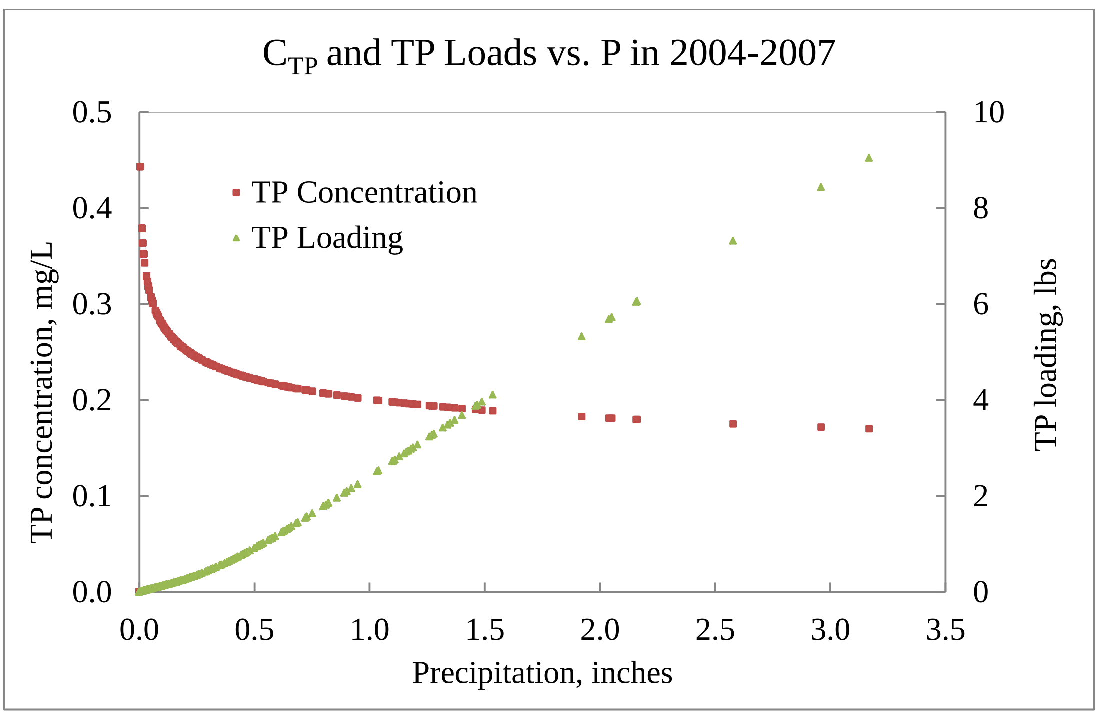


Figure 6.16: Prediction of changes of concentrations of Nitrogen species and TN loads over precipitation from the NCDOT road ROW network in the Lake Orange watershed

Table 6.7: A summary of nutrient loadings estimated by the PvbtWQM model

Nutrients		Total Nitrogen (TN)				Total Phosphorus (TP)			
Year	Unit	W_{TN_S}	Ew_{TN_S}	W_{TN_X}	Ew_{TN_X}	W_{TP_S}	Ew_{TP_S}	W_{TP_X}	Ew_{TP_X}
2004	kg/yr	371.5	290.7	163.2	167.5	73.3	84.1	35.2	48.7
	lb/ac.yr	3.516	2.751	1.544	1.585	0.693	0.796	0.333	0.461
2005	kg/yr	308.1	247.6	125.0	135.0	57.9	67.3	25.5	37.0
	lb/ac.yr	2.915	2.343	1.183	1.278	0.548	0.637	0.242	0.350
2006	kg/yr	403.1	297.8	210.4	184.8	86.8	97.5	49.7	60.8
	lb/ac.yr	3.815	2.818	1.991	1.749	0.821	0.923	0.470	0.575
2007	kg/yr	258.0	209.2	104.0	107.7	47.5	55.1	21.3	29.7
	lb/ac.yr	2.442	1.980	0.984	1.019	0.449	0.522	0.202	0.281
Average	kg/yr	335.2	261.3	150.7	148.7	66.4	76.0	32.9	44.1
	lb/ac.yr	3.172	2.473	1.426	1.408	0.628	0.719	0.312	0.417

area of highway ROW land use are 3.172 $\pm$2.473 and 1.426 $\pm$1.408 pounds per acre per year, respectively. For TP, the total source load is 66.4 $\pm$76.0 kilograms per year, and the total load in the runoff reaching streams is 32.9 $\pm$44.4 kilograms per year. Their loads from unit area of highway ROW land use are 0.628 $\pm$0.719 and 0.312 $\pm$0.417 pounds per acre per year, respectively. The second terms given in the yearly loadings above are propagation uncertainties with 90% confidence.

Table 6.8 summarizes the estimated stormwater runoff TN and TP TMDLs from NCDOT highway ROW land use at the Lake Orange watershed during the period of 2004 and 2007. The 4-year averaged total daily TN source loading is 0.918 $\pm$1.978 $\pm$0.715 kilograms, and the total daily TN loading in the runoff reaching streams is 0.412 $\pm$1.250 $\pm$0.407 kilograms, in which the second term is the standard deviation associated with the mean value and the third term is the propagated uncertainty with 90% confidence from the calculations of modeling. These propagation uncertainties are 78% and 99% of TN source loading and the loading reaching streams, respectively. For TP, its averaged total daily source loading and the total daily loading in the runoff reaching streams are 0.182 ± 0.478 ± 0.208 (115%) and 0.090 ± 0.326 ± 0.121 (134%) kilograms, respectively.

The afore-described has shown that propagation uncertainties in the final results for both TN and TP are quite large, ranging 78% to 134%, and would be a big concern in highway stormwater TMDL modeling.

Table 6.8: Nutrient TMDLs estimated by the PVbtWQM model

Nutrients	TN TMDL (kg/d)						TP TMDL (kg/d)					
	W_{TN_S}			W_{TN_X}			W_{TP_S}			W_{TP_X}		
Year	mean	SD	Ew_{TN_S}	mean	SD	Ew_{TN_X}	mean	SD	Ew_{TP_S}	mean	SD	Ew_{TP_X}
2004	1.015	2.024	0.794	0.446	1.248	0.458	0.200	0.484	0.230	0.096	0.325	0.133
2005	0.844	1.720	0.678	0.343	0.939	0.370	0.159	0.382	0.184	0.070	0.223	0.101
2006	1.104	2.445	0.816	0.576	1.703	0.506	0.238	0.627	0.267	0.136	0.459	0.167
2007	0.707	1.597	0.573	0.285	0.936	0.295	0.130	0.368	0.151	0.058	0.235	0.081
4-yr	0.918	1.978	0.715	0.412	1.250	0.407	0.182	0.478	0.208	0.090	0.326	0.121

CHAPTER 7: DISCUSSION AND CONCLUION

Chapter six has presented how to make the PVbtWQM work for predicting TN and TP loadings for highway stormwater runoff and its simulation results in the Lake Orange watershed. This chapter is intended to compare PVbtWQM's results to those given in the *Falls Lake WARMF Development* for the same source area; discuss the differences and their underlied reasons; and provide a few recommendations in model improvement for both PVbtWQM and WARMF as a conclusion.

7.1 Comparison of simulation results

Figure 7.1 summarizes the nutrient loadings that are estimated by both WARMF and PVbtWQM. Although two models simulate TN and TP loadings for the same NCDOT road ROW land use by using the same daily precipitation, the results of PVbtWQM are 6.6, 3.5, 8.7, and 8.2 times higher than those given by WARMF for TN source loading, TN delivered, TP source loading, and TP delivered, respectively.

What reasons cause the difference so significantly between two models' results? Did PVbtWQM overestimate nutrient loadings for road stormwater runoff or WARMF underestimate them for it? Of these two sets of estimates, whose are more reliable and why?

Firstly, prior to in-depth discussion of these results, it should be pointed out that the shaded values in Table 7.1 are the loadings reaching the streams or established drainage lines in their source area, Lake Orange Watershed, other than actually delivered loadings

Table 7.1: A summary of nutrient loadings estimated by PVbtWQM and WARMF for the same NCDOT road ROW land use

Model			PVbtWQM		WARMF	
Nutrients			Loading	Uncertainty	Loading	Uncertainty
TN	Source	kg/d (lb/ac.yr)	0.918 (3.172)	±0.715 (±2.473)	0.139 (0.480)	NA
	Delivered	kg/d (lb/ac.yr)	0.413 (1.426)	±0.407 (±0.1.408)	0.119 (0.411)	NA
TP	Source	kg/d (lb/ac.yr)	0.182 (0.628)	±0.208 (±0.719)	0.021 (0.072)	NA
	Delivered	kg/d (lb/ac.yr)	0.090 (0.312)	±0.121 (±0.417)	0.011 (0.039)	NA

Note: The values in shade are the loadings reaching streams, not ones delivered to Falls Lake.

to the downstream terminal Falls Lake. Therefore, these values can be considered as source loadings of kind, which will be reduced during their long journey of delivery in the waterways from the Lake Orange watershed to Falls Lake as those do in WARMF. Considering this, the shaded values may not be comparable to the delivered loadings. But, the estimates delivered of their initial source loading will be comparable. Assuming that these initial source loadings would experience a reduction of the same ratio as the ones of known delivered loadings did in the same delivery waterways, the delivered estimates can be given as,

$$\text{Deliverd estimate}_{\text{TN}} = \left(\frac{0.119}{0.139}\right)(0.918) = 0.786 \text{ (kg/d) (or 2.715 lb/ac.yr)}$$

$$\text{Deliverd estimate}_{\text{TP}} = \left(\frac{0.011}{0.021}\right)(0.182) = 0.095 \text{ (kg/d) (or 0.329 lb/ac.yr)}$$

Without considering the nutrient reduction caused by runoff lost over the diffuse flow pathway, it is found that the results of PVbtWQM are 6.6 higher than those given by WARMF for TN source and delivered loadings, and 8.6 times higher for TP source and delivered loadings. This may imply that a systematic error of prediction occur to either PVbtWQM or WARMF or the both.

Secondly, it is known by intuitive sense that the load (W) of a pollutant in the stormwater runoff generated from an area can be simply given as,

$$\mathrm{W} = \mathrm{VC} = (\mathrm{AP_e})\mathrm{C} = \mathrm{A}(\mathrm{PR_v})\mathrm{C}$$

where, V is runoff volume; C is pollutant concentration; A is drainage area; Pe is effective precipitation; P is precipitation; and Rv is runoff coefficient.

In the research area of Lake Orange Watershed, each parameter above is known as or can be estimated as,

A = 943,583 m^2 (233 acres) (NCDOT road ROW in Lake Orange Watershed)

P = 877 mm (34.5 inches) (Averaged rainfall of 4 years (2004-2007))

$R_v = 0.0621 + 0.0062\mathrm{I_a} = 0.0621 + 0.0062(49.2) = 0.367$

(See Table 6.4, Figure 6.11, and Equation 6.7)

$\mathrm{I_a} =$ 49.2 (Impervious fraction in percent of road ROW in Lake Orange Watershed)

C_{TN} = 1.52 mg/L, Mean of site-averaged EMCs with a range of 0.41 to 3.67 mg/L (See Table 6.4)

C_{TP} = 0.27 mg/L, Mean of site-averaged EMCs with a range of 0.41 to 3.67 mg/L (See Table 6.4)

Based on these known values of parameters, using the "Mean" of site-averaged EMCs of NCDOT road stormwater runoff in the Piedmont Region of NC, TN source loading of NCDOT road ROW at the Lake Orange watershed can be roughly estimated as,

$$\mathrm{W}_{TN_{Mean}} = \mathrm{APR_v}\mathrm{C}_{TN}$$

$$= (943{,}583\ \mathrm{m}^2)\left(877\,\frac{\mathrm{mm}}{\mathrm{yr}}\right)(0.367)\left(1.52\ \frac{\mathrm{mg}}{\mathrm{L}}\right)\left(10^{-6}\,\frac{\mathrm{kg}}{\mathrm{mg}}\right)\left(\frac{\mathrm{yr}}{365\ \mathrm{d}}\right) = 1.265\ (\mathrm{kg/d})$$

$$= \left(1.265\,\frac{\mathrm{kg}}{\mathrm{d}}\right)\left(2.205\,\frac{\mathrm{lb}}{\mathrm{kg}}\right)\left(365\,\frac{\mathrm{d}}{\mathrm{yr}}\right)\left(\frac{1}{233\ \mathrm{ac}}\right) = 4.369\ (\mathrm{lb/ac.yr})$$

Using the “Mean” of site-averaged EMCs, TP source loading can be roughly estimated similarly as 0.225 kg/d (0.776 lb/ac.yr).

Using the “Minimum” of site-averaged EMCs, TN and TP source loadings are given as 0.341 kg/d (1.178 lb/ac.yr) and 0.100 kg/d (0.345 lb/ac.yr).

All the estimated loading values above are summarized in Table 7.2, in combination with those predicted by PVbtWQM and WARMF.

Table 7.2: Comparison of nutrient loadings of NCDOT road stormwater runoff at Lake Orange watershed among PVbtWQM, WARMF, and Simple Method

Nutrients		TN		TP		Source
Methods	Unit	Kg/d	lb/ac.yr	Kg/d	lb/ac.yr	
PVbtWQM		0.92	3.17	0.18	0.63	
WARMF		0.14	0.48	0.02	0.07	NC DENR 2009
Simple Method	Mean*	1.27	4.37	0.23	0.78	
	Minimum*	0.34	1.18	0.10	0.35	
Piedmont region of NC	Primary roads	-	4.2	-	2.19	Wu & Allan 2001
	Secondary roads (Paved Edge)	-	1.06	-	0.22	Wu & Allan 2010
	Secondary roads (Grass swale)	-	0.35	-	0.09	Wu & Allan 2011
National	Low	-	2.19	-	0.54	Discoll et al. 1999
	High	-	35.64	-	7.33	

* Simply estimated based on the mean and minimal value of site-averaged EMCs in NC DOT highway stormwater monitoring data (Wu and Allan 1998, 2001, and 2010)

Finally, comparing source loadings of TN and TP of NCDOT road stormwater runoff at the Lake Orange watershed among three methodologies of PVbtWQM, WARMF, and the simple method, it is found that PVbtWQM’s simulation results fall in the range between the minimal EMCs based and mean EMCs based estimates of the simple method, lower than and approaching the upper quartile of that range for both TN and TP loadings; and that WARMF's simulation results are significantly lower than the minimal EMCs based estimates of the simple method by 59% and 79% for TN and TP source loadings, respectively. It has been also known in Chapter 4 that the average loadings of NCDOT land use in Falls Lake Watershed are 1.166 lb/ac.yr for TN and 0.147 lb/ac.yr for TP, respectively (see Table 4.8). The average Falls Lake-wide TN loading is approximately equal to the minimal TN EMCs-based estimate of the simple method, but the average TP loading is still 57% lower than the minimal TP EMCs-based estimate. For both TN and TP loads, the estimates from road land uses in the Lake Orange watershed are lower than the national low values and NC secondary road runoff nutrient loads.

Apparently, PVbtWQM's simulation results are acceptable for both TN and TP source loadings from NCDOT road ROW land use at the Lake Orange watershed. In contrast, WARMF's results are less reliable at the aspect of simulating nutrient loadings from NCDOT road ROWs because it extremely underestimated source loadings for both TN and TP, and so did TN and TP delivered loadings in the Lake Orange watershed.

The major reasons that lead to the prediction errors and lower reliability of the simulation results for NCDOT highways in WARMF include:

- Low or incorrect values assigned for some system coefficients. Basically, highways are not a primary pollution source of nutrients. But, if the entire highway ROW land use is evaluated separately, almost a half vegetated area of it (forest and grassland) should be fully taken into consideration.
- Lack of calibration of pollutant loadings for individual types of land use. WARMF is calibrated by the outlet control from downstream to upstream. This

measure is suitable to calibrate the model catchment by catchment from bottom to up according to field water quality monitoring data, but for each type of land use, each catchment has to be looked into and calibrated individually. However, there are usually no existing qualified field monitoring data for each catchment to do it.

7.2 Contributions and limitations

Development of PVbtWQM is intended to exclusively focus highway stormwater runoff quantification and qualification by using the watershed approach to support TMDL development and implementation. Comparing with WARMF and other highway stormwater simulation models, the major contributions of PVbtWQM include:

- Further introducing the concepts of “volume-to-breakthrough” and road-to-stream hydrologic connectivity into the watershed-scaled road stormwater runoff simulation process.
- Fully integrating the existing road stormwater field monitoring data into the processes of model development, model calibration and model simulation to assure and increase the reliability of modeling results.
- Creatively providing a three-component integrated modeling methodology to support the watershed approach for highway stormwater runoff quantification and qualification.

  (1) HC component – for estimating the amounts of road stormwater runoff and evaluating road-to-stream Hydrologic Connectivity (HC) for individual road segments and the entire road network in a watershed.

(2) TN component – for estimating stormwater runoff Total Nitrogen (TN) loads or loading rates for both individual road segments and the entire road network and calculating TN TMDL for the road network in a watershed.

(3) TP component – for estimating stormwater runoff Total Phosphorus (TP) loads or loading rates for both individual road segments and the entire road network and calculating TP TMDL for the road network in a watershed.

- Successfully integrating uncertainty propagation and error analysis theories into the model development process and providing an opportunity to evaluate the uncertainty associated with the predicted result.

PVbtWQM has shown its reliability with its satisfied simulation results in the debut at the Lake Orange watershed. However, it also has the following limitations:

- No data about road runoff drainage patterns and lengths of the diffuse overland flow pathway are available in the current road system geo-database. These data were prepared by author using ArcGIS and Arc Hydro tools, based on the high resolution LiDAR DEM and satellite image. The error in them needs to be further investigated.
- A global value of Vbt5 is used in the model for all the diffuse flow pathways due to lack of Vbt5 data and limited knowledge on the concept of "volume-to-breakthrough". This may not be true. A site-based Vbt5 value should be used for each diffuse flow pathway in the future simulation.
- The nutrient EMCs at each road segments are currently estimated by adapting the MLR equations (Kayhanian et al., 2007) through adjusting the constant. These estimated EMCs are also used for calculating nutrient loading in the runoff

reaching streams via diffuse overland pathways. Both may cause some extra error and should be improved.

- The accounting of uncertainty is incomplete. For instance, the error in the original estimates of runoff has not been taken into account.

Therefore, cracking these limitations will be in the top priority of future research. Besides these, the following tasks will be also added.

- Standardizing the modeling process to provide a user-friendly spreadsheet-format PVbtWQM template for universal use.
- Developing a GIS-based PVbtWQM template to visualize its modeling process and support highway stormwater geo-spatial analysis as well as highway stormwater management decision-making.
- Improving WARMF in nutrient loading simulation for highway land use by performing the parameter sensitive analysis and system coefficients adjustment, based on the observed highway stormwater data.

REFERENCES

Ambrose, R. B., Wool, T.A, Martin, J. L., Connolly, J. P., and Schanz, R. W. (1991). "WASP5x, a hydrodyanmic and water quality model – model theory, user's manual, and programer's guide." Environmental Research Laboratory, Environmental Protection Agency, Athens, GA.

Barrett, M. E., Irish, L. B., Malina, J. F., and Charbeneau, R. J. (1998). "Characterization of highway runoff in Austin, Texas, area." *Journal of Environmental Engineering* 124 (2), 131–137.

Barrett, M. E., Malina, J. F., Charbeneau, R.J., and Ward, G. H. (1995). "Water quality and quantity impacts of highway construction and operation: summary and conclusions." Technical Report CRWR 266. Center for Research in Water Resources, Bureau of Engineering Research, University of Texas at Austin, Austin, TX. 35 p.

Beasley, D. B. and Huggins, L. F. (1991). "ANSWERS user's manual." Publication No. 5. Agricultural Engineering Department, University of Georgia, Coastal Plain Experiment Station, Tifton, GA.

Beasley, D.B., Huggins, L. F., and Monke, E. J. (1980). "ANSWERS – a model for watershed planning." *Transaction of ASAE*, 23(4), 938–944.

Bracken, L. J., Croke, J., and Kirkby, M. (2004). "Connectivity in geomorphology: definition and evaluation." *Geophysical Research Abstracts*, 6, 04039.

Characklis, G.W. and Wiesner, M.R. (1997). "Particles, metals, and water quality in runoff from large urban watershed." *Journal of Environmental Engineering*, 123 (8), 753–759.

Chen, C.W., Herr, J., and Weintraub, L. (2001). "Watershed analysis risk management framework (WARMF): update one – a decision support system for watershed analysis and total maximum daily load calculation, allocation and implementation." Publication No. 1005181. Electric Power Research Institute, Palo Alto, CA.

Chen, C.W., Gherini, S. A., Judson, R. J. M., and Dean, J. D. (1983). "Integrated lake-watershed acidification study, volume 1: model principles and application procedures, final report." Electric Power Research Institute, Palo Alto, CA.

Chui, T. W., Mar, B. W., and Horner, R. R. (1982). "Pollutant loading model for highway runoff." *Journal of Environmental Engineering*, 108 (6), 1193–1210.

Croke, J. C., Hairsine, P. B., and Fogarty, P. (1999). "Runoff generation and redistribution in logged eucalyptus forests, Southeastern Australia." *Journal of Hydrology*, 101, 55–77.

Cunningham, P. A. (1988). "Nonpoint source impacts on aquatic life – literature review." Prepared for Monitoring and Data Support Division, Office of Water Regulations and

Standards, U.S. Environmental Protection Agency, Research Triangle Institute, Research Triangle Park, NC.

Davis, A.P., Shokouhian, M., and Ni, S.B. (2001). “Loading estimates of lead, copper, cadmium, and zinc in urban runoff from specific sources.” *Chemosphere*, 44 (5), 997–1009.

Djokic, D. (2008). “Comprehensive terrain preprocessing using Arc Hydro Tools.” Electric Power Research Institute, Palo Alto, CA. <http://resources.arcgis.com/content/hydro-data-model> (January 12, 2011)

Driscoll, E. D., Shelley, P. E., and Strecker, E. W. (1990). “Pollutant loadings and impacts from highway stormwater runoff, volume III: analytical investigation and research report.” Federal Highway Administration, Publication No. FHWA-RD-88-008. 160 p.

Driver, N. E. and Tasker, G. D. (1990). “Techniques for estimation of storm-runoff loads, volumes, and selected constituent concentrations in urban watersheds in the United States.” U.S. Geological Survey, Washington, DC.

Dupuis, T., Kaster, J., Bertram, P., Meyer, J., Smith, M., and Kobriger, N. (1985). “Effects of highway runoff on receiving waters, volume II – research report.” Report No. FHWA/RD-84/063. Rexnord Inc., EnviroEnergy Technology Center, Milwaukee, WI. 406 p.

East-West Gateway Coordinating Council. (2000). “Highway runoff and water quality impacts.” Saint Louis, MO. <http://www.ewgateway.org/pdffiles/library/aq/wqhwywords.pdf > (October 10, 2010)

Eastaugh, C. S., Rustomji, P. K., and Hairsine, P. B. (2008). “Quantifying the altered hydrologic connectivity of forest roads resulting from decommissioning and relocation.” *Hydrological Processes*, 22,2438–2448, doi: 10.1002/hyp.6836.

Gherini, S. A., Mok, L., Hudson, R. J., Davis, G., Chen, C. W., and Goldstein, R. A. (1985). “The ILWAS model: formulation and application.” *Water, Air, and Soil Pollution*, 26, 425–459.

Gupta, M. K., Agnew, R. W., and Kobriger, N. P. (1981). “Constituents of highway runoff, Volume I, state-of-the-art report.” Report No. FHWA/RD-81/042. Envirex Inc., Environmental Sciences Division, Milwaukee, WI. 121 p.

Hairsine, P. B., Croke, J. C., Matthews, H., Fogarty, P., and Mockler, S. P. (2002). “Modelling plumes of overland flow from roads and logging tracks”. *Hydrological Processes*, 16, 2311–2327, doi: 10D1002/hyp.1002.

Hellweger, F. (1997). “AGREE - DEM Surface Reconditioning System”. <http://www.ce.utexas.edu/prof/maidment/GISHYDRO/ferdi/research/agree/agree.html> (December 20, 2010).

Irish, L.B., Barrett, M. E., Malina, J. F., and Charbeneau, R. J. (1998). "Use of regression models for analyzing highway stormwater loads." *Journal of Environmental Engineering*, 124 (10), 987–993.

Kayhanian, M., Hollingsworth, L., Regenmorter, L., Spongberg, M., and Tsay, K. (2002). "Characteristics of stormwater runoff from Caltrans facilities." Transportation Research Board, 81th Annual Conference, January 9-13, Washington, DC.

Kayhanian, M., Suverkropp, C., Ruby, A., and Tsay, K. (2007). "Characterization and prediction of highway runoff constituent event mean concentration." *Journal of Environmental Management*, 85, 279–295.

Kerri, K. D., Racin, J. A., and Howell, R. B. (1985). "Forecasting pollutant loads from highway runoff." *Transportation Research Record*, 1017, 39–46.

Kreyszig, E. (2006). "Advanced engineering mathematics (9th Edition)". John Wiley & Sons, Inc., New York, NY, 995-996.

Kobriger, N. P., Meinholz, T. L., Gupta, M. K., and Agnew, R. W. (1981). "Constituents of highway runoff, Volume III, predictive procedure for determining pollution characteristics in highway runoff." Report No. FHWA/RD-81/044. Envirex Inc., Environmental Sciences Division, Milwaukee, WI. 205 p.

Konrad, J. (1985). "The Wisconsin nonpoint source program." National Conference on Perspectives on Nonpoint Pollution, EPA 440/5-85-001, U.S. Environmental Protection Agency, Washington, DC.

Lane, P. N.J., Hairsine, P. B., Croke, J. C., and Takken, I. (2006). "Quantifying diffuse pathways for overland flow between the roads and streams of the Mountain Ash Forests of Central Victoria Australia." *Hydrological Process*, 20, 1875–1884.

Papedes, D.N. (1978). "McGraw-Hill dictionary of scientific and technical terms." 2nd Ed. New York, N.Y.: McGraw-Hill.

Mar, B. W., Horner, R. R., Ferguson, J. F., Spyridakis, D. E., and Welch, E. B. (1982). "Summary – Washington State highway runoff water quality study, 1977 – 1982." Report No. WA-RD-39.17. University of Washington, Department of Civil Engineering, Seattle, WA. 131 p.

McGowen, S., Smith, B., Taylor, S., Brindle, F., Cazenas, P. A., Davis, V. W., Hemmerlein, M., Herbert, R., Lauffer, M. S., Lewis, J., and Ripka, T. (2009). "Scan 08-03: Best practices in addressing NPDES and other water quality issues in highway system management." Scan Management, Arora and Associates, P.C., Lawrenceville, NJ.

Meyer, L. D. and Wischmeier, W. H. (1969). "Mathematical simulation of the processes of soil erosion by water." *Transaction of ASAE*, 12(6), 754–758.

National Research Council (NRC). (2001). “Assessing the TMDL approach to water quality management.” National Academy Press, Washington, D.C.

NC DENR. (1998). “Neuse River basinwide water quality plan.” N.C. Department of Environment and Natural Resources, Division of Water Quality, Planning Section. <http://h2o.enr.state.nc.us/basinwide/Neuse/neuse_wq_management_plan.htm> (June 20, 2010).

NC DENR. (2009). “Falls Lake watershed analysis risk management framework (WARMF) development – final report.” N.C. Department of Environment and Natural Resources, Division of Water Quality, Planning Section, Modeling/TMDL Unit. October, 2009.

Novotny, V. and Chesters, G. (1981). “Handbook of nonpoint pollution: sources and management.” Van Nostrand Reinhold, New York.

Novotny, V. and Olem, H. (1994). “Water quality: prevention, identification, and management of diffuse pollution.” Van Nostrand Reinhold, New York.

Novotny, V. (2003). “Water quality: diffuse pollution and watershed management (2^{nd} ed.).” John Wiley & Sons, Inc., New York.

NRC. (2001). “Assessing the TMDL approach to water quality management.” National Research Council of the National Academy of Science. Washington DC.

NRCS. (1977). “Soil survey of Orange County, North Carolin.” U.S. Department of Agriculture, Natural Resources Conservation Service (former Soil Conservation Service). <http://soils.usda.gov/survey/online_surveys/north_carolina/NC135/text.pdf> (July 20, 2010).

NRCS. (2010). “Soil Survey Geographic (SSURGO) database for Orange County, North Carolina.” U.S. Department of Agriculture, Natural Resources Conservation Service. < http://SoilDataMart.nrcs.usda.gov/ > (February 19, 2010).

Reckhow, K. H. (2003). “On the need for uncertainty assessment in TMDL modeling and implementation.” *Journal of Water Resources Planning and Management. (ASCE)* 129(4), 245-246.

Rossman, L.A. (2009). “Storm Water Management Model User’s Manual, Version 5.0.” EPA/600/R-05/040, U.S. Environmental Protection Agency, Water Supply and Water Resources Division, National Risk Management Research Laboratory, Cincinnati, OH.

Schueler, T. (1987). “Controlling urban runoff: a practical manual for planning and designing urban BMPs.” Metropolitan Washington Council of Governments. Washington, DC

Serway, R.A. and Jewett, J.W. (2004). “Physics for scientists and engineers.” Thomson, 6^{th} edition, A.28–29.

Shirmohammadi, A., Chaubey, I., Harmel, R.D., Bosch, D.D., Munoz-Carpena, R., Dharmasri, C., Sexton, A., Arabi, M., Wolfe, M.L., Frankenberger, J., Graff, C., and Sohrabi, T.M. (2006). "Uncertainty in TMDL models." *American Society of Agricultural and Biological Engineers*, 49(4), 1033-1049.

Takken, I., Croke, J. C., and Lane, P. (2008). "A methodology to assess the delivery of road runoff in forestry environments." *Hydrological Processes*, 22(2), 254–264.

Taylor, S. (2009). "Source control as the compliance end game." *Proceedings from 2009 StormCon*, Anaheim, CA.

Thomann, R.V. and Mueller J.A. (1987). "Principles of surface water quality modeling and control." Harper Collins Publishers Inc, New York, 17–21.

Thompson, C., Newham, L. T. H., Croke, B., Jakeman, A., and Takken, I. (2009). "Road runoff and sediment connectivity assessment tool: ROADCAT". < http://fennerschool-research.anu.edu.au/roads_dss/publications/pdfs/model_specifications_b5.pdf> (March 1, 2011).

USEPA. (1983). "Results of the nationwide urban runoff program, volume 1 - final report." National Technical Information Service (NTIS), Publication No. PB84-185552, Washington, DC. 200 p.

USEPA. (1992). "SWMM: storm water management model, version 4.2." Center of Exposure Assessment Modeling, U.S. Environmental Protection Agency, Athens, GA.

USEPA. (1993). "Guidance specifying management measures for sources of nonpoint pollution in coastal waters." U.S. Environmental Protection Agency, Office of Water. Washington, DC.

USEPA. (2005a). "Partition coefficients for heavy metals in surface water, soil, and waste." EPA 600-R-05-074, U.S. Environmental Protection Agency, Office of Research and Development, Washington, DC.

USEPA. (2005b). "TMDL Model Evaluation and Research Needs." EPA/600/R-05/149. U.S. Environmental Protection Agency, Office of Research and Development, National Risk Management Research Laboratory, Cincinnati, OH.

USEPA. (2008). "Handbook for developing watershed TMDLs (draft)." U.S. Environmental Protection Agency, Office of Water, Office of Wetlands, Oceans, and Watersheds, Washington, DC. December 15, 2008.

USEPA. (2009). "Guidance on the development, evaluation, and application of environmental models." EPA/100/K-09/003. U.S. Environmental Protection Agency, Office of the Science Advisor, Washington, DC. March, 2010.

USEPA. (2010). "Fact Sheet: Total Maximum Daily Loads." TMDL Program Results Analysis Fact Sheet # EPA841-F-10-001. U.S. Environmental Protection Agency, Office of Water, Washington, DC. January , 2010.

USEPA. (2011). “National summary of impaired waters and TMDL information.” U.S. Environmental Protection Agency. Washington, DC. <http://iaspub.epa.gov/waters10 /attains_nation_cy.control?p_report_type=T > (March 1, 2011).

Vaze, J. and Chiew, F. H. S. (2004). “Nutrient loads associated with different sediment sizes in urban stormwater and surface pollutants.” *Journal of Environmental Engineering*, 130 (4), 391–396.

Wemple, B. C., Jones, J. A., and Grant, G. E. (1996). “Channel network extension by logging roads in two basins, western cascades, Oregon.” *Water Resources Bulletin*, 23 (6), 1195–1207.

Wu, J. S. and Allan, C. J. (2001). “Sampling and testing of stormwater runoff from North Carolina highways (final report).” CTE/NCDOT Joint Environmental Research Program. University of North Carolina at Charlotte, Charlotte, NC. 101 p.

Wu, J. S. and Allan, C. J. (2004). “Development of a GIS-based methodology to estimate stormwater runoff pollutant loadings from North Carolina highways (final report).” CTE/NCDOT Joint Environmental Research Program. University of North Carolina at Charlotte, Charlotte, NC. 71 p.

Wu, J. S. and Allan, C. J. (2010a). “Final report: evaluation of nutrient loading rates and effectiveness of roadside vegetative connectivity for managing runoff from secondary roadways (in review).” DCNOT Stormwater Research Project 2007-04. University of North Carolina at Charlotte, Charlotte, NC. 96 p.

Wu, J. S. and Allan, C. J. (2010b). “Unified methodology for site-characterization and sampling of highway runoff.” Front. Environ. Sci. Engin. China, 4(1), 47-58.

Wu, J. S., Allan, C. J., Saunders, W. L., and Evett, J. B. (1998). “Characterization and pollutant loading estimation for highway runoff.” *Journal of Environmental Engineering*, 124 (7), 584–592.

Wu, J. S. and Meng, Z. (2010). “Adapting TMDL approach for sustainable watershed management.” *Proceedings of Global Chinese Scientists Environmental Protection Forum*, Shanghai, China. 94–99.

APPENDIX A: VBT5 DATA OF TWO FIELD EXPERIMENTS

Vbt5 Values from Croke et al.'s Experiment (Hairsine et al. 2006)

Site	Soil type	Mean surface gradient	Rainfall intensity	Vbt5
		%	mm/hr	L
7	Light granite	25	54	550
7	Light granite	25	68	450
7	Light granite	25	123	648
1	Light granite	25	49	234
1	Light granite	25	67	500
1	Light granite	25	113	690
2	Light granite	29	56	No connection
2	Light granite	29	69	No connection
2	Light granite	29	121	345
6	Metasediments	22	49	57
6	Metasediments	22	78	96
6	Metasediments	22	144	113
4	Metasediments	30	43	No connection
4	Metasediments	30	53	200
4	Metasediments	30	92	459
5	Metasediments	28	75	No connection
5	Metasediments	28	80	150
5	Metasediments	28	148	215
9	Red granite	30	43	No connection
9	Red granite	30	66	390
9	Red granite	30	100	513
8	Red granite	27	50	300
8	Red granite	27	64	105
8	Red granite	27	117	360
3	Red granite	29	53	No connection
3	Red granite	29	65	No connection
3	Red granite	29	124	350

Vbt5 Values from Lane et al.'s Experiment (Lane et al. 2006)

Site	Surface gradient	Discharge rate	Catchment area	Vbt5
	5m	L/min	m^2	L
1	28	7.00	175	864
2	16	0.08	232	177
3	4	Unknown	103	330
4	8	39.00	160	258
5	29	0.04	205	735
6	22	Unknown	75	3360
7	3	Unknown	200	NF
8	25	2.20	300	156
9	29	8.40	142	147
10	21	Unknown	102	156
11	30	29.50	281	123
12	28	7.20	186	240
13	17	4.40	240	1020
14	13	23.00	581	261
15	22	0.02	325	135
16	11	8.70	180	540
17	12	10.00	300	135
18	4	Unknown	264	666
19	23	1.25	405	240

APPENDIX B: PRECIPITATION DATA IN THE ENO RIVER WATERSHED

Rainfalls during January to April of 2004

(Data source: Andy McDaniel, NC DOT Estimation)

Date	P, mm	Date	P, mm	Date	P, mm	Date	P, mm
1/1/2004	0	2/1/2004	0	3/1/2004	0	4/1/2004	13.2
1/2/2004	0	2/2/2004	0	3/2/2004	3.8	4/2/2004	0
1/3/2004	0	2/3/2004	17.3	3/3/2004	0	4/3/2004	0
1/4/2004	0	2/4/2004	0	3/4/2004	0	4/4/2004	0
1/5/2004	4.6	2/5/2004	0	3/5/2004	0	4/5/2004	0
1/6/2004	0	2/6/2004	12.7	3/6/2004	1	4/6/2004	0
1/7/2004	0	2/7/2004	0	3/7/2004	0.8	4/7/2004	0
1/8/2004	0	2/8/2004	0	3/8/2004	0	4/8/2004	0
1/9/2004	1.8	2/9/2004	0	3/9/2004	0	4/9/2004	0
1/10/2004	0	2/10/2004	0	3/10/2004	0	4/10/2004	0
1/11/2004	0	2/11/2004	0	3/11/2004	0	4/11/2004	0
1/12/2004	0	2/12/2004	8.1	3/12/2004	0	4/12/2004	18.3
1/13/2004	0	2/13/2004	0	3/13/2004	0	4/13/2004	4.3
1/14/2004	0	2/14/2004	0	3/14/2004	0	4/14/2004	2.5
1/15/2004	0	2/15/2004	6.1	3/15/2004	4.3	4/15/2004	0
1/16/2004	0	2/16/2004	0.5	3/16/2004	6.6	4/16/2004	0.8
1/17/2004	0.3	2/17/2004	1	3/17/2004	0	4/17/2004	1
1/18/2004	2.8	2/18/2004	0	3/18/2004	2.8	4/18/2004	0
1/19/2004	0	2/19/2004	0	3/19/2004	0	4/19/2004	0
1/20/2004	0	2/20/2004	0	3/20/2004	0	4/20/2004	0
1/21/2004	0	2/21/2004	0	3/21/2004	0	4/21/2004	0
1/22/2004	0	2/22/2004	0	3/22/2004	0	4/22/2004	0
1/23/2004	0	2/23/2004	0	3/23/2004	0	4/23/2004	0
1/24/2004	0	2/24/2004	0	3/24/2004	0	4/24/2004	0
1/25/2004	13	2/25/2004	0	3/25/2004	0	4/25/2004	0.5
1/26/2004	0	2/26/2004	2.3	3/26/2004	0	4/26/2004	7.4
1/27/2004	0	2/27/2004	16.3	3/27/2004	0.3	4/27/2004	0
1/28/2004	0	2/28/2004	0	3/28/2004	0	4/28/2004	0
1/29/2004	0	2/29/2004	0	3/29/2004	0	4/29/2004	0
1/30/2004	0			3/30/2004	1.5	4/30/2004	0.3
1/31/2004	0			3/31/2004	11.4		

Rainfalls during May to August of 2004

(Data source: Andy McDaniel, NC DOT Estimation)

Date	P, mm	Date	P, mm	Date	P, mm	Date	P, mm
5/1/2004	9.7	6/1/2004	0	7/1/2004	0	8/1/2004	0
5/2/2004	20.6	6/2/2004	0	7/2/2004	0	8/2/2004	12.7
5/3/2004	1	6/3/2004	0	7/3/2004	2	8/3/2004	2.3
5/4/2004	0	6/4/2004	32.3	7/4/2004	1	8/4/2004	0
5/5/2004	0.5	6/5/2004	0	7/5/2004	0	8/5/2004	4.8
5/6/2004	0	6/6/2004	0	7/6/2004	0	8/6/2004	0
5/7/2004	0.5	6/7/2004	0	7/7/2004	2	8/7/2004	0
5/8/2004	0.5	6/8/2004	3.6	7/8/2004	0.5	8/8/2004	0
5/9/2004	1.3	6/9/2004	0	7/9/2004	0	8/9/2004	0
5/10/2004	0.3	6/10/2004	0	7/10/2004	1.3	8/10/2004	0
5/11/2004	0	6/11/2004	7.4	7/11/2004	0.5	8/11/2004	1.8
5/12/2004	0	6/12/2004	0	7/12/2004	1	8/12/2004	11.4
5/13/2004	0	6/13/2004	0	7/13/2004	0	8/13/2004	19.1
5/14/2004	0	6/14/2004	0	7/14/2004	8.1	8/14/2004	23.4
5/15/2004	0	6/15/2004	4.6	7/15/2004	0	8/15/2004	1.3
5/16/2004	4.8	6/16/2004	0	7/16/2004	0	8/16/2004	0
5/17/2004	0	6/17/2004	0	7/17/2004	7.9	8/17/2004	13
5/18/2004	0	6/18/2004	0	7/18/2004	5.3	8/18/2004	0
5/19/2004	1.3	6/19/2004	2	7/19/2004	0	8/19/2004	0
5/20/2004	0	6/20/2004	0	7/20/2004	7.9	8/20/2004	0.3
5/21/2004	0	6/21/2004	0	7/21/2004	0	8/21/2004	10.2
5/22/2004	4.1	6/22/2004	0	7/22/2004	5.6	8/22/2004	0.8
5/23/2004	4.1	6/23/2004	14.7	7/23/2004	8.9	8/23/2004	0
5/24/2004	0	6/24/2004	0	7/24/2004	0	8/24/2004	0
5/25/2004	0	6/25/2004	3.6	7/25/2004	0	8/25/2004	0
5/26/2004	1.8	6/26/2004	11.9	7/26/2004	0	8/26/2004	0
5/27/2004	0.3	6/27/2004	1.5	7/27/2004	13.5	8/27/2004	0
5/28/2004	0	6/28/2004	3.6	7/28/2004	7.4	8/28/2004	0
5/29/2004	0	6/29/2004	0	7/29/2004	35.6	8/29/2004	1.8
5/30/2004	14.7	6/30/2004	0	7/30/2004	0	8/30/2004	75.2
5/31/2004	0			7/31/2004	8.1	8/31/2004	0.3

Rainfalls during September to October of 2004

(Data source: Andy McDaniel, NC DOT Estimation)

Date	P, mm	Date	P, mm	Date	P, mm	Date	P, mm
9/1/2004	0.3	10/1/2004	0.3	11/1/2004	1	12/1/2004	3.3
9/2/2004	0	10/2/2004	14.7	11/2/2004	0	12/2/2004	0
9/3/2004	0	10/3/2004	1.8	11/3/2004	0.3	12/3/2004	0
9/4/2004	0	10/4/2004	2	11/4/2004	18.5	12/4/2004	0
9/5/2004	0	10/5/2004	0.3	11/5/2004	0	12/5/2004	0
9/6/2004	13.7	10/6/2004	0	11/6/2004	0	12/6/2004	3
9/7/2004	19.1	10/7/2004	0	11/7/2004	0	12/7/2004	0
9/8/2004	37.3	10/8/2004	0	11/8/2004	0	12/8/2004	0
9/9/2004	0	10/9/2004	0.3	11/9/2004	0	12/9/2004	4.8
9/10/2004	0	10/10/2004	1	11/10/2004	0	12/10/2004	48.8
9/11/2004	0	10/11/2004	0.3	11/11/2004	0	12/11/2004	0.3
9/12/2004	0	10/12/2004	0	11/12/2004	29.7	12/12/2004	0
9/13/2004	0	10/13/2004	30.2	11/13/2004	0	12/13/2004	0
9/14/2004	1	10/14/2004	0	11/14/2004	0	12/14/2004	0
9/15/2004	5.6	10/15/2004	1.8	11/15/2004	0	12/15/2004	0
9/16/2004	0	10/16/2004	0	11/16/2004	0	12/16/2004	0
9/17/2004	21.8	10/17/2004	0	11/17/2004	0	12/17/2004	0
9/18/2004	4.8	10/18/2004	0	11/18/2004	0	12/18/2004	0
9/19/2004	0	10/19/2004	8.1	11/19/2004	0	12/19/2004	3.3
9/20/2004	0	10/20/2004	0	11/20/2004	0	12/20/2004	0
9/21/2004	0.3	10/21/2004	0	11/21/2004	0	12/21/2004	0
9/22/2004	0	10/22/2004	0.3	11/22/2004	0	12/22/2004	0
9/23/2004	0	10/23/2004	0.3	11/23/2004	16.3	12/23/2004	5.8
9/24/2004	0	10/24/2004	1	11/24/2004	4.6	12/24/2004	0
9/25/2004	0	10/25/2004	1.3	11/25/2004	0.5	12/25/2004	0
9/26/2004	0	10/26/2004	2.5	11/26/2004	0	12/26/2004	0
9/27/2004	5.6	10/27/2004	0.3	11/27/2004	15.7	12/27/2004	0
9/28/2004	14.2	10/28/2004	0	11/28/2004	2.5	12/28/2004	0
9/29/2004	0	10/29/2004	0	11/29/2004	0	12/29/2004	0
9/30/2004	0	10/30/2004	0	11/30/2004	0	12/30/2004	0
		10/31/2004	0.3			12/31/2004	0

Rainfalls during January to April of 2005

(Data source: Andy McDaniel, NC DOT Estimation)

Date	P, mm	Date	P, mm	Date	P, mm	Date	P, mm
1/1/2005	0	2/1/2005	0	3/1/2005	0	4/1/2005	0.5
1/2/2005	0	2/2/2005	0	3/2/2005	0	4/2/2005	9.4
1/3/2005	0	2/3/2005	11.4	3/3/2005	0	4/3/2005	0
1/4/2005	0	2/4/2005	0	3/4/2005	0	4/4/2005	0
1/5/2005	0	2/5/2005	0	3/5/2005	2.5	4/5/2005	0
1/6/2005	0	2/6/2005	0	3/6/2005	0	4/6/2005	0
1/7/2005	0	2/7/2005	0	3/7/2005	0	4/7/2005	2.5
1/8/2005	0	2/8/2005	0	3/8/2005	18.3	4/8/2005	6.6
1/9/2005	0	2/9/2005	0	3/9/2005	0	4/9/2005	0
1/10/2005	0	2/10/2005	1.5	3/10/2005	0	4/10/2005	0
1/11/2005	0	2/11/2005	0	3/11/2005	3	4/11/2005	0
1/12/2005	0	2/12/2005	0	3/12/2005	0	4/12/2005	2.8
1/13/2005	11.2	2/13/2005	1	3/13/2005	1.3	4/13/2005	0.8
1/14/2005	30.7	2/14/2005	4.6	3/14/2005	2.5	4/14/2005	0
1/15/2005	0	2/15/2005	0	3/15/2005	0	4/15/2005	0
1/16/2005	0	2/16/2005	0	3/16/2005	11.7	4/16/2005	0
1/17/2005	0	2/17/2005	0	3/17/2005	5.6	4/17/2005	0
1/18/2005	0	2/18/2005	0	3/18/2005	0	4/18/2005	0
1/19/2005	1	2/19/2005	0	3/19/2005	0	4/19/2005	0
1/20/2005	0.5	2/20/2005	1.3	3/20/2005	0	4/20/2005	1.5
1/21/2005	1.3	2/21/2005	0	3/21/2005	0	4/21/2005	0
1/22/2005	0	2/22/2005	0	3/22/2005	2	4/22/2005	3.3
1/23/2005	0	2/23/2005	0	3/23/2005	9.7	4/23/2005	1
1/24/2005	0	2/24/2005	12.2	3/24/2005	0	4/24/2005	0
1/25/2005	0	2/25/2005	0	3/25/2005	0	4/25/2005	0
1/26/2005	0	2/26/2005	0	3/26/2005	0	4/26/2005	0
1/27/2005	0	2/27/2005	5.6	3/27/2005	0	4/27/2005	0
1/28/2005	0	2/28/2005	20.3	3/28/2005	24.1	4/28/2005	0
1/29/2005	6.1			3/29/2005	0	4/29/2005	3.8
1/30/2005	16.8			3/30/2005	0	4/30/2005	0
1/31/2005	0			3/31/2005	0		

Rainfalls during May to August of 2005

(Data source: Andy McDaniel, NC DOT Estimation)

Date	P, mm	Date	P, mm	Date	P, mm	Date	P, mm
5/1/2005	13.2	6/1/2005	1	7/1/2005	0	8/1/2005	0
5/2/2005	0	6/2/2005	6.1	7/2/2005	0	8/2/2005	0
5/3/2005	0.3	6/3/2005	6.1	7/3/2005	0.5	8/3/2005	0
5/4/2005	0.3	6/4/2005	0	7/4/2005	6.1	8/4/2005	0
5/5/2005	1	6/5/2005	0	7/5/2005	0.5	8/5/2005	0
5/6/2005	5.1	6/6/2005	4.8	7/6/2005	0	8/6/2005	0
5/7/2005	1	6/7/2005	9.7	7/7/2005	20.3	8/7/2005	0
5/8/2005	0.3	6/8/2005	2.5	7/8/2005	1.3	8/8/2005	2
5/9/2005	1	6/9/2005	20.8	7/9/2005	0	8/9/2005	7.9
5/10/2005	2	6/10/2005	4.1	7/10/2005	0	8/10/2005	0
5/11/2005	0	6/11/2005	0	7/11/2005	0	8/11/2005	0
5/12/2005	2	6/12/2005	0	7/12/2005	0	8/12/2005	0
5/13/2005	0	6/13/2005	0.3	7/13/2005	0	8/13/2005	0
5/14/2005	0.8	6/14/2005	0	7/14/2005	3	8/14/2005	10.7
5/15/2005	1.8	6/15/2005	0	7/15/2005	0	8/15/2005	0
5/16/2005	0	6/16/2005	0	7/16/2005	0	8/16/2005	14.5
5/17/2005	0	6/17/2005	0	7/17/2005	0	8/17/2005	0.5
5/18/2005	0.3	6/18/2005	0	7/18/2005	0	8/18/2005	0
5/19/2005	8.9	6/19/2005	0.3	7/19/2005	2.3	8/19/2005	0.3
5/20/2005	10.9	6/20/2005	0	7/20/2005	0.5	8/20/2005	0
5/21/2005	0.3	6/21/2005	0	7/21/2005	0	8/21/2005	0
5/22/2005	0	6/22/2005	0.8	7/22/2005	0	8/22/2005	0.3
5/23/2005	0.5	6/23/2005	0	7/23/2005	0	8/23/2005	0.5
5/24/2005	4.6	6/24/2005	0	7/24/2005	0	8/24/2005	0
5/25/2005	0	6/25/2005	0	7/25/2005	0	8/25/2005	0
5/26/2005	0	6/26/2005	0.3	7/26/2005	0	8/26/2005	0
5/27/2005	0	6/27/2005	11.7	7/27/2005	0	8/27/2005	0
5/28/2005	0	6/28/2005	3	7/28/2005	7.9	8/28/2005	0
5/29/2005	0	6/29/2005	0	7/29/2005	13	8/29/2005	0
5/30/2005	0	6/30/2005	0	7/30/2005	0.8	8/30/2005	0
5/31/2005	0			7/31/2005	2.8	8/31/2005	0

Rainfalls during September to October of 2005

(Data source: Andy McDaniel, NC DOT Estimation)

Date	P, mm	Date	P, mm	Date	P, mm	Date	P, mm
9/1/2005	0	10/1/2005	0	11/1/2005	0	12/1/2005	0.5
9/2/2005	0	10/2/2005	0	11/2/2005	0.3	12/2/2005	0
9/3/2005	0	10/3/2005	0	11/3/2005	0.3	12/3/2005	0
9/4/2005	0	10/4/2005	0	11/4/2005	0	12/4/2005	3
9/5/2005	0	10/5/2005	1	11/5/2005	0	12/5/2005	29.2
9/6/2005	0	10/6/2005	4.8	11/6/2005	0	12/6/2005	0
9/7/2005	0	10/7/2005	15	11/7/2005	0	12/7/2005	0
9/8/2005	0	10/8/2005	10.9	11/8/2005	0	12/8/2005	0
9/9/2005	0	10/9/2005	0	11/9/2005	0	12/9/2005	7.6
9/10/2005	0	10/10/2005	1.3	11/10/2005	4.6	12/10/2005	0
9/11/2005	0	10/11/2005	0	11/11/2005	0	12/11/2005	0
9/12/2005	0	10/12/2005	0	11/12/2005	0	12/12/2005	0
9/13/2005	2.5	10/13/2005	1	11/13/2005	0	12/13/2005	0
9/14/2005	0	10/14/2005	0	11/14/2005	0	12/14/2005	0
9/15/2005	0	10/15/2005	0	11/15/2005	0	12/15/2005	37.1
9/16/2005	0.3	10/16/2005	0	11/16/2005	4.6	12/16/2005	0
9/17/2005	3.6	10/17/2005	0	11/17/2005	0	12/17/2005	0
9/18/2005	0	10/18/2005	0	11/18/2005	0	12/18/2005	4.8
9/19/2005	0.3	10/19/2005	0	11/19/2005	0	12/19/2005	0
9/20/2005	18.5	10/20/2005	0	11/20/2005	0	12/20/2005	0
9/21/2005	0	10/21/2005	6.1	11/21/2005	32.3	12/21/2005	0
9/22/2005	0	10/22/2005	0	11/22/2005	34.3	12/22/2005	0
9/23/2005	0.8	10/23/2005	0	11/23/2005	0	12/23/2005	0
9/24/2005	0.8	10/24/2005	0	11/24/2005	0	12/24/2005	0
9/25/2005	0	10/25/2005	0	11/25/2005	0	12/25/2005	6.9
9/26/2005	0	10/26/2005	0	11/26/2005	0	12/26/2005	0
9/27/2005	1.3	10/27/2005	0.3	11/27/2005	9.7	12/27/2005	0
9/28/2005	0	10/28/2005	0.8	11/28/2005	1.8	12/28/2005	3.6
9/29/2005	0.8	10/29/2005	0	11/29/2005	24.1	12/29/2005	1.8
9/30/2005	0	10/30/2005	0	11/30/2005	0	12/30/2005	0
		10/31/2005	0			12/31/2005	0

Rainfalls during January to April of 2006

(Data source: Andy McDaniel, NC DOT Estimation)

Date	P, mm	Date	P, mm	Date	P, mm	Date	P, mm
1/1/2006	0	2/1/2006	0	3/1/2006	0	4/1/2006	1.3
1/2/2006	4.8	2/2/2006	0.5	3/2/2006	0	4/2/2006	0
1/3/2006	1.3	2/3/2006	0	3/3/2006	0	4/3/2006	5.1
1/4/2006	0	2/4/2006	4.6	3/4/2006	0	4/4/2006	0
1/5/2006	1.3	2/5/2006	0	3/5/2006	0	4/5/2006	0
1/6/2006	2.5	2/6/2006	0	3/6/2006	2.8	4/6/2006	0
1/7/2006	0	2/7/2006	0	3/7/2006	0	4/7/2006	0
1/8/2006	0	2/8/2006	0	3/8/2006	0	4/8/2006	4.8
1/9/2006	0	2/9/2006	0	3/9/2006	0	4/9/2006	0
1/10/2006	0	2/10/2006	0	3/10/2006	0	4/10/2006	0
1/11/2006	1.8	2/11/2006	18.5	3/11/2006	2.3	4/11/2006	0
1/12/2006	0	2/12/2006	0	3/12/2006	0	4/12/2006	0.3
1/13/2006	0.8	2/13/2006	0	3/13/2006	0	4/13/2006	0
1/14/2006	3	2/14/2006	0	3/14/2006	0.8	4/14/2006	0.8
1/15/2006	0	2/15/2006	0	3/15/2006	0	4/15/2006	0
1/16/2006	0	2/16/2006	0	3/16/2006	0	4/16/2006	0
1/17/2006	0	2/17/2006	0	3/17/2006	0	4/17/2006	7.9
1/18/2006	6.4	2/18/2006	2.3	3/18/2006	0	4/18/2006	0
1/19/2006	0	2/19/2006	0	3/19/2006	0	4/19/2006	0
1/20/2006	0	2/20/2006	1	3/20/2006	9.9	4/20/2006	0
1/21/2006	2	2/21/2006	0	3/21/2006	3	4/21/2006	0
1/22/2006	0	2/22/2006	10.4	3/22/2006	0	4/22/2006	34
1/23/2006	0.8	2/23/2006	1.3	3/23/2006	0	4/23/2006	0
1/24/2006	0	2/24/2006	0	3/24/2006	0	4/24/2006	0
1/25/2006	0	2/25/2006	0	3/25/2006	2.8	4/25/2006	32
1/26/2006	0	2/26/2006	0	3/26/2006	0	4/26/2006	3
1/27/2006	0	2/27/2006	0	3/27/2006	0	4/27/2006	20.3
1/28/2006	0	2/28/2006	0	3/28/2006	0	4/28/2006	0
1/29/2006	0			3/29/2006	0	4/29/2006	0
1/30/2006	0			3/30/2006	0	4/30/2006	0
1/31/2006	3.6			3/31/2006	0		

Rainfalls during May to August of 2006

(Data source: Andy McDaniel, NC DOT Estimation)

Date	P, mm	Date	P, mm	Date	P, mm	Date	P, mm
5/1/2006	0	6/1/2006	0.8	7/1/2006	0	8/1/2006	0
5/2/2006	0	6/2/2006	1.3	7/2/2006	0	8/2/2006	0
5/3/2006	0	6/3/2006	7.9	7/3/2006	0.3	8/3/2006	0
5/4/2006	0	6/4/2006	3	7/4/2006	10.9	8/4/2006	0
5/5/2006	2.5	6/5/2006	1	7/5/2006	20.6	8/5/2006	0
5/6/2006	0	6/6/2006	2.3	7/6/2006	52.1	8/6/2006	0
5/7/2006	26.4	6/7/2006	0	7/7/2006	0	8/7/2006	1
5/8/2006	0	6/8/2006	6.4	7/8/2006	0	8/8/2006	1
5/9/2006	0	6/9/2006	0	7/9/2006	0	8/9/2006	0
5/10/2006	0	6/10/2006	0	7/10/2006	0	8/10/2006	0
5/11/2006	0	6/11/2006	27.9	7/11/2006	0	8/11/2006	0
5/12/2006	0	6/12/2006	20.3	7/12/2006	0	8/12/2006	7.6
5/13/2006	0.5	6/13/2006	0	7/13/2006	15	8/13/2006	0
5/14/2006	34.3	6/14/2006	54.9	7/14/2006	80.5	8/14/2006	0
5/15/2006	2.8	6/15/2006	0	7/15/2006	0	8/15/2006	0
5/16/2006	0	6/16/2006	0	7/16/2006	0	8/16/2006	0.5
5/17/2006	0	6/17/2006	0	7/17/2006	0	8/17/2006	0
5/18/2006	3.3	6/18/2006	0	7/18/2006	0	8/18/2006	0
5/19/2006	0	6/19/2006	0	7/19/2006	0	8/19/2006	0
5/20/2006	7.6	6/20/2006	0	7/20/2006	0	8/20/2006	0
5/21/2006	0	6/21/2006	0	7/21/2006	0	8/21/2006	0
5/22/2006	0	6/22/2006	0	7/22/2006	51.8	8/22/2006	1.8
5/23/2006	0	6/23/2006	16.5	7/23/2006	9.1	8/23/2006	0
5/24/2006	0	6/24/2006	5.8	7/24/2006	0	8/24/2006	0
5/25/2006	0	6/25/2006	65.5	7/25/2006	26.2	8/25/2006	0
5/26/2006	4.1	6/26/2006	3.3	7/26/2006	0	8/26/2006	0
5/27/2006	0	6/27/2006	2.5	7/27/2006	1	8/27/2006	0
5/28/2006	0	6/28/2006	0	7/28/2006	0	8/28/2006	0
5/29/2006	0	6/29/2006	0	7/29/2006	5.1	8/29/2006	0.8
5/30/2006	0	6/30/2006	0	7/30/2006	0	8/30/2006	33.5
5/31/2006	13			7/31/2006	0	8/31/2006	29.5

Rainfalls during September to October of 2006

(Data source: Andy McDaniel, NC DOT Estimation)

Date	P, mm	Date	P, mm	Date	P, mm	Date	P, mm
9/1/2006	6.4	10/1/2006	1.3	11/1/2006	0	12/1/2006	3.3
9/2/2006	0	10/2/2006	0	11/2/2006	2.3	12/2/2006	0
9/3/2006	0	10/3/2006	0	11/3/2006	0.8	12/3/2006	0
9/4/2006	2.3	10/4/2006	0	11/4/2006	0	12/4/2006	0
9/5/2006	0	10/5/2006	0	11/5/2006	0	12/5/2006	0
9/6/2006	0	10/6/2006	8.9	11/6/2006	0	12/6/2006	0
9/7/2006	0	10/7/2006	1.5	11/7/2006	32.5	12/7/2006	0
9/8/2006	1.3	10/8/2006	6.9	11/8/2006	0.5	12/8/2006	0
9/9/2006	0	10/9/2006	0	11/9/2006	0	12/9/2006	0
9/10/2006	0	10/10/2006	0	11/10/2006	0	12/10/2006	0
9/11/2006	0	10/11/2006	0.3	11/11/2006	0	12/11/2006	0
9/12/2006	0	10/12/2006	1.5	11/12/2006	21.8	12/12/2006	0
9/13/2006	37.8	10/13/2006	0.3	11/13/2006	0	12/13/2006	0
9/14/2006	6.4	10/14/2006	0	11/14/2006	0	12/14/2006	0
9/15/2006	0	10/15/2006	0	11/15/2006	0	12/15/2006	0
9/16/2006	0	10/16/2006	0	11/16/2006	28.2	12/16/2006	0
9/17/2006	0	10/17/2006	27.9	11/17/2006	0	12/17/2006	0
9/18/2006	0	10/18/2006	1.5	11/18/2006	0	12/18/2006	0
9/19/2006	6.6	10/19/2006	1.5	11/19/2006	0	12/19/2006	0
9/20/2006	0	10/20/2006	3.8	11/20/2006	0	12/20/2006	0
9/21/2006	0	10/21/2006	0	11/21/2006	26.4	12/21/2006	0
9/22/2006	0	10/22/2006	2.8	11/22/2006	30	12/22/2006	16
9/23/2006	0	10/23/2006	0	11/23/2006	0	12/23/2006	0
9/24/2006	1.3	10/24/2006	0	11/24/2006	0	12/24/2006	0
9/25/2006	1	10/25/2006	0.8	11/25/2006	0	12/25/2006	28.7
9/26/2006	0	10/26/2006	0.8	11/26/2006	0	12/26/2006	0
9/27/2006	0	10/27/2006	14.5	11/27/2006	0	12/27/2006	0
9/28/2006	12.2	10/28/2006	6.6	11/28/2006	0	12/28/2006	0
9/29/2006	0	10/29/2006	0	11/29/2006	0	12/29/2006	0
9/30/2006	0.3	10/30/2006	0	11/30/2006	1	12/30/2006	0
		10/31/2006	0			12/31/2006	0

Rainfalls during January to April of 2007

(Data source: Andy McDaniel, NC DOT Estimation)

Date	P, mm	Date	P, mm	Date	P, mm	Date	P, mm
1/1/2007	10.8	2/1/2007	2.6	3/1/2007	5.3	4/1/2007	2.4
1/2/2007	0	2/2/2007	0.9	3/2/2007	18.4	4/2/2007	0
1/3/2007	0	2/3/2007	0	3/3/2007	0	4/3/2007	0
1/4/2007	0	2/4/2007	0	3/4/2007	0	4/4/2007	0
1/5/2007	6.5	2/5/2007	0	3/5/2007	0	4/5/2007	0
1/6/2007	3.8	2/6/2007	0	3/6/2007	0	4/6/2007	0
1/7/2007	15.8	2/7/2007	0	3/7/2007	0	4/7/2007	1.1
1/8/2007	12.7	2/8/2007	0	3/8/2007	0	4/8/2007	0
1/9/2007	0	2/9/2007	0	3/9/2007	0	4/9/2007	0
1/10/2007	0	2/10/2007	0	3/10/2007	0	4/10/2007	0.1
1/11/2007	0	2/11/2007	0	3/11/2007	0	4/11/2007	17.4
1/12/2007	0	2/12/2007	0	3/12/2007	0	4/12/2007	9
1/13/2007	0	2/13/2007	10.5	3/13/2007	0	4/13/2007	0
1/14/2007	0	2/14/2007	4.5	3/14/2007	0	4/14/2007	5.4
1/15/2007	0	2/15/2007	0	3/15/2007	0.1	4/15/2007	39
1/16/2007	0.4	2/16/2007	0	3/16/2007	28	4/16/2007	0
1/17/2007	0	2/17/2007	0	3/17/2007	0	4/17/2007	0
1/18/2007	3.1	2/18/2007	0	3/18/2007	0	4/18/2007	0.8
1/19/2007	0	2/19/2007	0	3/19/2007	0	4/19/2007	1.3
1/20/2007	0	2/20/2007	0	3/20/2007	0	4/20/2007	0
1/21/2007	13.3	2/21/2007	0	3/21/2007	0	4/21/2007	0.3
1/22/2007	4.2	2/22/2007	0	3/22/2007	0	4/22/2007	0.6
1/23/2007	0	2/23/2007	0	3/23/2007	0	4/23/2007	0.1
1/24/2007	0	2/24/2007	0	3/24/2007	0	4/24/2007	0
1/25/2007	0	2/25/2007	17.5	3/25/2007	0	4/25/2007	0
1/26/2007	0	2/26/2007	0	3/26/2007	0	4/26/2007	0.8
1/27/2007	0	2/27/2007	0	3/27/2007	3.5	4/27/2007	2.7
1/28/2007	0	2/28/2007	0	3/28/2007	0	4/28/2007	0
1/29/2007	0			3/29/2007	4.8	4/29/2007	0
1/30/2007	0			3/30/2007	0	4/30/2007	0
1/31/2007	0			3/31/2007	0		

Rainfalls during May to August of 2007

(Data source: Andy McDaniel, NC DOT Estimation)

Date	P, mm	Date	P, mm	Date	P, mm	Date	P, mm
5/1/2007	0	6/1/2007	0	7/1/2007	0	8/1/2007	0
5/2/2007	0	6/2/2007	0.8	7/2/2007	0	8/2/2007	0
5/3/2007	0	6/3/2007	22.6	7/3/2007	0	8/3/2007	0
5/4/2007	0	6/4/2007	1.1	7/4/2007	0	8/4/2007	0
5/5/2007	0.3	6/5/2007	6.1	7/5/2007	0.1	8/5/2007	0.5
5/6/2007	0	6/6/2007	2.1	7/6/2007	0	8/6/2007	0
5/7/2007	0	6/7/2007	0	7/7/2007	0	8/7/2007	0
5/8/2007	0	6/8/2007	0	7/8/2007	0	8/8/2007	0
5/9/2007	7.3	6/9/2007	0.8	7/9/2007	0	8/9/2007	0
5/10/2007	1.4	6/10/2007	0	7/10/2007	8	8/10/2007	0
5/11/2007	1.1	6/11/2007	8.4	7/11/2007	4.9	8/11/2007	0
5/12/2007	20.9	6/12/2007	0	7/12/2007	0	8/12/2007	0
5/13/2007	0.3	6/13/2007	4.3	7/13/2007	0.1	8/13/2007	0
5/14/2007	0	6/14/2007	0	7/14/2007	0	8/14/2007	0
5/15/2007	0	6/15/2007	0.4	7/15/2007	0	8/15/2007	0
5/16/2007	1	6/16/2007	0	7/16/2007	0.4	8/16/2007	0
5/17/2007	1.5	6/17/2007	0	7/17/2007	3.6	8/17/2007	8.5
5/18/2007	0.3	6/18/2007	0	7/18/2007	0.5	8/18/2007	0
5/19/2007	0	6/19/2007	4.7	7/19/2007	0	8/19/2007	0
5/20/2007	0	6/20/2007	1	7/20/2007	0.3	8/20/2007	0
5/21/2007	0.4	6/21/2007	0	7/21/2007	0	8/21/2007	7.3
5/22/2007	0.4	6/22/2007	0	7/22/2007	1.4	8/22/2007	0
5/23/2007	0	6/23/2007	0	7/23/2007	0	8/23/2007	0.1
5/24/2007	0	6/24/2007	1.9	7/24/2007	0.9	8/24/2007	0
5/25/2007	0	6/25/2007	2.5	7/25/2007	0	8/25/2007	0
5/26/2007	0	6/26/2007	0	7/26/2007	0	8/26/2007	1.9
5/27/2007	0	6/27/2007	0	7/27/2007	1.9	8/27/2007	0
5/28/2007	0	6/28/2007	6	7/28/2007	0.3	8/28/2007	0.1
5/29/2007	0	6/29/2007	2.8	7/29/2007	0	8/29/2007	0
5/30/2007	0	6/30/2007	0	7/30/2007	4	8/30/2007	0.4
5/31/2007	0			7/31/2007	0	8/31/2007	0

Rainfalls during September to October of 2007

(Data source: Andy McDaniel, NC DOT Estimation)

Date	P, mm	Date	P, mm	Date	P, mm	Date	P, mm
9/1/2007	0	10/1/2007	0	11/1/2007	0	12/1/2007	0
9/2/2007	0	10/2/2007	0.3	11/2/2007	0	12/2/2007	0
9/3/2007	0	10/3/2007	0.3	11/3/2007	0	12/3/2007	0.1
9/4/2007	0	10/4/2007	0	11/4/2007	0	12/4/2007	0
9/5/2007	0	10/5/2007	1.9	11/5/2007	0	12/5/2007	0
9/6/2007	0	10/6/2007	0	11/6/2007	0.8	12/6/2007	0
9/7/2007	0	10/7/2007	0.3	11/7/2007	0	12/7/2007	0
9/8/2007	0	10/8/2007	0.9	11/8/2007	0	12/8/2007	0
9/9/2007	0.1	10/9/2007	0.4	11/9/2007	0.3	12/9/2007	0
9/10/2007	0.3	10/10/2007	1.4	11/10/2007	0.1	12/10/2007	0
9/11/2007	0.1	10/11/2007	1	11/11/2007	0	12/11/2007	0
9/12/2007	0	10/12/2007	0	11/12/2007	0.3	12/12/2007	0
9/13/2007	0	10/13/2007	0	11/13/2007	0	12/13/2007	0.5
9/14/2007	15.9	10/14/2007	0	11/14/2007	0	12/14/2007	0
9/15/2007	0.5	10/15/2007	0.3	11/15/2007	2.1	12/15/2007	11.6
9/16/2007	0.1	10/16/2007	0	11/16/2007	0	12/16/2007	9.4
9/17/2007	0	10/17/2007	0	11/17/2007	0	12/17/2007	0
9/18/2007	0	10/18/2007	0	11/18/2007	0	12/18/2007	0
9/19/2007	0	10/19/2007	2.3	11/19/2007	0	12/19/2007	0.4
9/20/2007	0.8	10/20/2007	0.8	11/20/2007	0	12/20/2007	0
9/21/2007	0	10/21/2007	0.8	11/21/2007	0	12/21/2007	2
9/22/2007	0.5	10/22/2007	0	11/22/2007	1.8	12/22/2007	0
9/23/2007	0.8	10/23/2007	1.5	11/23/2007	0	12/23/2007	1.8
9/24/2007	0	10/24/2007	22.9	11/24/2007	0	12/24/2007	0
9/25/2007	0	10/25/2007	5.8	11/25/2007	0.9	12/25/2007	0
9/26/2007	0	10/26/2007	54.8	11/26/2007	0.5	12/26/2007	13.5
9/27/2007	0.4	10/27/2007	4.3	11/27/2007	0	12/27/2007	0
9/28/2007	1.4	10/28/2007	0	11/28/2007	0	12/28/2007	2.9
9/29/2007	0	10/29/2007	0.4	11/29/2007	0	12/29/2007	3
9/30/2007	0	10/30/2007	0.4	11/30/2007	0	12/30/2007	34.8
		10/31/2007	0			12/31/2007	0

APPENDIX C: APPROACHES TO PREPARING NCDOT AND NLCD LULC DATA AND INTEGRATING THE BOTH FOR THE LAKE ORANGE WATERSHED

Sources of data

- LULC: Orange County NLCD2001 raster data (30-m resolution) downloaded from USGS web site (http://seamless.usgs.gov).
- NC DOT roads: Road Characteristics Arcs from NC DOT web site (http://www.ncdot.org/it/gis/DataDistribution/DOTData/). This layer includes NC DOT roadways defined by interstates, US routes, NC routes, secondary routes, and ramps.
- Watershed boundary: National Hydrography Dataset (NHD) personal geodatabase downloaded from USGS web site (http://nhd.usgs.gov/data.html).

Approach to preparing the NLCD LULC data for the Lake Orange watershed

Summary: Create a 500-meter buffer of the Lake Orange watershed and use it to clip the NLCD2001 raster data before converting it into a polygon layer.

Steps:

1. Load the Data sources into ArcMap and set the Display Coordinate system to be the same as the NLCD 2001 layer (GCS North American 1983).
2. Buffer the Research Area (Lake Orange watershed boundary) by 500 meters. This buffer area is chosen as a conservative buffer of the watershed area and hopefully should include the final watershed boundary used in the model.
3. Export the new project area buffer layer to a new layer that is in the same coordinate system as the Display (and NLCD layer).
4. Use the “Extract by Mask” tool to reduce the size of the NLCD raster dataset

before converting it to a polygon layer from a raster dataset. Use the project area layer as the input mask and the NLCD raster layer as the input raster. The “Environment Settings->General Settings-> Output Extent” should be set to be the same as the polygon layer and the “Snap Raster” option should be set to snap to the NLCD layer.

5. Use the “Raster to Polygon” tool to convert the NLCD subset to a polygon layer making sure that the extents of the layers are aligned. When using this tool the “Simplify Polygons” option should not be used (i.e. unchecked). The “Environment Settings->General Settings-> Output Extent” should be set to be the same as the NLCD subset raster layer.
6. Join the NLCD code lookup table with descriptions of the NLCD codes to the new Lake Orange LULC polygon layer.
7. Project the new polygon layer to the projection, NC State Plane, NAD83, meters.

Approach to preparing the NCDOT road LULC data in the Lake Orange watershed

Following the methodology proposed by NCDOT in the *Falls Lake Watershed Analysis Risk Management Framework Development* project, the NC DOT road LULC data is prepared based on the follow attributes in the NCDOT Road Characteristics Arcs GIS layer:

Width of road right-of-way:	ROW	(RW_WID)
Width of the road:	SF	(SRFC_WID)
Width of left shoulder:	L	(SHLDR_WID_)
Width of right shoulder:	R	(SHLDR_WID1)

Width of the median:	M	(MDN_WID)
Type of the median	MT	(MDN_TYP_CD)

Steps:

1. Add the NCDOT Road Characteristics Arcs (i.e., Rd_Char_Mlpst) to ArcMap.
2. Clip the NCDOT Road Characteristics Arcs to the buffer of the LOwatershed.
3. Add four fields to hold the estimated ROW (RW), buffer distance of both sides (BB), left buffer distance (LB), and right buffer distance (RB), respectively.
4. Calculate the width of the ROW (RW) for each road segment in the following ways:

   If ROW > 0 and ROW > = SF + L + R + M, then

   RW = ROW

   If ROW > 0 and ROW < SF + L + R + M, then

   RW = SF + L + R + M

   If ROW = 0, SF > 0, and M < 100 ft; then

   RW = SF + L + R + M

   If ROW = 0, SF > 0, and (M > 100 ft or MT < 3), then

   RW = SF + L + R

   If ROW = 0 and SF = 0, assume the segment is a standard ramp, then

   RW = 14 ft (SF) + 8 ft (L) + 8 ft (R) = 30 ft

5. Calculate the buffer distances for the different road segments in the following ways:

   If ROW > 0 and (M = 0 or MT < 3), then

   BB = RW / 2

If ROW >0, M > 0, and MT > 2, then

LB = M + SF / 2

RB = RW - LS

If ROW = 0, SF > 0, R = 0, L = 0, M > 0, MT > 2, and M < 100 ft, then

BB = (SF + M) / 2

If ROW = 0, SF > 0, R = 0, L = 0, M > 0, and (MT < 3 or M > 100 ft), then

BB = SF / 2

If ROW = 0; SF > 0; R = 0, L = 0, and M = 0, then

BB = SF / 2

If ROW = 0, SF > 0, L > 0, R = L, then

BB = (SF + L + R + M) / 2

If ROW = 0, SF > 0, R <> L, then

LB = M + SF / 2 + L

RB =SF / 2 + R

If ROW = 0 and SF = 0, assume as standard ramps, then

BB = (8+14+8)/2 = 15 ft

6. Buffer three groups (i.e., BB, LB, or RB) of road segments separately.
7. Merge the three different buffers.
8. Add a GridCode field to the merged buffers layer and calculate it to equal the NCDOT code (e.g., 29).
9. Dissolve the merged buffers on ID and GridCode.

<u>Approach to integrating the LULC data and DOT Road data</u>

Summary: Once the NLCD LULC data and NCDOT road LULC data have been prepared, the NLCD LULC data is replaced with the NCDOT ROW road centerline buffers wherever they overlap by using the Update tool to integrate the Lake Orange NLCD with the dissolved road buffers. Lastly, clip the integrated LULC layer by the Lake Orange watershed boundary.

Methodology for preparing the impervious layer

Steps:

1. ADD the Lake Orange boundary layer and the NCDOT Road_Char layer to ArcMap.
2. BUFFER the Lake Orange boundary layer using a 500-meter distance to secure that all the impervious surface of roads will be covered.
3. CLIP the NCDOT Road_Char layer using the 500-m buffered layer of Lake Orange boundary.
4. OPEN ATTRIBUT_TABLE of the clipped Road_Char layer to check with the median and left and right of shoulders.
5. Click OPTIONS on the bottom of the clipped Road_Char attribute table, ADD FIELD named as Buff_Distance in the number format, and then fill buffer distances in the FIELD with FIELD CALCULATOR in the half of SRFC_Wid.
6. Prepare the impervious road surface layer by buffering the clipped Road_Char layer using FIELD of buffer distance other than Linear Unit.
7. CLIP the buffered Road_Char layer using the Lake Orange boundary layer.
8. INTERSECT the impervious road surface layer with the *Catchment* layer created in the comprehensive terrain preprocessing. This is for geometrically calculating the impervious area for the catchments with roads.

APPENDIX D: NLCD 2001 LAND COVER CLASS DESCRIPTIONS

(Modified from *NLCD2001 Product Legend* <mrlc.gov/nlcd01_leg.php>)

Code	Class Name	Class Definition/Classification Description
	Water	*Areas of open water or permanent ice/snow cover.*
11	Open Water*	Areas of open water, generally with less than 25% cover of vegetation or soil.
12	Perennial Ice/Snow	Areas characterized by a perennial cover of ice and/or snow, generally greater than 25% of total cover.
	Developed	*Areas characterized by a high percentage (30% or greater) of constructed materials (e.g. asphalt, concrete, buildings, etc.).*
21	Developed, Open Space*	Areas with a mixture of some constructed materials, but mostly vegetation in the form of lawn grasses. Impervious surfaces account for less than 20% of total cover. These areas most commonly include large-lot single-family housing units, parks, golf courses, and vegetation planted in developed settings for recreation, erosion control, or aesthetic purposes.
22	Developed, Low Intensity*	Areas with a mixture of constructed materials and vegetation. Impervious surfaces account for 20% to 49% percent of total cover. These areas most commonly include single-family housing units.
23	Developed, Medium Intensity*	Areas with a mixture of constructed materials and vegetation. Impervious surfaces account for 50% to 79% of the total cover. These areas most commonly include single-family housing units.
24	Developed High Intensity	Areas highly developed where people reside or work in high numbers. Examples include apartment complexes, row houses and commercial/industrial. Impervious surfaces account for 80% to 100% of the total cover.
	Barren	*Areas characterized by bare rock, gravel, sand, silt, clay, or other earthen material, with little or no "green" vegetation present regardless of its inherent ability to support life. Vegetation, if present, is more widely spaced and scrubby than that in the green vegetated categories; lichen cover may be extensive.*
31	Barren Land (Rock/Sand/ Clay)*	Areas of bedrock, desert pavement, scarps, talus, slides, volcanic material, glacial debris, sand dunes, strip mines, gravel pits and other accumulations of earthen material. Generally, vegetation accounts for less than 15% of total cover.
	Forest	*Areas characterized by tree cover (natural or semi-natural woody vegetation, generally greater than 6 meters tall); tree canopy accounts for 25% to 100% of the cover.*

Code	Class Name	Class Definition/Classification Description
41	Deciduous Forest*	Areas dominated by trees generally greater than 5 meters tall, and greater than 20% of total vegetation cover. More than 75% of the tree species shed foliage simultaneously in response to seasonal change.
42	Evergreen Forest*	Areas dominated by trees generally greater than 5 meters tall, and greater than 20% of total vegetation cover. More than 75% of the tree species maintain their leaves all year. Canopy is never without green foliage.
43	Mixed Forest*	Areas dominated by trees generally greater than 5 meters tall, and greater than 20% of total vegetation cover. Neither deciduous nor evergreen species are greater than 75% of total tree cover.
	Shrubland	*Areas characterized by natural or semi-natural woody vegetation with aerial stems, generally less than 6 meters tall, with individuals or clumps not touching to interlocking. Both evergreen and deciduous species of true shrubs, young trees, and trees or shrubs that are small or stunted because of environmental conditions are included..*
51	Dwarf Scrub	Alaska only areas dominated by shrubs less than 20 centimeters tall with shrub canopy typically greater than 20% of total vegetation. This type is often co-associated with grasses, sedges, herbs, and non-vascular vegetation.
52	Shrub/Scrub*	Areas dominated by shrubs; less than 5 meters tall with shrub canopy typically greater than 20% of total vegetation. This class includes true shrubs, young trees in an early successional stage or trees stunted from environmental conditions.
	Herbaceous	*Areas characterized by natural or semi-natural herbaceous vegetation; herbaceous vegetation accounts for 75% to 100% of the cover.*
71	Grassland/ Herbaceous*	Areas dominated by gramanoid or herbaceous vegetation, generally greater than 80% of total vegetation. These areas are not subject to intensive management such as tilling, but can be utilized for grazing.
72	Sedge/ Herbaceous	Alaska only areas dominated by sedges and forbs, generally greater than 80% of total vegetation. This type can occur with significant other grasses or other grass like plants, and includes sedge tundra, and sedge tussock tundra.
73	Lichens	Alaska only areas dominated by fruticose or foliose lichens generally greater than 80% of total vegetation.
74	Moss	Alaska only areas dominated by mosses, generally greater than 80% of total vegetation.

Code	Class Name	Class Definition/Classification Description
	Planted/ Cultivated	*Areas characterized by herbaceous vegetation that has been planted or is intensively managed for the production of food, feed, or fiber; or is maintained in developed settings for specific purposes. Herbaceous vegetation accounts for 75% to 100% of the cover.*
81	Pasture/Hay*	Areas of grasses, legumes, or grass-legume mixtures planted for livestock grazing or the production of seed or hay crops, typically on a perennial cycle. Pasture/hay vegetation accounts for greater than 20% of total vegetation.
82	Cultivated Crops*	Areas used for the production of annual crops, such as corn, soybeans, vegetables, tobacco, and cotton, and also perennial woody crops such as orchards and vineyards. Crop vegetation accounts for greater than 20% of total vegetation. This class also includes all land being actively tilled.
	Wetlands	*Areas where the soil or substrate is periodically saturated with or covered with water as defined by Cowardin et al., (1979).*
90	Woody Wetlands*	Areas where forest or shrubland vegetation accounts for greater than 20% of vegetative cover and the soil or substrate is periodically saturated with or covered with water.
95	Emergent Herbaceous Wetlands	Areas where perennial herbaceous vegetation accounts for greater than 80% of vegetative cover and the soil or substrate is periodically saturated with or covered with water.

* The classes of land cover included in the Lake Orange watershed.

APPENDIX E: COMPREHENSIVE TERRAIN PREPROCESSING FOR THE LAKE ORANGE WATERSHED

This appendix is intended to illustrate the 12-step procedure of a comprehensive terrain preprocessing for the Lake Orange watershed with known drainage patterns (i.e., known streams and lakes) by using Arc Hydro 1.4 with ArcGIS 9.3.

Before executing the whole process, make sure that:

a) For all the supporting layers (e.g., Stream and Lake/Waterbody), their coordinate system and projection should be converted as same as DEM's, also use the same unit in foot.

b) For the "Streams" layer, it must be cleaned using ArcEdit; It also need to be made ready for use by executing the following functions under "Attribute Tools": "Assign HydroID"; "Generate From/To Node for Lines"; and "Find Downstream Line".

c) For DEM data, Z unit should be changed from "None" to "feet", same as ground units (x,y).

The process should be performed in the sequential order from Figures A-E1 to A-E14. During the process, using the default name is highly recommended. Also, be careful of the input file(s) for each function. Double check them before running.

The "map" on the page of current function is the result of previous function from Figures A-E2 to A-E14.

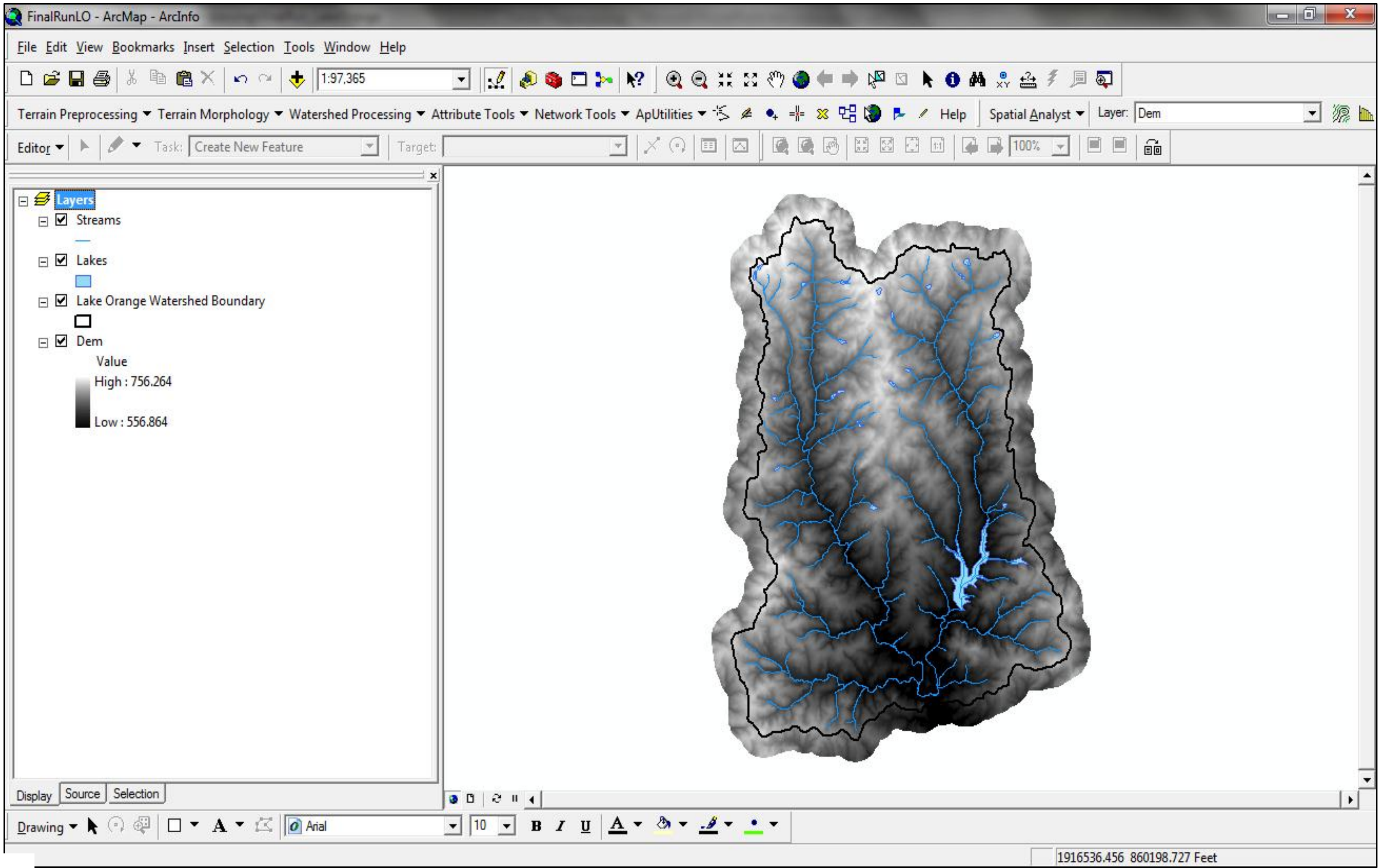


Figure A-E1: Add data and change the styles of display for vector layers

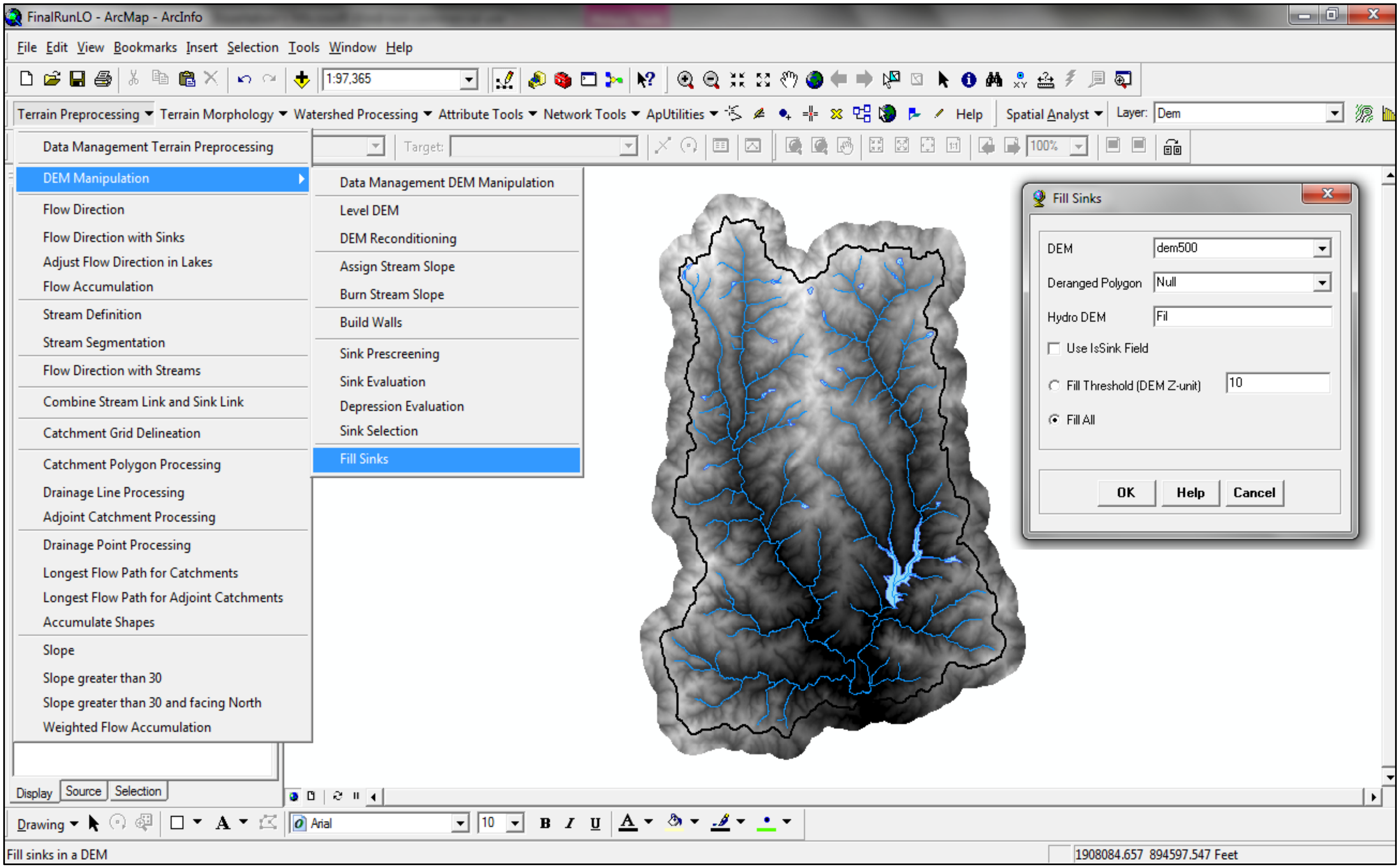


Figure A-E2: Fill Sinks

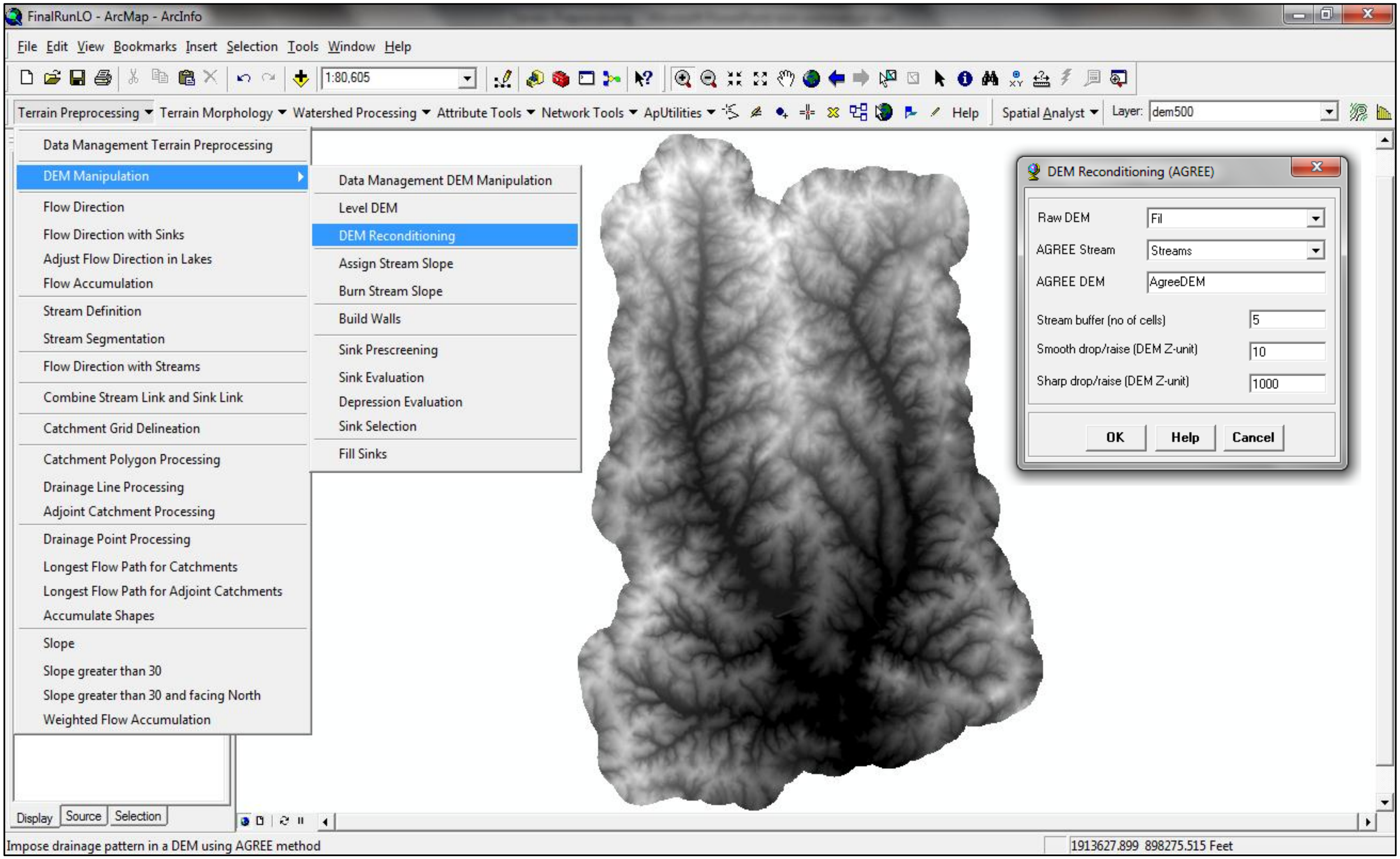


Figure A-E3: DEM Reconditioning

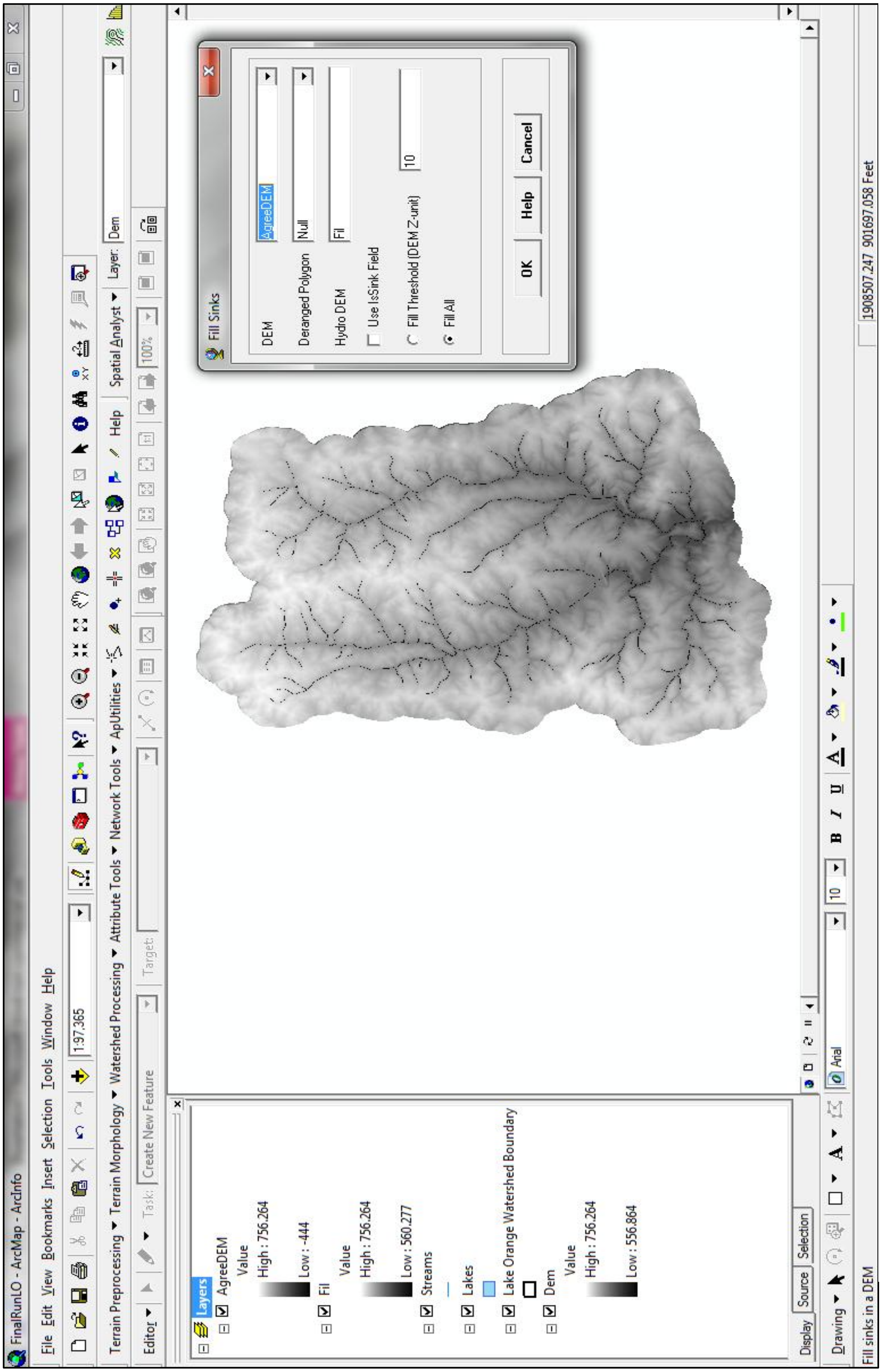


Figure A-E4: Fill Sinks

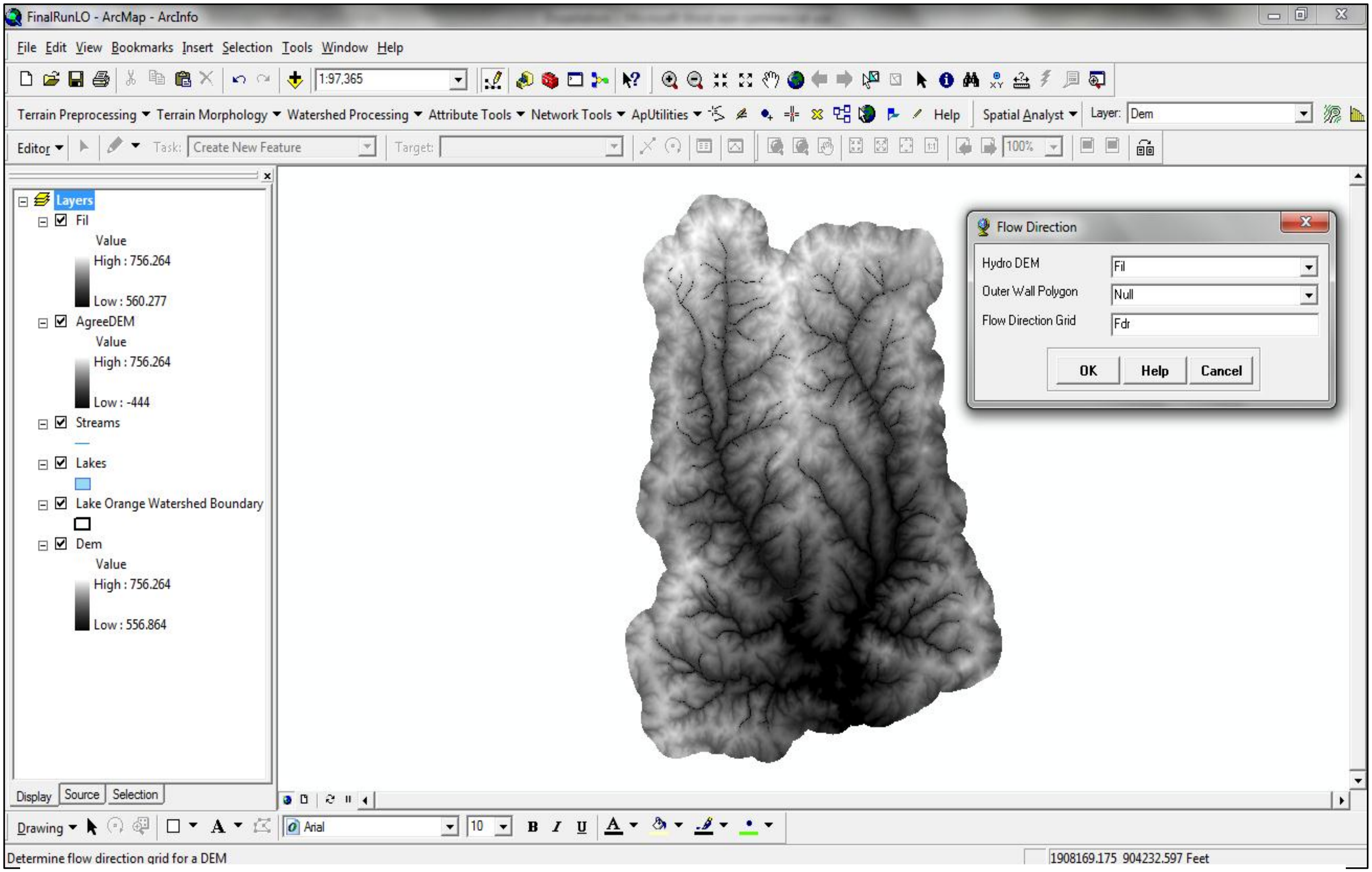


Figure A-E5: Flow Direction

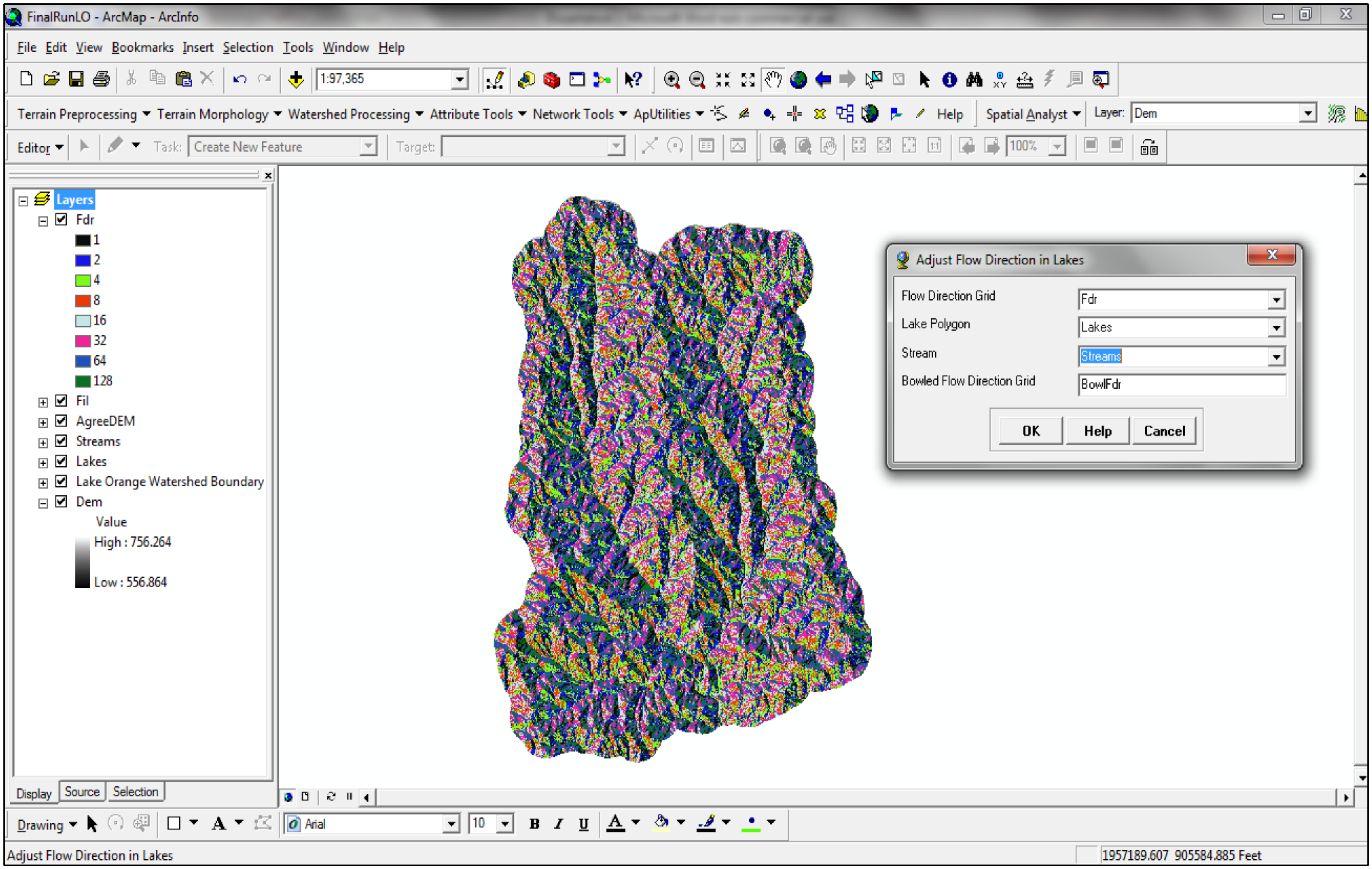


Figure A-E6: Adjust Flow Direction in Lakes

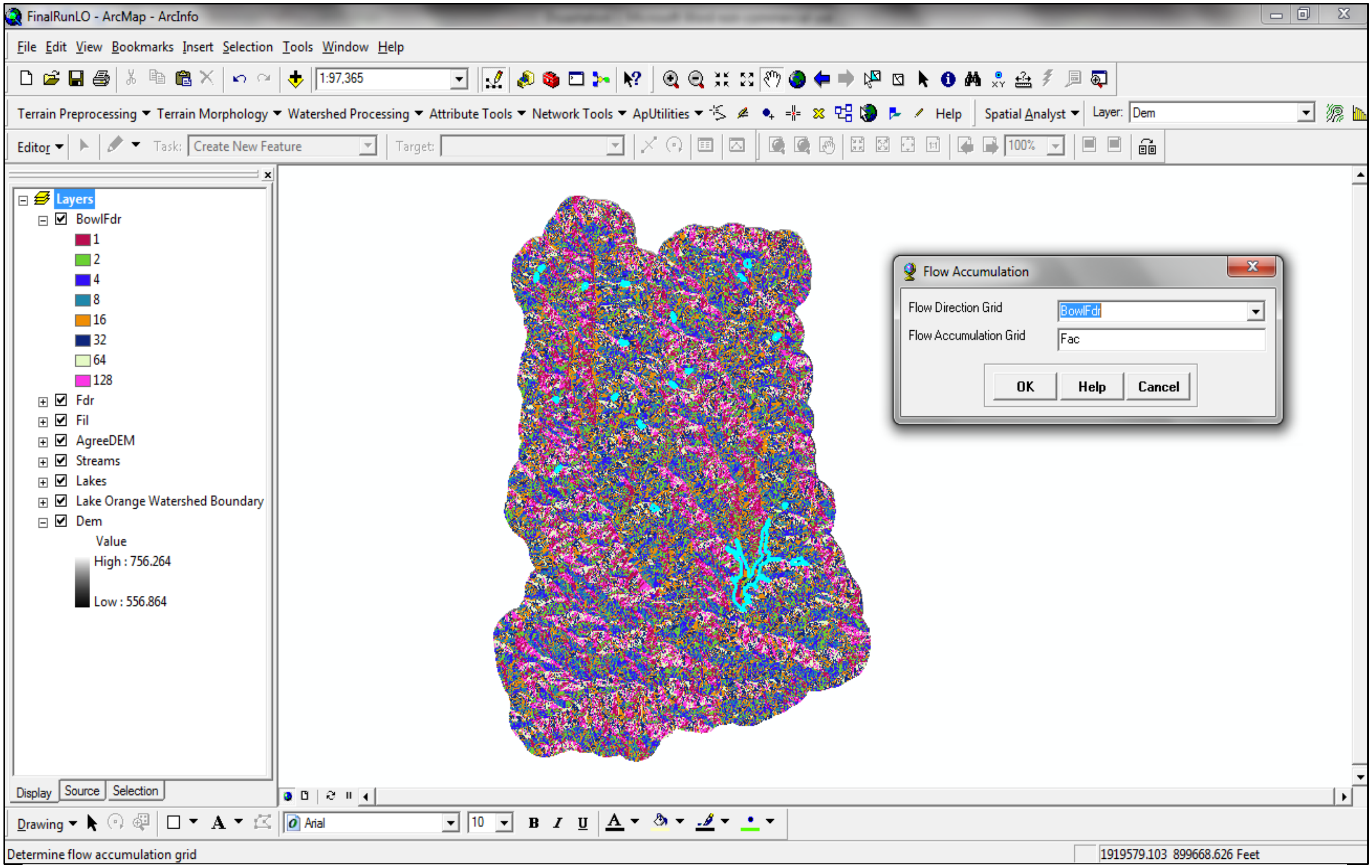


Figure A-E7: Flow Accumulation

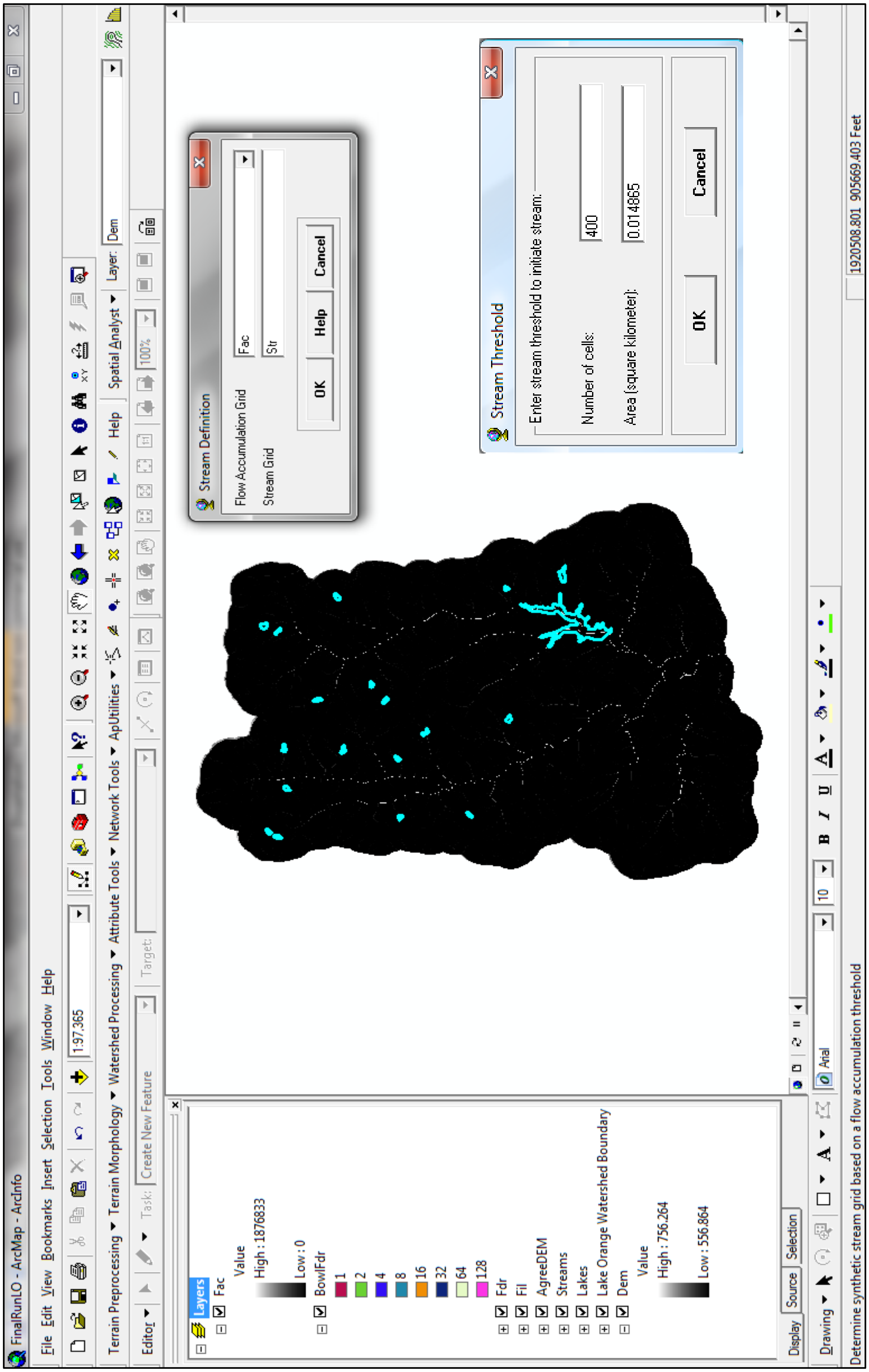


Figure A-E8: Stream Definition

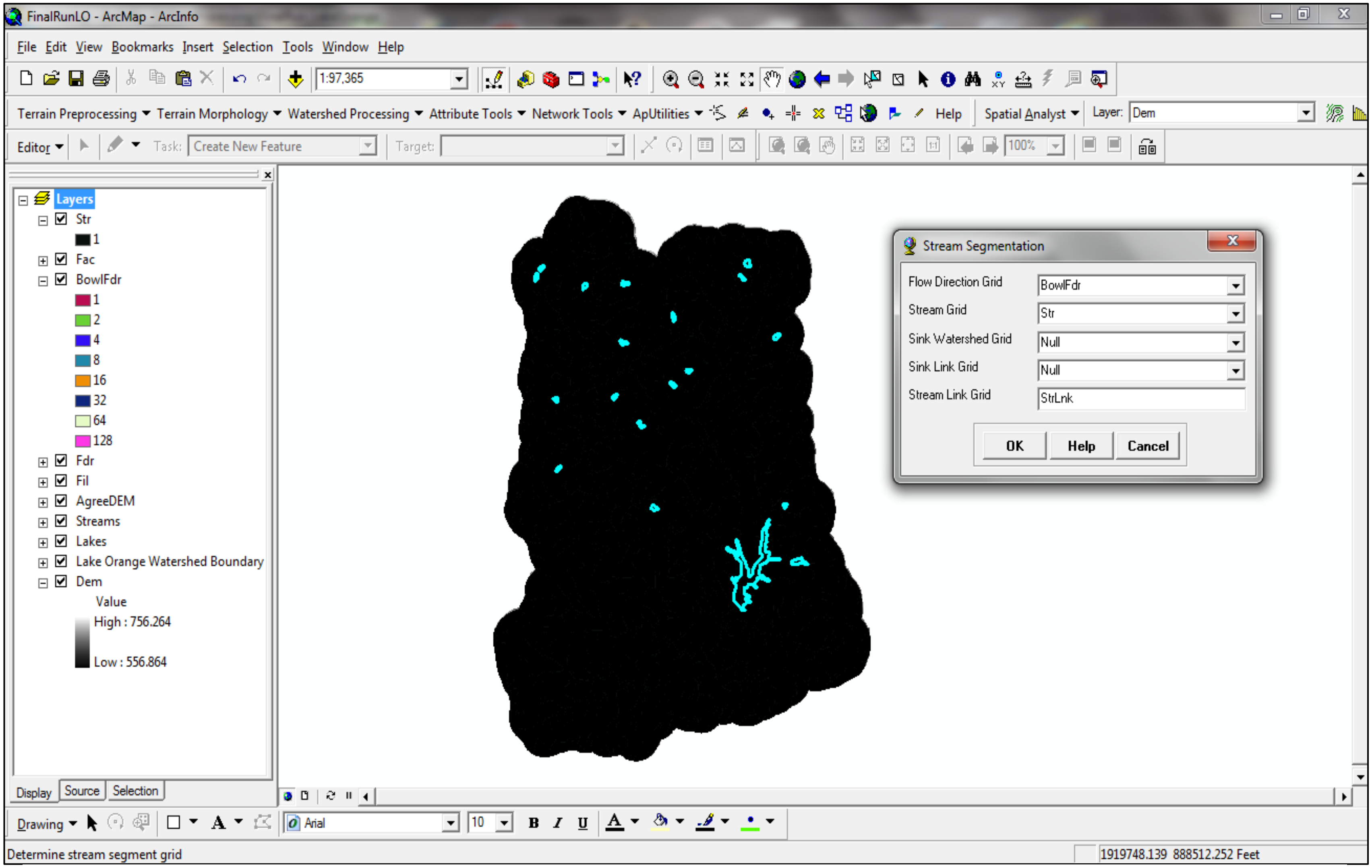


Figure A-E9: Stream Segmentation

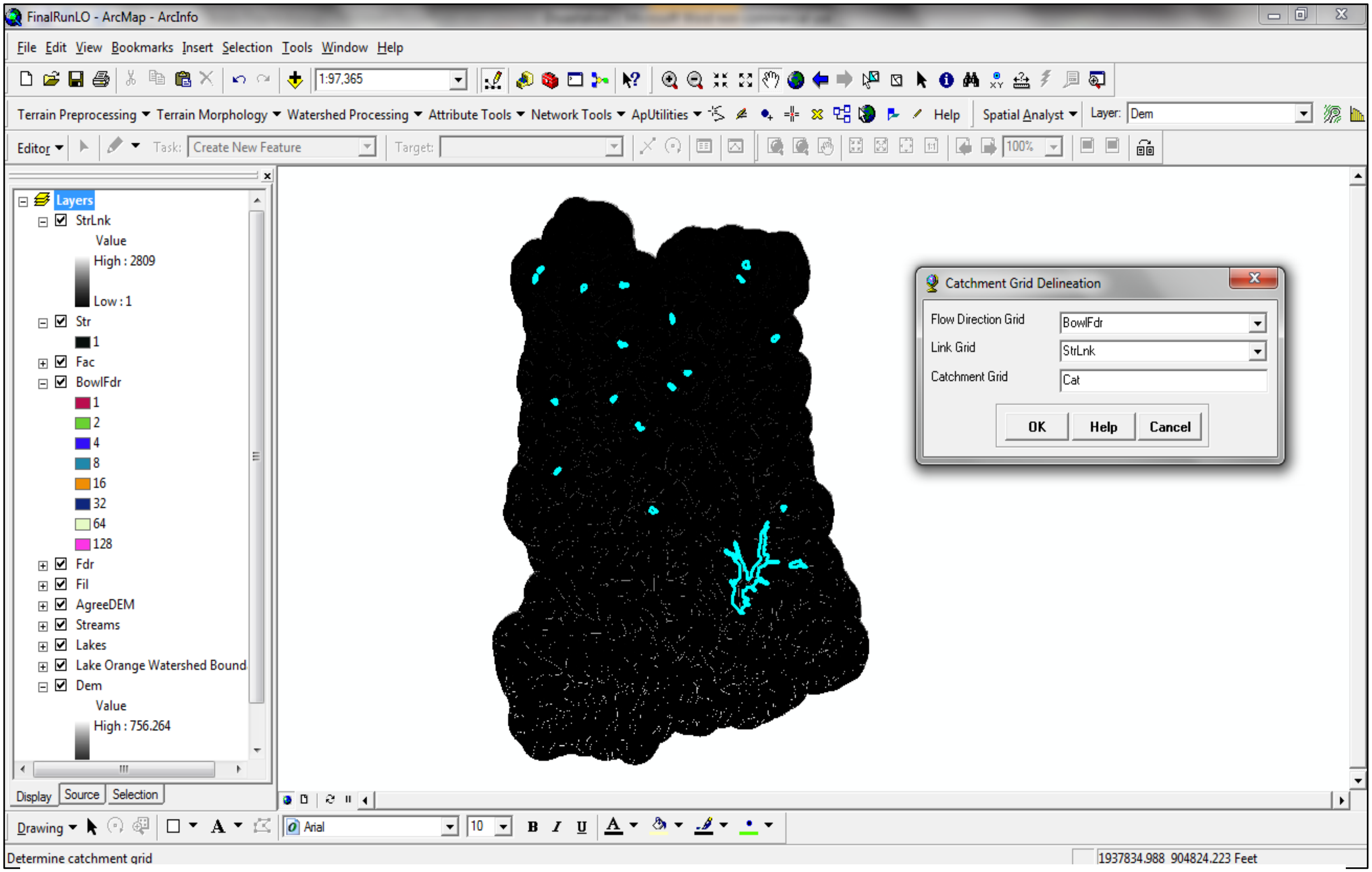


Figure A-E10: Catchment Grid Delineation

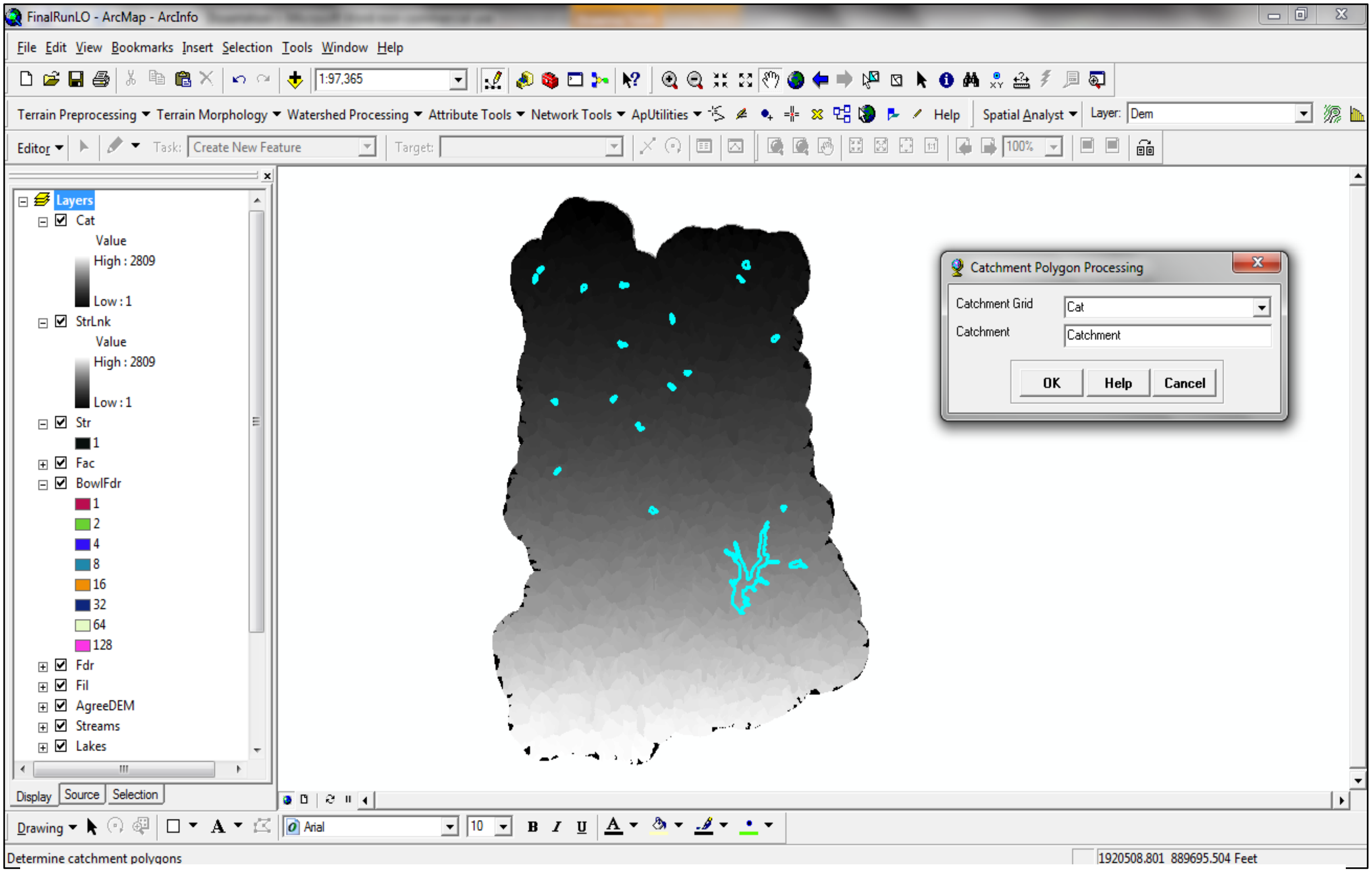


Figure A-E11: Catchment Polygon Processing

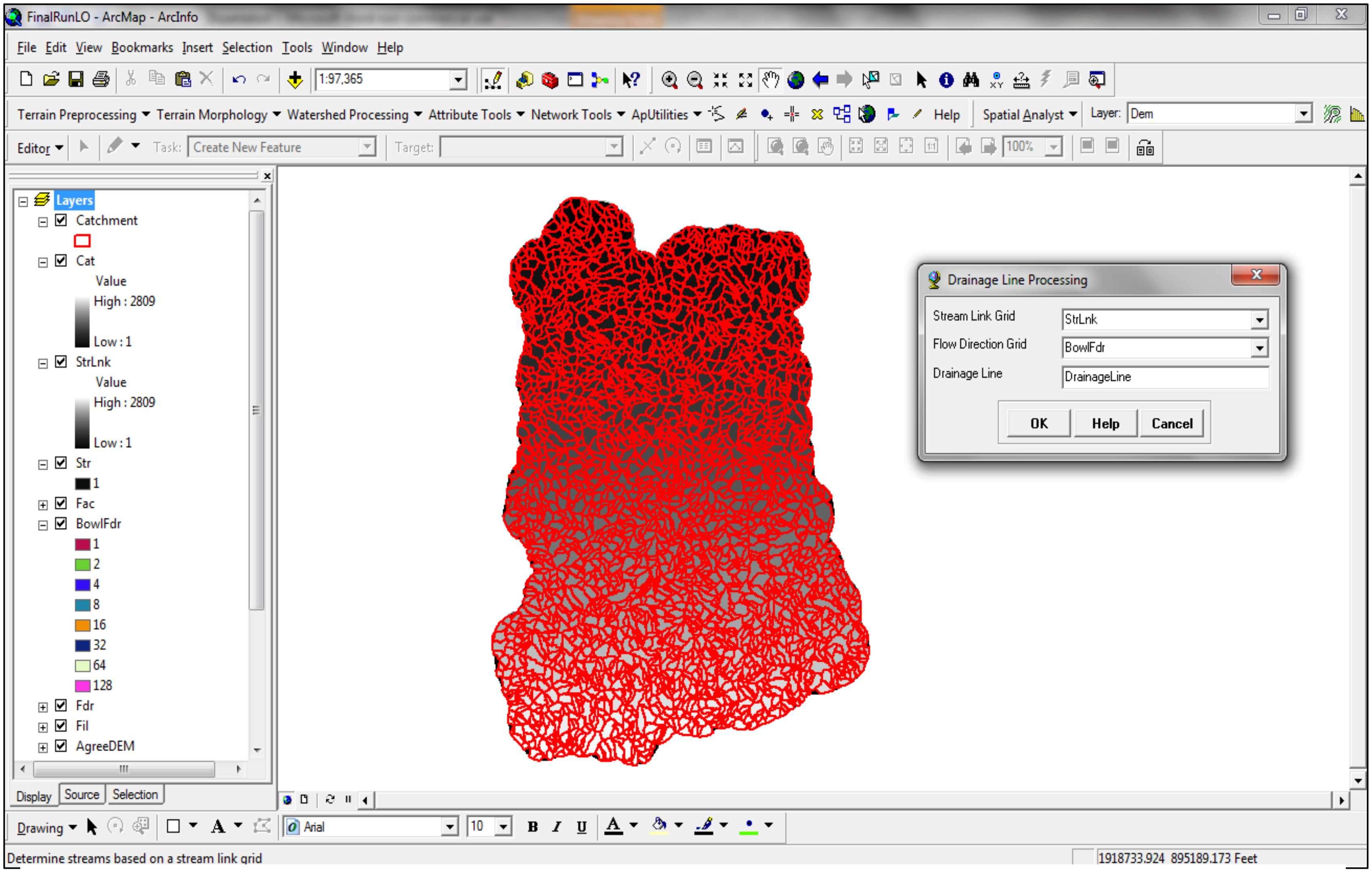


Figure A-E12: Drainage Line Processing

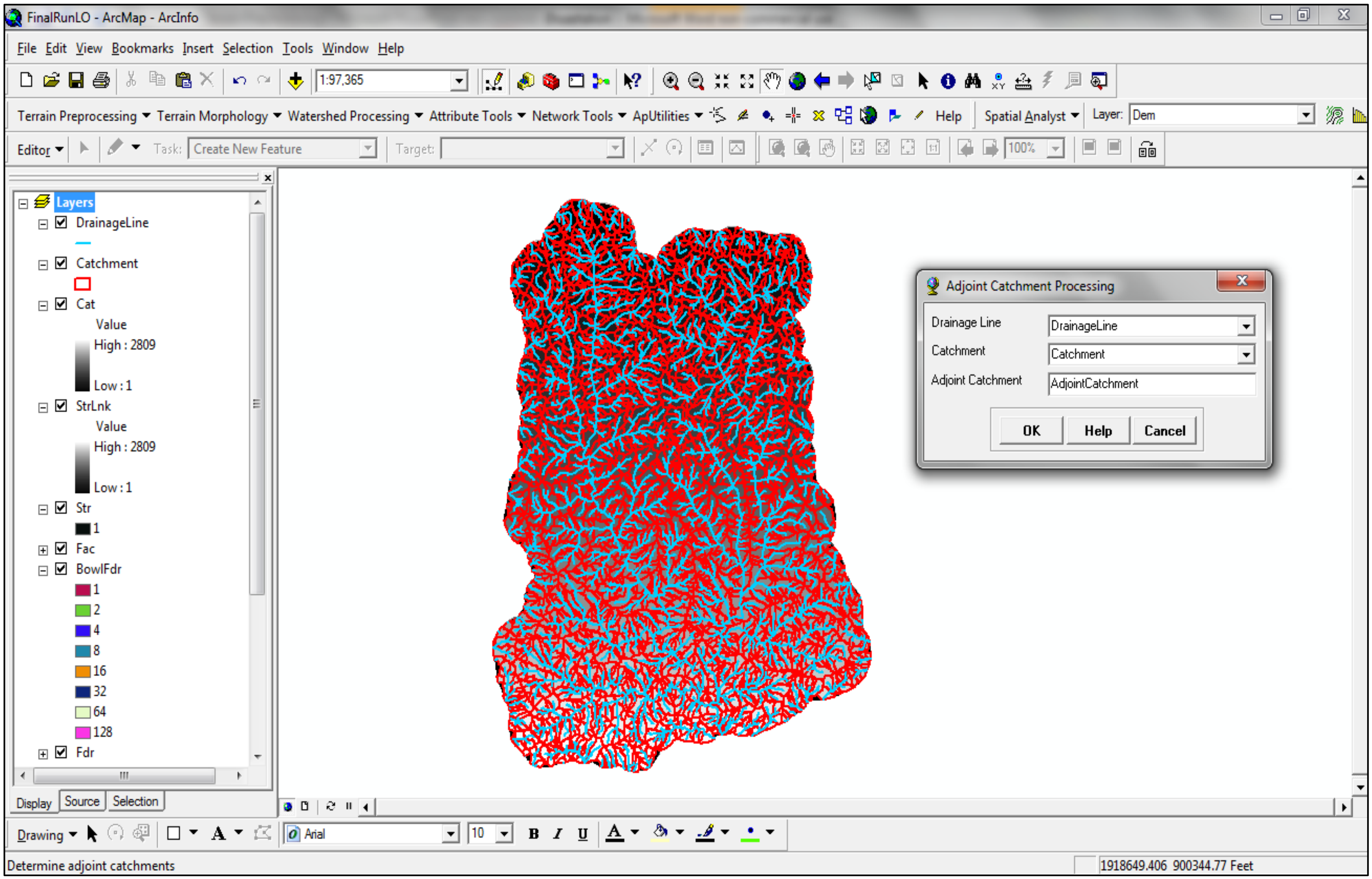


Figure A-E13: Adjoint Catchment Processing

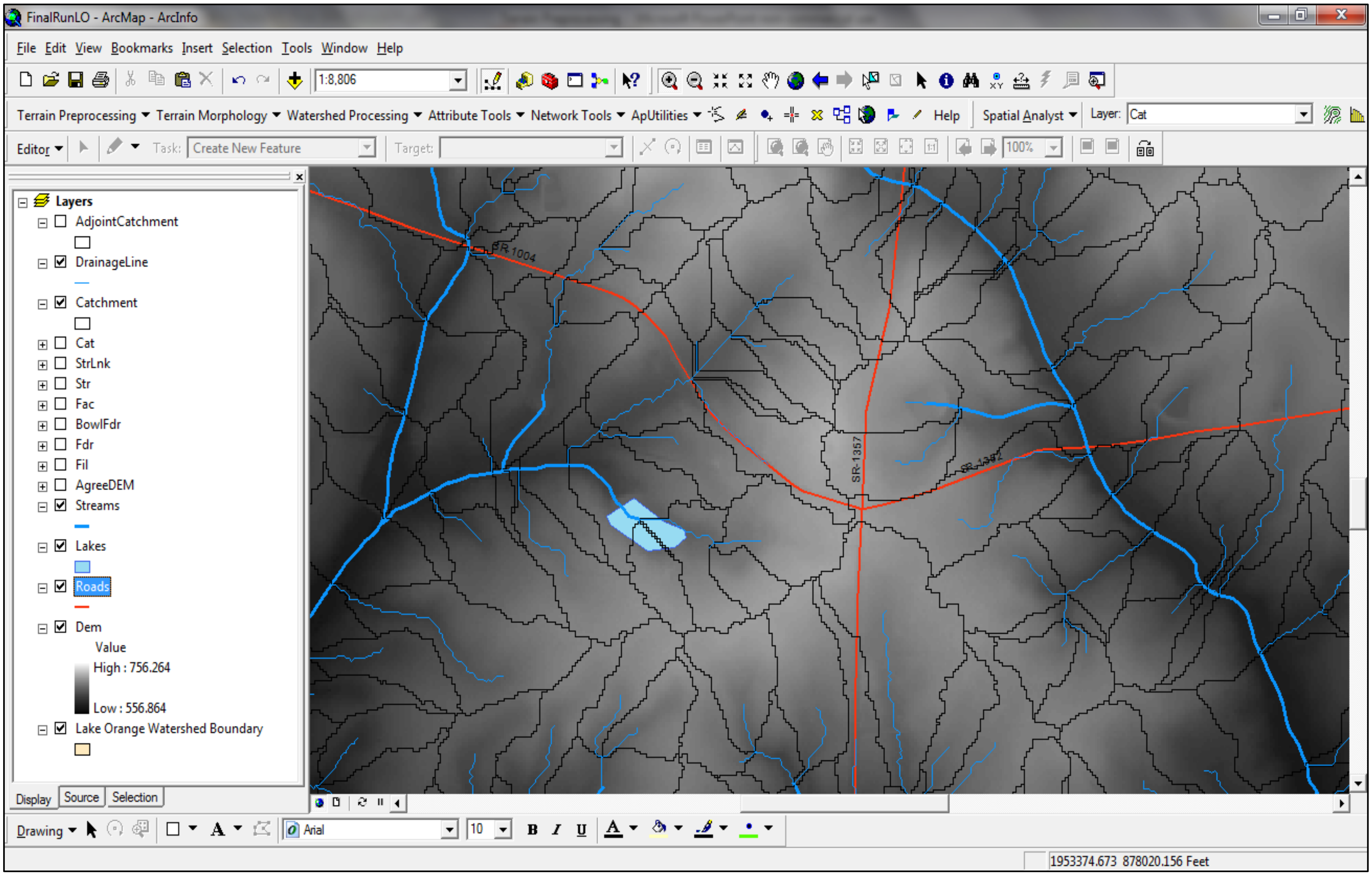


Figure A-E14: Final Results at the intersection of SR-1004, SR-1352, and SR-1357

APPENDIX F: LENGTHS OF FLOW PATHWAYS, ROAD DRAINAGE AREAS, AND TRAFFIC VOLUMES

# of Segment	# of Catchment	Road name	Road segment (m)	Length of flowpath (m)	DA (m^2)	Imp (m^2)	AADT (Vehicles/d)
1	19	NC-86	40.8	26.6	798.0	308.9	4500
2	52	NC-86	49.2	131.6	864.0	349.2	4500
3	52	NC-86	49.2	129.7	899.6	359.8	4500
5	75	SR-1361	59.1	57.9	1081.4	369.9	1000
6	75	SR-1422	50.6	44.9	701.5	290.2	300
9	89	SR-1371	15.5	125.5	556.9	115.6	600
10	101	SR-1371	60.5	101.5	1214.6	371.1	600
11	102	SR-1504	151.2	0.0	2764.8	829.4	800
12	102	SR-1504	85.7	51.6	1567.1	470.1	800
13	102	SR-1504	67.0	46.5	1226.1	367.8	800
14	104	SR-1506	46.4	85.4	655.8	265.8	500
15	106	SR-1371	69.8	51.1	1239.5	423.0	600
16	106	SR-1371	63.3	16.3	579.1	193.0	600
17	106	SR-1371		32.9	579.1	193.0	600
18	106	SR-1371	66.3	30.7	579.1	193.0	600
19	106	SR-1371		39.3	579.1	193.0	600
20	106	SR-1371	66.3	94.1	579.1	193.0	600
21	106	SR-1371		108.6	579.1	193.0	600
22	106	SR-1371	142.4	126.5	2622.4	891.8	600
23	115	SR-1361	59.2	149.7	1046.7	361.1	1000
24	115	SR-1361 SR-1371	58.4	87.7	1067.0	327.0	1000
27	116	SR-1371	152.2	62.7	3020.3	890.3	600
28	116	SR-1371	57.9	24.5	1059.3	353.1	600
29	116	SR-1371	57.9	42.2	785.0	387.3	600
30	125	SR-1506	15.8	109.2	492.6	113.2	500
31	126	SR-1371	62.3	102.9	921.7	371.6	600
32	126	SR-1371	53.9	54.4	986.5	328.8	600
33	126	SR-1371	53.9	55.8	986.5	328.8	600
34	126	SR-1371	53.9	39.8	986.5	328.8	600
35	126	SR-1371	53.9	44.3	986.5	328.8	600
36	126	SR-1371	53.9	45.5	986.5	328.8	600
37	128	SR-1361	22.6	49.6	1015.2	181.1	1000
38	132	SR-1501	48.8	130.6	240.0	240.0	600
39	132	SR-1501	48.8	116.2	240.0	240.0	600

# of Segment	# of Catchment	Road name	Road segment (m)	Length of flowpath (m)	DA (m^2)	Imp (m^2)	AADT (Vehicles/d)
40	133	SR-1576	103.7	41.3	526.3	526.3	300
41	133	SR-1576	36.5	0.0	168.3	168.3	300
42	136	NC-86	7.9	205.0	194.4	68.5	4300
43	138	SR-1371	206.7	114.3	2914.1	966.7	600
44	138	SR-1371		119.9	878.7	292.9	600
45	138	SR-1371	59.3	113.0	1085.4	361.8	600
46	138	SR-1371	59.3	197.5	1085.4	364.2	600
47	143	SR-1576	109.7	0.0	565.4	565.4	300
48	145	SR-1504	40.1	91.9	734.0	217.6	800
49	145	SR-1504	40.1	83.3	714.1	220.2	800
50	146	SR-1504	53.4	98.5	976.9	293.1	800
51	146	SR-1504	53.4	120.4	1020.0	295.3	800
52	153	SR-1361	65.1	244.5	1126.7	408.9	1000
53	153	SR-1361	65.1	128.7	1079.3	387.1	1000
54	153	SR-1361	112.7	110.1	1713.8	655.5	1000
55	153	SR-1361	43.8	81.0	771.6	265.0	1000
56	157	NC-86	57.3	67.5	1048.5	419.0	4500
57	157	NC-86	57.3	61.4	1047.6	437.2	4500
58	157	NC-86	57.3	92.9	1047.6	437.2	4500
59	157	NC-86	57.3	150.3	1047.6	437.2	4500
60	157	NC-86	24.1	0.0	439.7	176.4	4500
61	157	SR-1356	142.5	169.5	1053.7	1053.7	350
62	158	SR-1576	18.3	72.2	185.5	185.5	300
64	162	SR-1501	64.8	173.9	311.8	311.8	600
65	162	SR-1501	140.0	0.0	682.6	682.6	600
66	162	SR-1501	89.0	0.0	434.1	434.1	600
67	164	SR-1576	122.3	40.4	616.5	616.5	300
68	164	SR-1576	62.3	0.0	405.2	405.2	300
69	164	SR-1576	65.0	32.0	356.8	356.8	300
70	164	SR-1576	68.7	63.8	377.2	377.2	300
71	164	SR-1576	52.5	177.8	293.3	293.3	300
72	165	SR-1361	149.7	100.6	2750.7	916.0	1000
73	167	SR-1506	279.4	68.1	5077.2	1694.2	500
74	167	SR-1506	104.5	75.0	1757.7	640.2	500
75	169	SR-1576	121.9	95.7	689.6	689.6	300
76	170	SR-1504	68.5	119.2	1195.2	375.6	800
77	170	SR-1504	68.5	92.6	1219.3	375.6	800

# of Segment	# of Catchment	Road name	Road segment (m)	Length of flowpath (m)	DA (m^2)	Imp (m^2)	AADT (Vehicles/d)
78	170	SR-1504	68.5	103.5	1219.3	375.6	800
79	170	SR-1504	68.5	73.5	1219.3	375.6	800
80	170	SR-1504	68.5	106.0	1219.3	375.6	800
81	170	SR-1504	68.5	70.2	1013.4	361.1	800
82	170	SR-1576	52.3	67.3	287.2	287.2	300
83	170	SR-1576	52.3	64.7	287.2	287.2	300
84	170	SR-1576	67.4	80.8	355.1	355.1	300
85	174	SR-1506	18.1	121.8	538.7	128.1	500
86	174	SR-1506	65.0	99.9	1073.4	385.9	500
87	175	NC-86	13.9	0.0	262.4	102.5	4300
88	175	NC-86	57.8	0.0	927.8	398.3	4300
89	184	SR-1356	34.9	124.1	276.6	276.6	350
90	184	SR-1356	119.8	77.4	949.6	949.6	350
91	184	SR-1356	64.8	39.9	513.4	513.4	350
92	184	SR-1356	126.2	0.0	955.5	955.5	350
93	184	SR-1356	69.3	90.5	549.2	549.2	350
94	184	SR-1356	69.3	88.6	549.2	549.2	350
95	184	SR-1356	69.3	58.8	549.2	549.2	350
96	184	SR-1357	57.9	132.7	510.5	510.5	920
97	184	SR-1357	57.9	131.4	494.1	494.1	920
98	184	SR-1357	57.9	97.3	494.1	494.1	920
99	184	SR-1357	57.9	112.3	521.2	521.2	920
100	186	NC-86	58.3	76.1	1018.9	415.8	4300
101	186	NC-86	58.3	26.7	1043.1	426.6	4300
102	186	NC-86	20.7	11.9	422.4	174.9	4300
103	186	NC-86	35.1	0.0	658.7	245.1	4300
104	187	SR-1361	61.0	63.9	1080.8	369.4	1000
105	187	SR-1361	61.0	69.7	1116.4	372.1	1000
106	191	SR-1361	57.7	113.2	1000.6	348.6	1000
107	191	SR-1361	57.7	91.9	1057.1	352.4	1000
108	191	SR-1361	57.7	113.7	1132.7	354.3	1000
109	192	NC-86	23.0	92.1	334.0	104.9	4300
110	192	NC-86	23.0	57.6	431.9	203.9	4300
111	192	NC-86	23.0	0.0	454.8	180.4	4300
112	195	SR-1504	169.1	48.5	3462.8	940.1	800
113	195	SR-1504	82.1	14.3	1494.0	449.3	800
114	196	SR-1361	97.4	70.7	1788.7	595.9	1000

# of Segment	# of Catchment	Road name	Road segment (m)	Length of flowpath (m)	DA (m^2)	Imp (m^2)	AADT (Vehicles/d)
115	196	SR-1361	61.3	28.5	1005.3	376.3	1000
116	198	NC-86	27.5	11.0	454.4	199.0	4300
117	201	NC-86	37.8	13.9	734.6	281.8	4300
118	201	NC-86	37.8	24.4	665.7	276.0	4300
119	209	NC-86	53.8	87.8	1238.0	514.7	4300
120	209	NC-86	19.5	27.1	528.6	149.0	4300
121	209	NC-86	19.5	57.7	367.6	86.9	4300
122	213	NC-86	19.5	66.8	356.9	115.3	4300
123	213	NC-86	19.5	0.0	519.9	196.2	4300
124	213	NC-86	42.1	0.0	813.1	307.7	4300
125	216	SR-1501	272.3	0.0	1313.3	1313.3	600
126	216	SR-1501	44.0	19.2	214.4	214.4	600
127	216	SR-1576	44.0	47.2	214.4	214.4	300
128	216	SR-1576	44.0	65.0	214.4	214.4	300
129	222	NC-86	50.6	54.2	914.5	396.6	4300
130	222	NC-86	50.6	83.3	562.4	297.3	4300
131	224	SR-1357	68.7	20.5	293.0	209.3	920
132	224	SR-1357		38.0	294.8	209.3	920
133	229	NC-86	84.0	277.6	1565.4	628.8	4300
134	231	SR-1357	137.0	162.4	1141.9	824.2	920
135	231	SR-1357	28.8	106.6	245.6	175.5	920
137	238	SR-1357	62.4	120.2	531.1	380.6	920
138	238	SR-1357	62.4	144.9	532.8	380.6	920
139	243	NC-86	101.2	126.2	1859.5	743.8	4300
140	243	NC-86	50.8	111.2	929.8	371.9	4300
141	243	NC-86	50.8	59.6	929.8	371.9	4300
142	243	NC-86	50.8	42.0	907.5	371.9	4300
143	243	NC-86	41.4	34.6	632.6	297.7	4300
144	243	SR-1355	37.4	37.5	159.6	159.6	600
145	243	SR-1501	36.8	30.0	157.0	157.0	600
146	243	SR-1501	47.2	8.5	230.2	230.2	600
147	243	SR-1501	42.1	0.0	205.5	205.5	600
148	244	NC-86	15.7	46.6	410.7	132.2	4300
149	244	NC-86	15.7	15.3	287.2	114.9	4300
150	244	NC-86	15.7	18.3	259.2	114.9	4300
151	244	NC-86	27.3	0.0	873.8	236.7	4300
152	244	SR-1355	123.9	81.1	604.5	604.5	600

# of Segment	# of Catchment	Road name	Road segment (m)	Length of flowpath (m)	DA (m^2)	Imp (m^2)	AADT (Vehicles/d)
153	245	NC-86	70.5	70.7	1235.7	514.6	4300
154	245	NC-86	70.5	79.1	1289.4	515.7	4300
155	245	NC-86	70.5	80.0	1289.4	515.7	4300
156	245	NC-86	70.5	44.5	1251.8	515.7	4300
157	245	SR-1504	72.4	53.0	1331.0	376.8	800
158	245	SR-1504	60.9	28.5	1114.0	334.2	800
159	245	SR-1504	61.9	29.0	1131.9	339.6	800
160	245	SR-1504	140.3	67.1	2529.9	772.7	800
161	247	SR-1358	80.5	221.4	745.4	460.8	800
162	247	SR-1358	55.3	150.1	539.0	349.4	800
163	252	NC-86	41.7	80.2	492.5	241.1	4300
164	252	NC-86	41.7	65.2	505.9	321.3	4300
165	252	NC-86	52.9	78.0	1000.2	359.6	4300
166	265	SR-1361	236.3	0.0	4541.8	1449.7	1000
167	265	SR-1361	6.1	222.9	200.4	28.7	1000
168	268	SR-1357	102.0	0.0	870.3	621.6	920
169	268	SR-1357	77.1	86.5	658.0	470.0	920
170	268	SR-1357	75.3	165.4	632.9	452.4	920
171	269	SR-1361	73.0	51.2	1734.5	429.3	1000
172	269	SR-1361	100.1	0.0	1430.9	647.2	1000
173	272	SR-1355	104.2	158.0	508.4	508.4	600
174	272	SR-1355	90.2	176.4	439.0	439.0	600
175	274	SR-1358 SR-1361	260.5	163.9	2298.5	1599.8	800
176	274	SR-1358	31.4	95.6	701.7	193.0	800
178	277	NC-86	20.9	46.3	526.6	171.3	4300
179	278	SR-1508	77.1	83.5	1425.4	469.8	500
180	278	SR-1508	85.0	43.2	1554.3	518.1	500
181	278	SR-1508	67.1	51.9	1227.3	409.1	500
182	278	SR-1508	149.8	56.5	2715.1	913.0	500
183	282	SR-1357	89.2	205.3	771.1	550.6	920
184	285	SR-1361	115.2	0.0	1851.5	669.8	1000
185	290	SR-1357	102.5	215.9	878.7	627.3	920
186	292	SR-1508	62.4	29.8	1225.8	380.5	500
187	292	SR-1508	150.2	0.0	2747.5	915.8	500
188	292	SR-1508	167.2	95.2	3042.7	1020.8	500
189	294	NC-86	22.5	51.5	411.5	164.6	4300
190	294	NC-86	22.5	20.8	411.5	164.6	4300

# of Segment	# of Catchment	Road name	Road segment (m)	Length of flowpath (m)	DA (m^2)	Imp (m^2)	AADT (Vehicles/d)
191	294	NC-86	23.1	24.0	423.0	169.2	4300
192	294	NC-86	222.6	0.0	4133.3	1740.5	4300
193	294	SR-1354	54.0	52.4	385.3	226.1	800
194	294	SR-1354	45.8	60.2	384.5	266.2	800
195	294	SR-1504	45.8	103.2	384.5	266.2	800
197	299	SR-1361 SR-1370	224.1	112.5	3909.7	1335.9	1000
199	300	SR-1354	27.3	137.0	199.0	141.3	800
200	301	SR-1355	40.2	61.3	191.4	191.4	600
201	301	SR-1355	40.2	122.3	202.0	202.0	600
202	302	NC-86	46.4	27.3	629.8	303.6	4300
203	303	SR-1355	248.6	28.2	1212.1	1212.1	600
204	303	SR-1355	34.5	19.3	168.5	168.5	600
205	304	NC-86	41.4	52.2	979.5	342.5	4300
206	305	SR-1358	201.2	58.8	1935.5	1219.3	800
207	305	SR-1358	72.8	27.3	710.1	443.8	800
208	305	SR-1358	72.8	0.0	690.8	436.8	800
209	306	SR-1358	15.9	45.6	165.8	102.8	800
210	307	NC-86	72.1	0.0	1440.4	551.3	4300
211	309	SR-1358	59.5	20.7	588.9	363.8	800
212	309	SR-1358	59.5	0.0	580.0	362.5	800
213	309	SR-1358	69.7	32.6	680.1	425.1	800
214	309	SR-1358	69.7	53.6	680.1	425.1	800
215	314	NC-86	393.0	0.0	6838.2	2843.9	4300
216	314	NC-86	101.8	48.7	1861.6	744.6	4300
217	314	SR-1508	127.1	0.0	2320.8	752.3	500
218	315	SR-1508	51.9	172.1	993.1	316.5	500
219	315	SR-1508	38.4	0.0	676.2	234.1	500
220	318	SR-1357	56.3	122.3	454.3	324.7	920
221	318	SR-1357	56.3	36.0	480.2	343.0	920
222	318	SR-1357	38.2	26.7	375.0	260.0	920
223	324	SR-1354	45.4	104.5	360.3	249.4	800
224	324	SR-1354	45.4	78.4	360.3	249.4	800
225	324	SR-1354	45.4	49.3	360.3	249.4	800
226	324	SR-1354	45.4	39.3	375.8	256.7	800
227	326	SR-1361	103.1	38.0	1921.0	640.3	1000
228	326	SR-1361	57.1	0.0	1041.7	342.9	1000
229	326	SR-1370	23.7	55.8	466.9	157.0	300

# of Segment	# of Catchment	Road name	Road segment (m)	Length of flowpath (m)	DA (m^2)	Imp (m^2)	AADT (Vehicles/d)
230	327	SR-1358	23.6	0.0	272.1	155.8	800
231	328	SR-1354	224.3	36.8	1778.5	1231.3	800
232	328	SR-1354	50.2	6.1	396.7	274.6	800
233	335	SR-1361	78.9	51.0	1582.6	482.2	1000
234	339	SR-1358	23.2	24.4	226.1	140.9	800
235	339	SR-1358	36.5	0.0	292.5	203.6	800
236	342	SR-1358	366.3	0.0	3594.1	2240.2	800
237	344	SR-1355	42.7	0.0	210.0	210.0	600
238	345	SR-1355	33.5	55.6	163.3	163.3	600
239	345	SR-1355	210.9	67.2	1024.7	1024.7	600
240	347	SR-1355	56.3	53.9	274.7	274.7	600
241	347	SR-1355	56.3	76.6	274.7	274.7	600
242	347	SR-1355	56.3	99.5	274.7	274.7	600
243	347	SR-1355	56.3	43.6	274.7	274.7	600
244	347	SR-1355	56.3	41.1	274.7	274.7	600
245	347	SR-1355 SR-1357	154.0	106.8	922.4	801.1	920
248	353	SR-1357	50.9	88.6	450.3	316.1	920
249	353	SR-1357	50.9	38.5	393.3	294.2	920
250	353	SR-1357	50.9	74.4	434.8	310.6	920
251	353	SR-1357	50.9	109.0	434.8	310.6	920
252	353	SR-1357	50.9	157.0	434.8	310.6	920
253	354	NC-86	25.5	101.9	781.3	213.7	4300
254	371	SR-1361	78.1	82.6	1257.7	466.7	1000
255	372	SR-1354	27.5	0.0	218.3	151.1	800
256	372	SR-1354	39.7	23.4	376.5	255.9	800
257	373	NC-86	283.2	0.0	4765.2	2038.3	4300
259	374	NC-86		70.1	71.2	39.7	4300
260	375	SR-1354	51.4	47.1	274.6	204.6	800
261	375	SR-1354	217.0	69.7	1703.1	1180.7	800
262	378	SR-1361	53.9	0.0	745.4	302.5	1000
264	388	NC-86	220.9	0.0	3794.6	1586.4	4300
266	391	SR-1357	60.5	195.8	516.3	368.8	920
267	391	SR-1357	60.5	123.7	516.3	368.8	920
268	391	SR-1357	51.2	101.2	396.0	286.0	920
269	391	SR-1357 SR-1355	68.6	106.3	559.0	418.0	920
270	393	SR-1354	36.6	240.1	307.4	211.0	800

# of Segment	# of Catchment	Road name	Road segment (m)	Length of flowpath (m)	DA (m^2)	Imp (m^2)	AADT (Vehicles/d)
271	396	SR-1361	49.1	0.0	1155.3	325.4	1000
272	398	SR-1357	44.9	34.5	399.7	282.2	920
273	398	SR-1357	181.4	127.9	1548.4	1106.0	920
274	404	NC-86	11.3	52.9	423.6	86.2	4300
275	404	NC-86	28.7	51.2	601.9	218.8	4300
276	404	NC-86	26.6	71.2	506.8	202.7	4300
277	404	NC-86	12.4	72.4	261.2	94.3	4300
278	404	SR-1506	192.1	153.6	1562.9	1132.1	500
281	410	SR-1506	12.6	0.0	116.0	81.2	500
282	416	SR-1358	160.3	0.0	1488.0	953.8	800
283	417	NC-86	32.1	78.1	506.8	202.7	4300
284	417	NC-86	32.1	55.5	506.8	202.7	4300
285	417	NC-86	32.1	130.3	816.6	318.8	4300
286	418	SR-1546	51.4	30.7	437.4	313.1	300
287	420	SR-1358	108.0	196.5	1142.0	683.5	800
288	433	SR-1357	53.7	173.0	458.2	327.3	920
289	433	SR-1357	53.7	103.6	458.2	327.3	920
290	433	SR-1357	53.7	133.9	458.2	327.3	920
291	433	SR-1357	53.7	167.8	458.1	327.3	920
292	436	SR-1358	35.6	84.8	269.7	166.8	800
293	436	SR-1358	62.5	54.8	665.2	423.7	800
294	449	SR-1354	82.8	68.7	656.5	454.5	800
295	449	SR-1354	82.8	35.8	656.5	454.5	800
296	449	SR-1354	82.8	50.9	656.5	454.5	800
297	449	SR-1354	82.8	133.7	650.2	453.2	800
299	453	NC-86	108.6	114.4	2107.3	807.8	4300
300	453	SR-1506	151.2	160.9	1235.7	919.5	500
302	455	SR-1357	19.7	61.5	282.1	167.7	920
303	461	NC-86	102.9	0.0	1695.5	738.2	4300
304	461	NC-86	31.7	36.5	602.4	227.5	4300
305	462	NC-86	62.6	21.9	1283.8	520.0	4300
306	462	NC-86	62.6	0.0	1059.9	424.0	4300
307	462	NC-86	62.6	0.0	1090.9	424.8	4300
308	465	SR-1361	63.5	191.1	1244.6	395.7	1000
309	480	SR-1354	360.4	0.0	2865.8	1978.7	800
310	488	SR-1358	445.1	0.0	4351.6	2715.4	800
311	489	SR-1358	53.9	45.3	532.2	333.0	800

# of Segment	# of Catchment	Road name	Road segment (m)	Length of flowpath (m)	DA (m^2)	Imp (m^2)	AADT (Vehicles/d)
312	489	SR-1358	53.9	67.6	525.8	328.6	800
313	489	SR-1358	53.9	66.1	525.8	328.6	800
314	489	SR-1358	135.9	109.0	1312.5	824.6	800
315	490	SR-1361	59.8	113.2	1020.2	347.4	1000
316	490	SR-1361	59.8	80.1	1065.6	355.2	1000
317	490	SR-1361	48.3	86.0	883.3	294.4	1000
318	490	SR-1361	48.3	96.6	883.3	294.4	1000
319	490	SR-1361	48.3	107.8	832.9	311.8	1000
321	502	SR-1361	56.9	165.3	1148.4	348.8	1000
322	502	SR-1361	56.9	174.4	1039.9	346.6	1000
323	502	SR-1361	56.9	84.4	1039.9	346.6	1000
324	502	SR-1361	56.9	96.6	1107.7	346.6	1000
325	507	SR-1361	54.7	121.5	932.3	333.3	1000
326	507	SR-1361	43.3	42.2	792.4	264.1	1000
327	507	SR-1361	43.3	93.9	792.4	264.1	1000
328	508	SR-1357	47.7	143.2	406.9	290.7	920
329	508	SR-1357	56.3	86.7	402.7	321.5	920
330	508	SR-1357	52.9	57.8	451.6	322.6	920
331	508	SR-1357	52.9	48.4	451.6	322.6	920
332	508	SR-1357	52.9	107.8	451.6	322.6	920
333	508	SR-1357	52.9	103.3	428.8	307.5	920
334	510	SR-1358	57.2	76.9	484.5	326.8	800
335	510	SR-1358	57.2	74.6	568.0	358.4	800
336	523	SR-1357	63.4	34.1	570.8	406.5	920
337	523	SR-1357	106.3	43.7	864.2	617.3	920
338	525	NC-86	218.0	0.0	3992.5	1581.4	4900
339	528	SR-1354	51.6	237.5	408.7	283.0	800
340	528	SR-1354	51.6	248.6	396.3	279.6	800
341	532	SR-1353	48.1	110.1	293.3	293.3	600
342	532	SR-1353	48.1	78.3	293.3	293.3	600
343	532	SR-1353	48.1	46.6	293.3	293.3	600
344	532	SR-1353	48.1	32.9	303.6	303.6	600
345	534	SR-1354	333.6	0.0	2643.3	1830.3	800
346	535	NC-86	55.8	116.7	986.8	407.4	4300
347	535	NC-86	55.8	124.0	1020.6	408.2	4300
348	535	NC-86	55.8	79.0	1049.1	414.0	4300
349	535	SR-1353	52.4	115.7	296.9	296.9	600

# of Segment	# of Catchment	Road name	Road segment (m)	Length of flowpath (m)	DA (m^2)	Imp (m^2)	AADT (Vehicles/d)
350	535	SR-1353	52.4	66.4	327.5	327.5	600
351	537	SR-1353	55.8	250.4	321.6	321.6	600
352	537	SR-1353	55.8	188.9	340.5	340.5	600
353	537	SR-1353	55.8	85.1	340.5	340.5	600
354	537	SR-1353	55.8	61.8	340.5	340.5	600
355	537	SR-1353	55.8	70.6	340.5	340.5	600
356	537	SR-1353	55.8	159.7	340.5	340.5	600
357	537	SR-1353	55.8	226.6	348.2	348.2	600
358	538	NC-86	70.3	77.0	1232.6	513.1	4300
359	538	NC-86	70.3	52.8	1096.2	486.4	4900
360	539	NC-86	21.0	14.6	594.2	190.1	4900
361	540	SR-1353	189.9	0.0	1156.4	1156.4	600
362	540	SR-1353	61.9	71.3	377.2	377.2	600
363	547	SR-1359	10.3	337.1	72.1	72.1	400
364	548	SR-1358	44.7	108.3	448.1	275.6	800
365	548	SR-1358	85.7	120.3	832.4	521.9	800
366	549	SR-1354	58.5	33.7	463.6	321.0	800
367	549	SR-1354	45.6	38.3	374.5	258.3	800
368	550	SR-1354	50.0	155.3	405.6	277.6	800
369	552	SR-1353	53.6	25.2	333.3	333.3	600
370	552	SR-1353	53.6	45.3	326.7	326.7	600
371	552	SR-1353	53.6	21.7	326.7	326.7	600
372	552	SR-1353	106.9	64.2	638.8	638.8	600
373	555	SR-1353	38.3	22.3	221.0	221.0	600
374	555	SR-1353	25.9	12.2	155.9	155.9	600
375	561	SR-1358	1.2	53.7	101.2	28.3	800
376	562	SR-1357	54.9	113.6	469.3	335.2	1300
377	562	SR-1357	54.9	101.2	469.3	335.2	920
378	562	SR-1357	54.9	103.5	467.6	333.4	920
379	565	SR-1359	48.6	184.9	277.9	277.9	400
380	565	SR-1359	58.3	101.8	355.5	355.5	400
381	565	SR-1359	85.3	92.8	538.2	538.2	400
382	567	SR-1354	92.4	29.6	718.7	498.4	800
383	567	SR-1354	116.7	71.9	924.5	640.3	800
384	571	SR-1353	40.7	84.0	255.2	255.2	600
385	571	SR-1353	42.9	81.1	257.0	257.0	600
386	575	SR-1353	23.5	109.6	152.7	152.7	600

# of Segment	# of Catchment	Road name	Road segment (m)	Length of flowpath (m)	DA (m^2)	Imp (m^2)	AADT (Vehicles/d)
387	575	SR-1353	54.7	115.2	333.2	333.2	600
388	575	SR-1353	109.3	136.9	674.5	674.5	600
389	577	SR-1361	42.1	0.0	769.8	256.6	1000
390	579	SR-1359	95.6	0.0	564.5	564.5	400
391	579	SR-1358	67.7	81.3	635.7	401.6	800
392	579	SR-1358	67.7	85.5	660.1	412.6	800
393	579	SR-1358	313.9	0.0	2901.9	1882.1	800
394	585	NC-86	62.7	62.8	1106.4	457.8	4900
395	585	NC-86	62.7	76.5	1146.2	458.5	4900
396	585	NC-86	62.7	162.2	1152.4	458.5	4900
397	592	SR-1353	58.3	56.5	345.0	345.0	600
398	592	SR-1353	58.3	53.0	355.2	355.2	600
399	596	SR-1359	54.3	131.3	285.8	285.8	400
400	596	SR-1359	54.3	145.7	331.0	331.0	400
401	596	SR-1359	54.3	131.8	331.0	331.0	400
402	596	SR-1359	54.3	74.9	331.0	331.0	400
403	596	SR-1358	16.4	0.0	346.9	171.6	800
405	601	SR-1357 SR-1354	279.6	88.6	2060.2	1604.6	1300
406	601	SR-1357	76.2	58.5	474.9	425.3	1300
408	601	SR-1358	63.0	51.7	614.4	384.0	800
409	601	SR-1358	63.0	61.9	584.7	365.4	800
410	606	NC-86	155.9	0.0	2884.8	1140.5	4900
411	613	SR-1359	44.7	94.7	266.9	266.9	400
412	613	SR-1359	49.3	128.9	300.6	300.6	400
413	613	SR-1359	49.3	101.6	300.6	300.6	400
414	613	SR-1359	49.3	55.8	314.7	314.7	400
415	614	SR-1357	194.1	0.0	1162.1	1052.2	1300
416	614	SR-1357	118.1	103.5	720.1	648.1	1300
417	619	SR-1359	18.4	76.1	109.8	109.8	400
418	619	SR-1359	166.4	38.5	1006.9	1006.9	400
419	619	SR-1359	42.9	28.1	261.7	261.7	400
420	629	NC-86	60.9	102.8	1156.4	478.5	4900
421	629	NC-86	60.9	91.0	839.2	394.4	4900
422	634	SR-1353	54.8	108.2	333.8	333.8	600
423	634	SR-1353	54.8	74.0	333.8	333.8	600
424	634	SR-1353	54.8	50.9	333.8	333.8	600
425	634	SR-1353	66.7	69.4	404.1	404.1	600

# of Segment	# of Catchment	Road name	Road segment (m)	Length of flowpath (m)	DA (m^2)	Imp (m^2)	AADT (Vehicles/d)
426	635	SR-1359	92.4	67.9	564.2	564.2	400
427	635	SR-1359	96.8	35.7	590.2	590.2	400
428	635	SR-1359	76.3	28.2	464.9	464.9	400
429	636	SR-1353	54.2	67.8	329.4	329.4	600
430	636	SR-1353	54.2	75.2	330.3	330.3	600
431	636	SR-1353	54.2	58.7	330.3	330.3	600
432	636	SR-1353	54.2	0.0	330.3	330.3	600
433	636	SR-1353	246.6	0.0	1506.8	1506.8	600
434	644	NC-86	71.1	112.8	1604.1	579.7	4900
435	644	NC-86	71.1	102.0	1249.5	499.8	4900
436	644	NC-86	71.1	134.7	1301.5	518.3	4900
437	658	SR-1359	158.6	148.9	966.1	966.1	400
438	659	NC-86	66.4	36.9	1154.3	467.0	4900
439	659	NC-86	66.4	74.3	1214.0	485.6	4900
440	659	NC-86	66.4	20.7	1257.1	495.9	4900
441	662	SR-1359	101.8	128.5	620.8	620.8	400
442	662	SR-1359	50.9	25.3	310.4	310.4	400
443	662	SR-1359	108.1	0.0	659.2	659.2	400
444	662	SR-1359	36.6	62.0	223.3	223.3	400
445	669	SR-1357	40.8	142.4	259.8	229.4	1300
446	675	SR-1359	25.8	85.6	155.7	155.7	400
447	677	SR-1360	66.4	243.3	404.6	404.6	900
448	677	SR-1360	66.4	76.8	404.5	404.5	900
449	677	SR-1360	66.4	63.0	404.5	404.5	900
450	677	SR-1360	66.4	82.6	404.5	404.5	900
451	677	SR-1360	79.0	52.1	481.8	481.8	900
452	677	SR-1360	79.0	0.0	481.8	481.8	900
453	678	SR-1357	153.6	139.6	936.4	842.8	1300
454	678	SR-1357	55.3	105.3	347.7	312.2	1300
455	680	SR-1357 SR-1360	90.3	86.0	819.1	751.9	1300
456	680	SR-1357	47.9	47.0	292.0	262.8	1300
457	680	SR-1357	101.1	109.3	314.4	289.0	1300
460	686	NC-86	11.1	27.7	120.9	74.2	4900
461	694	SR-1359	53.4	91.8	325.4	325.4	400
462	694	SR-1359	53.4	64.4	325.4	325.4	400
463	694	SR-1360	32.2	238.3	207.6	207.6	900
464	695	NC-86	70.5	87.3	1245.2	505.3	4900

# of Segment	# of Catchment	Road name	Road segment (m)	Length of flowpath (m)	DA (m^2)	Imp (m^2)	AADT (Vehicles/d)
465	695	NC-86	70.5	43.1	1289.3	515.7	4900
466	695	NC-86	70.5	0.0	1359.6	520.5	4900
467	707	SR-1004	67.5	139.9	763.5	411.8	990
468	712	SR-1357	55.9	88.0	343.3	1154.5	1300
469	712	SR-1357	61.4	97.0	374.5	337.0	1300
470	712	SR-1357	61.4	66.6	374.5	337.0	1300
471	712	SR-1357	61.4	140.3	354.8	319.6	1300
472	712	SR-1360	46.4	235.3	284.0	284.0	900
473	712	SR-1360	46.4	160.6	283.1	283.1	900
474	712	SR-1360	46.4	156.0	282.3	282.3	900
475	717	SR-1004	58.1	148.9	708.4	354.2	990
476	717	SR-1004	58.1	90.1	708.1	353.9	990
477	717	SR-1004	58.1	58.4	708.1	354.1	990
478	717	SR-1004	58.1	0.0	708.1	354.1	990
479	717	SR-1004	58.1	0.0	708.1	354.1	990
480	717	SR-1004	58.1	31.3	708.1	354.1	990
481	717	SR-1004	35.8	71.4	458.6	228.2	990
482	727	SR-1357	79.9	180.0	506.7	455.6	1300
483	734	SR-1004	51.7	56.5	665.7	320.7	990
484	734	SR-1004	51.7	47.4	629.9	315.0	990
485	734	SR-1004	51.7	86.4	636.1	315.0	990
486	736	SR-1360	12.6	139.3	76.8	76.8	900
487	739	SR-1004	31.0	0.0	356.3	179.0	990
488	739	SR-1004	40.4	0.0	492.9	246.5	990
489	739	SR-1004	40.4	65.2	488.4	246.5	990
490	740	SR-1359	233.7	0.0	1408.9	1408.9	400
491	740	SR-1360	57.5	0.0	337.0	337.0	900
492	740	SR-1360	121.0	57.3	737.5	737.5	900
493	741	SR-1004	38.2	146.2	442.0	224.9	990
494	744	SR-1004	21.9	0.0	295.6	141.6	990
495	744	SR-1004	68.3	34.0	797.2	410.9	990
496	752	SR-1360	55.2	78.0	336.2	336.2	900
497	752	SR-1360	45.3	70.7	276.1	276.1	900
498	752	SR-1360	48.6	59.4	296.2	296.2	900
499	752	SR-1360	48.6	34.8	296.2	296.2	900
500	752	SR-1360	47.2	28.7	287.5	287.5	900
501	752	SR-1360	47.2	61.9	287.5	287.5	900

# of Segment	# of Catchment	Road name	Road segment (m)	Length of flowpath (m)	DA (m^2)	Imp (m^2)	AADT (Vehicles/d)
502	752	SR-1360	47.2	74.8	298.0	298.0	900
503	756	SR-1353	113.8	132.6	693.4	693.4	600
504	756	SR-1353	182.3	33.7	1117.2	1117.2	600
505	756	SR-1353	62.5	0.0	377.8	377.8	600
506	760	SR-1004	144.5	104.6	1761.7	880.9	1200
507	760	SR-1004	72.2	26.9	860.7	433.3	1200
508	760	SR-1360	81.8	160.7	510.9	510.9	900
509	760	SR-1360	90.6	166.4	552.5	552.5	900
510	761	NC-86	47.6	142.5	1047.6	405.8	4900
511	761	NC-86	47.6	97.2	998.7	399.5	4900
512	761	NC-86	47.6	120.3	826.9	265.6	4900
513	763	SR-1353	50.1	131.3	303.2	303.2	600
514	763	SR-1353	50.1	162.1	305.5	305.5	600
515	777	SR-1004	74.5	0.0	901.9	454.0	990
516	777	SR-1004	74.5	0.0	908.0	454.0	990
517	777	SR-1004	74.5	0.0	454.0	227.0	990
518	777	SR-1004		54.6	454.0	227.0	990
519	777	SR-1004	52.9	0.0	645.1	322.5	990
520	777	SR-1004	52.9	77.9	673.6	331.3	990
521	778	SR-1004	78.7	128.5	742.2	439.5	1200
522	778	SR-1360	188.0	112.1	1146.0	1146.0	900
523	778	SR-1360	60.2	98.1	366.8	366.8	900
524	778	SR-1360	60.2	74.1	366.8	366.8	900
525	778	SR-1360	60.2	69.0	353.2	353.2	900
526	779	SR-1360	68.1	114.5	407.2	407.2	900
527	779	SR-1360	68.1	90.6	402.7	402.7	900
528	784	SR-1353	62.3	223.0	367.1	367.1	600
529	792	NC-86	88.8	154.3	1462.4	658.7	4900
530	792	NC-86 SR-1352	120.4	0.0	3088.5	828.9	4900
532	794	SR-1357	61.4	276.6	372.6	333.8	1300
534	807	SR-1357	271.1	89.2	1653.9	1490.2	1300
535	807	SR-1357	48.1	65.8	301.5	270.6	1300
536	808	SR-1357	79.7	0.0	492.7	443.4	1300
537	810	SR-1353	111.9	151.5	684.7	684.7	600
538	812	SR-1352	60.1	126.9	526.4	369.7	1300
539	812	SR-1352	60.1	102.6	513.0	366.4	1300
540	812	SR-1352	60.1	131.1	513.0	366.4	1300

# of Segment	# of Catchment	Road name	Road segment (m)	Length of flowpath (m)	DA (m^2)	Imp (m^2)	AADT (Vehicles/d)
541	812	SR-1352	60.1	60.4	513.0	366.4	1300
542	812	SR-1352	120.1	115.6	1049.1	742.9	1300
543	813	SR-1352	80.4	67.6	696.0	500.3	1300
544	814	SR-1357	122.6	50.2	743.4	668.7	1300
545	815	SR-1352	138.5	43.0	1146.9	827.1	1300
546	818	SR-1004	82.5	80.7	1708.9	860.5	990
547	818	SR-1004	72.9	70.8	418.1	202.6	990
548	818	SR-1004	72.6	27.2	614.4	318.3	990
549	819	SR-1004 SR-1343	90.7	71.7	1537.6	544.9	990
551	820	SR-1004	39.7	104.8	470.2	241.5	990
552	820	SR-1004	20.2	61.7	270.4	124.2	990
553	820	SR-1004	13.8	0.0	191.6	88.0	990
554	821	SR-1004	40.1	44.4	247.1	126.0	990
555	821	SR-1004		0.0	229.4	112.8	1200
556	821	SR-1004	40.1	10.9	244.2	122.1	1200
557	821	SR-1004		0.0	218.8	116.1	1200
558	821	SR-1343	21.8	45.1	310.3	124.5	760
559	822	SR-1004	51.3	28.9	883.3	388.3	1200
560	822	SR-1004	173.7	0.0	2029.0	1013.1	1200
561	822	SR-1360	46.1	0.0	276.2	276.2	900
562	823	SR-1353	51.9	256.3	344.1	344.1	600
563	823	SR-1353	51.9	272.5	331.0	331.0	600
564	823	SR-1353	51.9	106.0	331.0	331.0	600
565	823	SR-1353	51.9	0.0	331.0	331.0	600
566	823	SR-1353	51.9	71.4	331.0	331.0	600
567	826	SR-1004	88.6	0.0	1097.9	545.8	1200
568	826	SR-1004	270.9	0.0	3336.4	1665.8	1200
570	828	SR-1352	51.6	40.1	1010.4	324.5	1300
571	830	SR-1357	43.6	49.7	265.6	239.1	1300
572	830	SR-1357	80.8	88.4	513.2	459.1	1300
573	831	SR-1357	171.9	122.5	1005.8	910.4	1300
574	835	SR-1353	50.5	132.5	318.3	318.3	600
575	835	SR-1353	50.5	135.3	293.7	293.7	600
576	837	SR-1004	29.2	18.6	324.7	165.9	1200
577	837	SR-1004	62.0	72.6	755.5	377.7	1200
578	837	SR-1004	124.1	93.0	1491.8	754.0	1200
579	842	SR-1352	211.7	0.0	1824.2	1299.8	1300

# of Segment	# of Catchment	Road name	Road segment (m)	Length of flowpath (m)	DA (m^2)	Imp (m^2)	AADT (Vehicles/d)
581	846	SR-1004	295.0	0.0	3594.4	1798.4	1200
582	848	SR-1352	142.1	202.8	1188.9	855.7	1300
583	851	SR-1343	150.0	0.0	2672.6	908.9	760
584	852	SR-1004	211.8	0.0	2630.9	1310.4	1200
586	853	SR-1352	157.2	0.0	1400.9	935.5	1300
587	853	SR-1353	85.4	81.7	494.3	494.3	600
590	854	SR-1352	63.6	30.7	532.0	384.7	1300
591	854	SR-1352	68.4	0.0	584.0	417.1	1300
592	854	SR-1352	203.5	111.9	1726.6	1236.3	1300
594	854	SR-1383	56.4	56.3	1042.3	388.6	500
596	856	SR-1352	45.6	100.8	400.9	281.6	1300
597	859	SR-1357	37.7	79.3	240.1	214.7	1300
598	863	SR-1343	49.4	175.8	879.9	301.2	760
599	863	SR-1343	49.4	159.8	949.1	301.6	760
600	873	SR-1383	52.9	59.7	970.1	323.4	500
601	873	SR-1383	52.9	51.8	970.1	323.4	500
602	873	SR-1383	52.9	44.8	807.9	278.1	500
603	876	SR-1343	42.9	0.0	437.9	135.2	760
604	876	SR-1343		20.7	379.0	130.3	760
605	876	SR-1343	67.7	29.5	1226.3	412.7	760
606	876	SR-1343	67.7	49.2	1238.1	412.7	760
607	876	SR-1343	67.7	58.7	1238.1	412.7	760
608	876	SR-1343	67.7	68.2	1238.1	412.7	760
609	876	SR-1343	188.2	109.8	3433.1	1147.4	760
610	876	SR-1350	89.4	150.0	519.9	519.9	400
611	881	SR-1352	214.3	51.4	1829.3	1306.7	1300
612	881	SR-1352	116.0	0.0	947.9	682.2	1300
614	891	SR-1547	24.4	171.8	117.4	117.4	300
615	899	SR-1004	104.9	79.2	1229.5	606.8	1200
616	899	SR-1004	49.6	33.8	604.7	302.4	1200
617	899	SR-1004	49.6	13.2	592.6	346.9	1200
618	900	SR-1004	422.9	0.0	3681.8	2392.1	1200
620	903	SR-1352	52.4	41.2	639.0	383.4	1300
621	903	SR-1352	52.4	25.1	639.0	383.4	1300
622	903	SR-1352	123.2	0.0	1492.7	901.3	1300
623	904	SR-1352	64.0	239.5	780.3	468.2	1300
624	904	SR-1352	64.0	94.3	780.3	468.2	1300

# of Segment	# of Catchment	Road name	Road segment (m)	Length of flowpath (m)	DA (m^2)	Imp (m^2)	AADT (Vehicles/d)
625	904	SR-1352	64.0	74.7	770.4	484.7	1300
626	905	SR-1383	63.5	62.4	1133.3	368.2	500
627	905	SR-1383	28.1	60.0	488.2	162.7	500
628	905	SR-1383	28.1	88.8	488.2	162.7	500
629	905	SR-1383	94.0	100.6	1933.6	638.0	500
630	906	SR-1383	47.3	158.8	970.7	320.6	500
631	906	SR-1383	47.3	148.9	920.0	306.7	500
632	906	SR-1383	47.3	107.5	920.0	306.7	500
633	906	SR-1383	47.3	104.0	753.0	267.1	500
634	908	SR-1357	51.8	72.0	315.7	284.1	1300
635	908	SR-1357	51.8	82.5	315.7	284.1	1300
636	908	SR-1357	51.8	87.3	315.7	284.1	1300
637	911	SR-1352	159.4	0.0	1403.9	984.5	1300
638	912	SR-1352	209.4	0.0	1823.5	1311.7	1300
641	913	SR-1350	54.1	56.9	339.9	339.9	400
642	913	SR-1350	54.1	62.2	335.2	335.2	400
643	913	SR-1350	54.1	73.1	335.2	335.2	400
644	913	SR-1350	54.1	43.7	321.0	321.0	400
645	915	SR-1352	33.7	75.4	346.5	225.5	1300
646	915	SR-1357	59.0	72.6	359.5	323.6	1300
647	915	SR-1357	69.2	72.1	422.0	379.8	1300
649	919	SR-1350	36.6	77.4	133.3	134.5	400
652	925	SR-1004 SR-1352 SR-1357	171.2	171.6	1469.7	1073.9	1900
654	925	SR-1352	114.8	130.4	806.6	587.2	1300
655	925	SR-1352	114.8	0.0	979.9	699.9	1300
656	925	SR-1352	95.2	0.0	812.3	580.2	1300
657	925	SR-1352	21.3	6.4	161.0	130.0	1300
659	926	SR-1352	30.6	47.5	236.0	176.5	1300
660	928	SR-1350	45.6	22.4	278.5	278.5	400
661	928	SR-1350	45.6	28.7	278.5	278.5	400
662	928	SR-1350	45.6	42.3	278.5	278.5	400
663	928	SR-1350	45.6	62.0	278.5	278.5	400
664	928	SR-1350	45.6	70.1	271.4	271.4	400
665	936	SR-1350	259.9	0.0	1660.4	1660.4	400
666	937	SR-1350	67.1	55.5	412.1	412.1	400
667	942	SR-1350	48.8	34.0	258.0	258.0	400

# of Segment	# of Catchment	Road name	Road segment (m)	Length of flowpath (m)	DA (m^2)	Imp (m^2)	AADT (Vehicles/d)
668	944	SR-1350	36.6	22.8	223.2	223.2	400
669	944	SR-1350	36.6	26.2	213.9	213.9	400
670	945	SR-1350	45.7	21.8	278.7	278.7	400
671	945	SR-1350	45.7	22.7	278.7	278.7	400
672	946	SR-1350	6.1	0.0	46.6	46.6	400
673	947	NC-86	92.1	78.3	2568.6	670.0	6800
674	947	NC-86	92.1	51.2	2807.3	673.7	6800
675	947	NC-86	60.5	0.0	1843.4	442.4	6800
676	947	NC-86	60.5	52.7	1843.4	442.4	6800
677	947	NC-86	120.6	96.0	3524.3	883.3	6800
678	947	SR-1547	69.4	111.7	320.6	320.6	300
679	947	SR-1547	45.0	171.7	221.0	221.0	300
680	948	SR-1350	12.2	12.8	124.3	124.3	400
682	963	SR-1383	54.8	123.4	919.6	300.8	500
683	963	SR-1383	54.8	119.5	1005.1	335.0	500
684	963	SR-1383	54.8	103.5	1005.1	335.0	500
685	963	SR-1383	54.8	87.9	1005.1	335.0	500
686	963	SR-1446	160.3	123.4	2497.6	899.2	200
687	976	SR-1446	69.5	102.2	1015.5	390.2	200
688	978	SR-1343	69.4	47.9	1242.4	423.0	760
689	978	SR-1343	69.4	50.0	1268.9	423.0	760
690	978	SR-1343	69.4	39.0	1308.6	433.9	760
691	981	NC-86	61.4	93.5	2023.4	452.3	6800
692	981	NC-86	61.4	98.5	1632.4	427.1	6800
694	983	SR-1004	238.0	84.9	2176.3	1450.8	1900
695	991	SR-1343	123.6	0.0	2238.7	739.6	760
696	991	SR-1343	50.8	14.5	444.0	148.0	760
697	991	SR-1343		0.0	518.9	165.1	760
698	991	SR-1343	50.8	70.6	927.1	315.4	760
700	1004	SR-1343	71.3	24.9	1270.7	433.8	760
701	1004	SR-1343	142.5	31.5	2607.6	869.2	760
702	1009	SR-1383	97.6	129.1	1786.4	625.5	500
703	1009	SR-1446		81.4	555.3	196.0	200
704	1009	SR-1446		66.1	589.4	181.3	200
705	1009	SR-1446	132.6	68.2	923.6	346.1	200
706	1009	SR-1447	57.6	96.2	944.8	338.6	100
707	1010	NC-86	59.8	182.8	2093.7	459.6	6800

# of Segment	# of Catchment	Road name	Road segment (m)	Length of flowpath (m)	DA (m^2)	Imp (m^2)	AADT (Vehicles/d)
708	1052	SR-1004	463.5	0.0	4256.9	2834.4	1900
709	1057	SR-1383	98.1	93.0	810.1	328.5	500
710	1057	SR-1383	54.5	38.8	498.5	166.2	500
711	1057	SR-1447	54.5	55.2	498.5	166.2	100
712	1057	SR-1447		0.0	1655.2	528.7	100
713	1057	SR-1447	43.3	78.8	792.1	264.0	100
714	1057	SR-1447	43.3	72.0	774.7	264.0	100
715	1058	NC-86	34.9	0.0	589.7	243.3	6800
717	1064	SR-1343	52.4	69.9	959.1	319.7	760
718	1064	SR-1343	52.4	50.4	959.1	319.7	760
719	1064	SR-1343	92.8	131.2	847.2	282.4	760
720	1064	SR-1343		30.3	847.2	282.4	760
721	1064	SR-1343	92.8	83.4	1698.2	566.1	760
722	1065	SR-1004	40.8	7.6	353.9	239.3	1900
723	1065	SR-1004	40.8	58.2	372.7	248.5	1900
724	1065	SR-1004	40.8	54.7	360.3	246.1	1900
725	1076	SR-1383	56.4	62.0	1052.6	345.2	500
726	1076	SR-1383	56.4	64.2	1035.5	345.2	500
727	1076	SR-1383	56.4	56.4	1035.5	345.2	500
728	1076	SR-1383	56.4	100.2	967.7	322.9	500
730	1092	SR-1351	165.1	183.4	493.2	493.2	700
731	1092	SR-1351		144.2	476.9	476.9	700
732	1092	SR-1351	53.9	130.7	348.2	348.2	700
733	1105	SR-1004	50.8	147.1	476.8	312.1	1900
734	1105	SR-1004	50.8	61.8	464.6	309.7	1900
735	1105	SR-1004	152.3	0.0	1392.3	928.6	1900
736	1106	SR-1343	49.9	59.0	913.2	304.4	760
737	1106	SR-1343	49.9	59.3	913.2	304.4	760
738	1109	SR-1004	12.4	131.8	114.0	75.6	1900
739	1117	SR-1343	60.4	44.5	1102.7	367.6	760
740	1117	SR-1343	81.8	12.0	748.4	249.5	760
741	1117	SR-1343		55.0	748.4	249.5	760
742	1117	SR-1343	81.8	78.9	748.4	249.5	760
743	1117	SR-1343		44.9	748.4	249.5	760
744	1117	SR-1343	81.8	81.6	1428.2	489.7	760
745	1117	SR-1351	78.2	100.8	470.0	470.0	700
746	1122	SR-1383	91.5	0.0	1682.9	569.3	500

# of Segment	# of Catchment	Road name	Road segment (m)	Length of flowpath (m)	DA (m^2)	Imp (m^2)	AADT (Vehicles/d)
747	1123	NC-86		180.6	626.2	0.7	6800
748	1140	SR-1004	24.5	0.0	259.5	164.7	1900
749	1155	NC-86	45.3	93.0	1300.6	333.9	6800
750	1155	NC-86	25.6	267.6	953.2	214.6	6800
752	1160	SR-1383	28.8	0.0	569.7	195.8	500
754	1165	SR-1004	149.3	0.0	1345.9	901.4	1900
755	1167	SR-1004	122.2	0.0	1101.9	738.7	1900
756	1170	NC-86	46.4	100.5	1103.0	319.4	6800
757	1170	NC-86	66.2	144.3	2016.6	484.0	6800
758	1170	NC-86	66.2	81.1	2043.5	481.4	6800
759	1171	SR-1351	225.7	53.2	707.2	707.2	700
760	1171	SR-1351	45.1	53.3	141.4	141.4	700
761	1171	SR-1351	45.1	25.6	141.4	141.4	700
762	1171	SR-1351	45.1	27.4	141.4	141.4	700
763	1171	SR-1351	45.1	24.5	141.4	141.4	700
764	1171	SR-1351	45.1	53.2	141.4	141.4	700
765	1171	SR-1351	46.4	47.6	225.5	225.5	700
766	1177	NC-86	51.9	57.1	1589.2	391.8	6800
767	1177	NC-86	51.9	61.2	1571.4	377.1	6800
768	1177	NC-86	51.9	45.0	1571.4	377.1	6800
769	1177	NC-86	51.9	0.0	1571.4	377.1	6800
770	1177	NC-86	51.9	0.0	1582.1	377.1	6800
771	1178	SR-1351	42.3	36.9	244.5	244.5	700
772	1178	SR-1351	42.3	52.5	258.1	258.1	700
773	1178	SR-1351	42.3	66.7	258.1	258.1	700
774	1182	SR-1351	16.6	14.4	120.7	120.7	700
775	1182	SR-1351	21.8	25.1	146.2	146.2	700
776	1183	SR-1351	46.4	0.0	281.2	281.2	700
777	1183	SR-1351	71.9	46.3	435.5	435.5	700
778	1183	SR-1351	74.1	64.6	454.2	454.2	700
779	1190	SR-1351	45.8	33.8	262.6	262.6	700
780	1190	SR-1351	45.8	69.9	298.1	298.1	700
781	1192	SR-1323	37.3	166.4	625.7	216.9	500
782	1194	SR-1004	73.2	135.6	669.0	446.0	1900
783	1198	SR-1351	80.1	0.0	470.0	470.0	700
784	1199	SR-1351	46.0	0.0	303.8	303.8	700
785	1211	SR-1004	132.8	20.4	1208.1	805.4	1800

# of Segment	# of Catchment	Road name	Road segment (m)	Length of flowpath (m)	DA (m^2)	Imp (m^2)	AADT (Vehicles/d)
786	1211	SR-1004	50.4	55.4	468.3	311.9	1900
787	1216	NC-86	25.9	47.9	149.6	138.5	6800
789	1225	SR-1351	17.9	20.3	122.2	122.9	700
790	1228	SR-1004	53.4	20.5	488.5	325.7	1800
791	1228	SR-1004	157.0	0.0	1435.2	957.1	1800
792	1232	SR-1351	129.2	0.0	367.3	367.3	700
793	1232	SR-1351		56.5	390.0	390.0	700
794	1232	SR-1351	53.7	34.6	163.7	163.7	700
795	1232	SR-1351		0.0	163.7	163.7	700
796	1232	SR-1351	53.7	72.6	327.3	327.3	700
797	1232	SR-1351	53.7	49.7	347.2	347.2	700
798	1235	SR-1323	20.8	108.7	764.5	161.6	500
799	1236	NC-86	22.9	171.3	1240.3	209.8	6800
800	1236	SR-1323	123.1	41.9	2250.8	750.3	500
801	1236	SR-1323	139.1	0.0	2419.4	841.2	500
802	1245	SR-1323	71.1	250.2	1557.9	491.9	500
803	1246	SR-1351	145.2	52.6	884.1	884.1	700
804	1246	SR-1351	38.6	39.4	233.2	233.2	700
805	1248	SR-1351	82.2	37.9	501.8	501.8	700
806	1248	SR-1351	131.5	0.0	400.0	400.0	700
807	1248	SR-1351		32.9	400.0	400.0	700
808	1259	SR-1323	55.9	133.0	972.5	333.2	500
809	1259	SR-1323	55.9	145.4	1022.9	341.0	500
810	1259	SR-1323	55.9	68.7	1022.9	341.0	500
811	1259	SR-1323	55.9	8.5	1022.9	341.0	500
812	1259	SR-1323	55.9	34.3	1100.2	347.3	500
813	1259	SR-1323	78.8	82.1	1474.1	501.6	500
814	1266	NC-86	69.5	90.5	1624.3	499.7	6800
815	1266	NC-86	71.8	132.1	1957.6	525.2	6800
816	1266	SR-1323	68.6	159.3	1208.7	399.5	500
817	1269	SR-1323	45.6	74.1	767.8	241.1	500
818	1269	SR-1450	37.9	109.6	600.9	207.7	100
820	1269	SR-1449 SR-1450	178.0	74.1	2606.8	979.6	200
821	1269	SR-1449	69.9	39.1	532.7	191.8	200
822	1269	SR-1449		43.9	532.7	191.8	200
823	1269	SR-1449	79.2	0.0	1091.2	419.6	200
824		SR-1450	141.8	77.6	2136.7	789.7	100

# of Segment	# of Catchment	Road name	Road segment (m)	Length of flowpath (m)	DA (m^2)	Imp (m^2)	AADT (Vehicles/d)
825	1271	SR-1004	97.0	41.7	887.4	591.6	1800
826	1271	SR-1004	49.0	29.4	466.4	307.2	1800
827	1273	SR-1323	30.5	238.0	503.2	168.5	500
828	1275	NC-86	69.1	176.1	1487.9	566.0	6800
829	1275	NC-86	74.1	146.8	3440.2	625.3	6800
830	1275	NC-86	74.1	66.0	2258.4	542.0	6800
831	1275	NC-86	74.1	118.4	2300.0	542.0	6800
832	1279	SR-1004	189.6	0.0	1700.9	1141.7	1800
833	1284	SR-1323	60.7	198.0	1007.5	361.4	500
834	1284	SR-1323	42.9	158.0	595.2	266.1	500
835	1284	SR-1323	64.2	89.0	1174.2	391.4	500
836	1284	SR-1323	64.2	91.1	1174.2	391.4	500
837	1284	SR-1323	64.2	122.8	1174.2	391.4	500
838	1284	SR-1323	64.2	117.2	1174.2	391.4	500
839	1284	SR-1323	64.2	201.9	801.0	302.5	500
840	1288	SR-1351	56.8	158.2	332.8	332.8	700
841	1288	SR-1351	56.8	122.8	353.0	353.0	700
842	1288	SR-1351	56.8	87.9	351.0	351.0	700
843	1289	SR-1323	112.2	151.0	1997.9	676.7	500
844	1291	SR-1351	84.8	140.8	516.1	516.1	700
845	1292	NC-86	68.0	259.1	2031.9	497.6	6800
846	1292	NC-86	68.0	107.3	2073.4	497.6	6800
847	1292	NC-86	68.0	152.0	2103.3	496.5	6800
848	1298	SR-1323	91.9	268.4	1751.5	572.6	500
850	1302	SR-1004	48.9	144.3	461.1	303.4	1800
851	1302	SR-1004	48.9	160.7	446.4	297.6	1800
852	1302	SR-1004	48.9	166.3	449.9	299.9	1800
853	1308	SR-1323	66.3	347.8	1192.0	399.6	500
854	1312	SR-1323	141.2	165.7	2576.2	854.9	500
855	1320	SR-1323	187.5	0.0	3406.1	1030.1	500
856	1320	SR-1323	73.5	0.0	671.9	201.6	500
857	1320	SR-1323 SR-1449		22.5	671.9	201.6	200
858	1320	SR-1323	73.5	0.0	671.9	201.6	500
859	1320	SR-1323		115.7	671.9	201.6	500
860	1320	SR-1323	73.5	0.0	1343.9	403.2	500
861	1320	SR-1323	64.7	85.1	1388.2	433.3	500
863	1322	SR-1323	190.6	189.3	3421.2	1159.9	500

# of Segment	# of Catchment	Road name	Road segment (m)	Length of flowpath (m)	DA (m^2)	Imp (m^2)	AADT (Vehicles/d)
865	1338	SR-1323	49.8	44.5	897.8	299.3	500
866	1338	SR-1323	49.8	64.4	897.8	299.3	500
867	1338	SR-1323	49.8	92.5	1030.4	319.8	500
868		SR-1450	72.9	186.0	1100.3	411.5	100
869	1357	SR-1323	90.6	66.9	1612.6	543.3	500
870	1357	SR-1323	109.3	131.8	2051.4	682.5	500
871	1366	SR-1351	259.7	85.4	1515.2	1515.2	700
872	1366	SR-1351	44.5	22.1	271.3	271.3	700
873	1366	SR-1351	44.5	40.0	327.3	327.3	700
874	1372	SR-1351	172.6	61.3	1097.0	1097.0	700
875	1375	SR-1004	180.0	78.1	1664.7	1106.5	1800
876	1375	SR-1004 SR-1332	83.9	33.8	890.6	472.9	1800
877	1375	SR-1004	48.5	60.1	443.6	295.8	1800
878	1375	SR-1004	48.5	68.1	443.6	295.8	1800
879	1375	SR-1004	48.5	91.2	443.6	295.8	1800
880	1375	SR-1004	48.5	98.1	439.4	295.8	1800
882	1379	NC-86	12.4	125.1	699.7	100.0	6800
883	1380	SR-1004	25.4	226.3	244.2	156.5	1800
884	1381	SR-1323	68.0	169.3	1062.3	404.6	500
886	1390	NC-86	95.5	119.4	2736.9	691.4	6800
888	1403	SR-1332	96.6	0.0	1014.0	315.6	700
889	1403	SR-1332		326.5	870.0	290.0	700
890	1403	SR-1332	96.6	0.0	870.0	290.0	700
891	1403	SR-1332		112.6	870.0	290.0	700
892	1403	SR-1332	96.6	0.0	870.0	290.0	700
893	1403	SR-1332		98.7	870.0	290.0	700
894	1403	SR-1332	89.9	0.0	821.8	273.9	700
895	1403	SR-1332		64.0	821.8	273.9	700
896	1403	SR-1332	89.9	61.9	1635.7	557.6	700
897	1408	NC-86	30.9	220.5	791.6	233.3	9200
898	1411	SR-1004	418.7	0.0	3741.0	2522.4	1800
899	1412	SR-1341	14.6	160.6	270.4	88.1	700
900	1433	SR-1351	46.8	58.5	250.0	250.0	700
901	1433	SR-1351	46.8	30.4	286.4	286.4	700
902	1444	SR-1351	37.8	0.0	241.2	241.2	700
903	1448	SR-1351	31.5	35.5	189.9	189.9	700
904	1449	SR-1351	49.2	40.3	370.0	370.0	700

# of Segment	# of Catchment	Road name	Road segment (m)	Length of flowpath (m)	DA (m^2)	Imp (m^2)	AADT (Vehicles/d)
905	1449	SR-1351	49.2	46.5	300.1	300.1	700
906	1449	SR-1351	259.7	140.5	1505.6	1505.6	700
907	1451	SR-1341	275.1	41.6	5023.2	1671.2	700
908	1451	SR-1341	53.4	30.2	976.4	325.5	700
909	1451	SR-1341	53.4	29.1	907.3	331.3	700
910	1462	SR-1004	23.7	125.4	325.0	181.8	1800
911	1463	SR-1341	77.5	112.0	1508.3	473.9	700
912	1463	SR-1341	56.4	35.9	1017.1	340.1	700
913	1471	NC-86	69.8	190.7	2064.8	495.3	9200
914	1471	NC-86	69.8	65.7	2127.4	510.6	9200
915	1471	NC-86	73.0	100.2	1112.9	267.1	9200
916	1471	NC-86		0.0	1112.9	267.1	9200
917	1471	NC-86	73.0	119.1	1112.9	267.1	9200
918	1471	NC-86		0.0	1112.9	267.1	9200
919	1471	NC-86	35.7	0.0	1089.5	261.5	9200
920	1471	NC-86	35.7	0.0	1089.5	261.5	9200
921	1471	NC-86	58.7	0.0	1265.8	172.0	9200
922	1475	SR-1341	63.4	0.0	600.7	191.3	700
923	1475	SR-1341		17.5	600.7	191.3	700
924	1475	SR-1341	126.9	48.1	2317.6	772.5	700
925	1476	SR-1335	189.3	125.4	1116.7	1116.7	600
926	1478	SR-1004	9.1	47.8	89.4	56.3	1800
927	1481	SR-1004	61.8	157.4	516.9	356.7	1800
928	1483	SR-1332	230.9	92.8	4261.7	1470.7	700
929	1483	SR-1332	26.9	18.2	322.5	90.0	700
930	1489	SR-1004	29.6	88.0	269.2	180.7	1800
931	1489	SR-1004	36.3	0.0	333.4	222.3	1800
932	1489	SR-1004	136.5	0.0	638.7	425.8	1800
933	1489	SR-1004		16.3	212.9	141.9	1800
934	1489	SR-1004		67.8	212.9	141.9	1800
935	1489	SR-1004		97.0	180.9	125.4	1800
936	1492	SR-1341	24.1	98.0	417.1	155.3	700
937	1492	SR-1341	31.0	92.6	543.3	188.7	700
938	1493	SR-1332	88.7	155.4	1827.4	554.2	700
939	1502	SR-1335	55.1	91.1	379.8	379.8	600
940	1504	SR-1004	56.9	21.7	553.7	364.9	1800
941	1504	SR-1004	45.9	45.2	413.1	269.8	1800

# of Segment	# of Catchment	Road name	Road segment (m)	Length of flowpath (m)	DA (m^2)	Imp (m^2)	AADT (Vehicles/d)
942	1507	SR-1332	68.3	0.0	1069.2	414.5	700
943	1507	SR-1332	68.3	0.0	624.9	208.3	700
944	1507	SR-1332		133.5	624.9	208.3	700
945	1507	SR-1332	68.3	0.0	624.9	208.3	700
946	1507	SR-1332		34.7	624.9	208.3	700
947	1507	SR-1332	93.9	35.4	858.5	286.2	700
948	1507	SR-1332		51.0	858.5	286.2	700
949	1507	SR-1332	282.3	72.5	5208.6	1730.3	700
950	1511	NC-86	26.6	193.2	1089.5	261.5	9200
951	1511	NC-86		165.4	1089.5	261.5	9200
952	1516	NC-86		109.0	141.3	0.2	9200
953	1517	NC-86	76.6	90.8	1396.8	467.0	9200
954	1517	NC-86 SR-1551	69.0	124.9	1510.3	472.3	9200
957	1519	SR-1551 NC-86	20.7	15.6	1017.1	264.5	600
958	1525	SR-1004	19.2	22.6	144.7	101.8	1800
959	1525	SR-1004	19.2	30.4	198.7	131.2	1800
960	1530	SR-1341	290.1	0.0	5229.9	1729.3	700
961	1530	SR-1341	52.6	0.0	481.1	160.4	700
962	1530	SR-1341		27.0	481.1	160.4	700
963	1530	SR-1341	52.6	0.0	481.1	160.4	700
964	1530	SR-1341		85.6	481.1	160.4	700
965	1530	SR-1341	52.6	0.0	430.6	160.6	700
966	1530	SR-1341		254.7	797.5	204.8	700
967	1536	SR-1335	134.1	238.2	779.7	779.7	600
968	1538	SR-1004	135.3	0.0	1234.3	824.0	1800
969	1538	SR-1004	106.9	81.2	977.9	651.9	1800
970	1538	SR-1004	106.9	93.8	984.4	653.5	1800
971	1540	SR-1335	170.7	198.7	1062.1	1062.1	600
972	1545	SR-1335	165.1	151.1	1001.2	1001.2	600
973	1546	SR-1335	58.4	90.7	354.1	354.1	600
974	1546	SR-1335	58.3	55.4	334.6	334.6	600
975	1549	SR-1335	76.3	48.6	476.9	476.9	600
976	1549	SR-1335	39.6	50.9	243.4	243.4	600
978	1556	NC-86	25.3	339.0	536.3	180.1	9200
979	1558	SR-1351	50.0	100.3	304.6	304.6	700
980	1558	SR-1351	50.0	56.4	304.6	304.6	700

# of Segment	# of Catchment	Road name	Road segment (m)	Length of flowpath (m)	DA (m^2)	Imp (m^2)	AADT (Vehicles/d)
981	1558	SR-1351	50.0	50.9	304.6	304.6	700
982	1558	SR-1351	50.0	53.6	304.6	304.6	700
983	1558	SR-1351	42.4	71.8	242.6	242.6	700
984	1562	SR-1335	28.4	12.1	173.1	173.1	600
985	1562	SR-1335	28.4	6.1	173.1	173.1	600
986	1562	SR-1335	172.2	0.0	1049.7	1049.7	600
987	1564	SR-1351	20.8	309.6	110.0	110.0	700
988	1564	SR-1351	62.9	124.0	385.6	385.6	700
989	1564	SR-1351	62.6	93.4	383.7	383.7	700
990	1565	SR-1335	61.1	100.5	394.3	394.3	600
991	1565	SR-1335	61.1	63.2	372.7	372.7	600
992	1565	SR-1335	61.1	58.4	372.7	372.7	600
993	1565	SR-1335	61.1	39.6	372.7	372.7	600
994	1565	SR-1335	61.1	57.0	372.7	372.7	600
995	1565	SR-1335	247.9	67.7	1510.4	1510.4	600
996	1567	SR-1332	68.6	77.3	1211.8	417.4	700
997	1567	SR-1332	68.6	36.8	627.5	209.2	700
998	1567	SR-1332		59.4	627.5	209.2	700
999	1567	SR-1332	127.7	0.0	2289.6	778.3	700
1000	1569	SR-1004	451.3	0.0	4106.4	2745.7	1800
1001	1570	SR-1332	76.3	127.3	1349.9	456.2	700
1002	1570	SR-1332	76.3	184.0	1438.9	464.1	700
1003	1574	SR-1335	158.5	127.4	874.9	874.9	600
1005	1576	SR-1335	134.1	190.6	910.8	910.8	600
1008	1578	SR-1351	66.7	265.0	434.7	434.7	700
1009	1580	SR-1335	44.9	157.9	274.0	274.0	600
1010	1580	SR-1335	44.9	158.1	258.5	258.5	600
1011	1581	SR-1335	24.4	267.6	165.1	163.2	600
1013	1586	SR-1341	98.0	55.4	1522.6	568.5	700
1014	1593	SR-1332	59.3	50.8	1126.2	362.9	700
1015	1593	SR-1332	59.2	62.5	1055.2	356.5	700
1016	1597	SR-1341	81.9	79.6	1626.5	534.4	700
1017	1597	SR-1341	14.4	54.2	334.4	87.7	700
1018	1597	SR-1341		29.1	246.2	8.1	700
1019	1597	SR-1341	3.9	20.8	519.1	52.0	700
1020	1599	SR-1341	10.0	31.9	386.3	63.9	700
1021	1599	SR-1341	20.9	26.9	507.3	134.0	700

# of Segment	# of Catchment	Road name	Road segment (m)	Length of flowpath (m)	DA (m^2)	Imp (m^2)	AADT (Vehicles/d)
1022	1599	SR-1341	36.0	20.9	492.8	230.9	700
1023	1601	SR-1335	80.8	60.3	492.6	492.6	600
1024	1601	SR-1335	80.8	82.9	492.6	492.6	600
1025	1613	SR-1332	47.9	63.8	1005.9	347.8	700
1026	1613	SR-1332	12.8	0.0	234.2	78.1	700
1027	1613	SR-1335	42.2	77.2	238.7	238.7	600
1028	1613	SR-1335	42.2	40.9	257.3	257.3	600
1029	1637	SR-1341	97.4	329.7	1463.0	580.6	700
1030	1641	SR-1341	333.3	95.5	5457.0	1960.5	700
1031	1641	SR-1341	146.7	91.8	1438.6	463.5	700
1032	1641	SR-1341		36.0	1291.2	456.1	700
1033	1643	SR-1332	104.7	141.2	1988.3	642.7	700
1034	1643	SR-1332	28.7	14.3	524.3	174.8	700
1035	1644	SR-1332	37.2	9.4	680.6	226.9	700
1036	1644	SR-1332	37.2	25.5	680.6	226.9	700
1037	1644	SR-1332	37.2	32.8	680.6	226.9	700
1038	1644	SR-1332	345.9	56.1	6164.7	2057.3	700
1040	1649	SR-1351	49.0	145.4	301.4	301.4	700
1041	1649	SR-1351	167.0	85.3	508.9	508.9	700
1042	1649	SR-1351		94.8	169.6	169.6	700
1043	1649	SR-1351		55.1	169.6	169.6	700
1044	1649	SR-1351		135.6	169.6	169.6	700
1045	1649	SR-1351	52.1	74.3	317.8	317.8	700
1046	1649	SR-1351	52.1	49.2	317.8	317.8	700
1047	1649	SR-1351	52.1	35.5	317.8	317.8	700
1048	1649	SR-1351	52.1	41.0	317.8	317.8	700
1049	1649	SR-1351	52.1	39.5	317.8	317.8	700
1050	1649	SR-1351	52.1	25.5	315.6	315.6	700
1051	1665	SR-1332	63.4	50.5	1046.7	380.1	700
1052	1665	SR-1332	63.7	72.7	1222.9	389.3	700
1053	1666	SR-1341	49.0	99.5	837.2	287.8	700
1054	1666	SR-1341	49.0	55.8	896.5	298.8	700
1055	1666	SR-1341	49.0	80.9	1130.4	305.8	700
1056	1669	SR-1351	19.2	0.0	130.2	130.2	700
1057	1672	SR-1004 SR-1351	41.7	17.7	380.7	266.0	1800
1058	1672	SR-1004	33.8	16.8	280.1	186.0	1800
1060	1684	SR-1004	42.4	22.0	417.0	278.7	1800

# of Segment	# of Catchment	Road name	Road segment (m)	Length of flowpath (m)	DA (m^2)	Imp (m^2)	AADT (Vehicles/d)
1061	1684	SR-1004	47.3	23.5	432.5	288.3	1800
1062	1684	SR-1004	99.0	40.5	865.0	574.5	1800
1063	1690	SR-1004	35.1	21.4	321.1	214.1	1800
1064	1690	SR-1004	35.1	22.3	321.1	214.1	1800
1065	1690	SR-1004	35.1	35.8	321.1	214.1	1800
1066	1690	SR-1004	35.3	30.3	327.6	215.4	1800
1067	1698	SR-1341	119.3	26.0	1954.0	720.5	700
1068	1698	SR-1341	451.6	0.0	8231.3	2742.9	700
1069	1720	SR-1341	108.0	210.0	2029.3	660.5	700
1070	1729	SR-1418	72.8	23.2	1166.2	399.5	100
1071	1731	SR-1416	123.4	0.0	1765.1	660.5	50
1072	1731	SR-1415	246.6	116.0	3811.6	1503.2	300
1074	1731	SR-1418	162.8	0.0	1182.2	438.1	100
1075	1731	SR-1418		61.4	562.0	214.9	100
1076	1731	SR-1418		94.3	620.1	223.2	100
1077	1735	SR-1004	21.1	11.9	307.9	195.0	1800
1080	1743	SR-1339	78.6	67.2	1436.6	478.9	700
1081	1743	SR-1341	53.9	23.4	985.1	328.4	700
1082	1743	SR-1341	100.3	50.0	1598.8	592.5	700
1084	1762	SR-1340		0.0	114.9	33.6	700
1085	1762	SR-1415	67.8	55.0	947.2	386.5	300
1086	1765	SR-1339	54.5	27.6	1060.0	340.7	700
1087	1765	SR-1339	108.5	67.4	2039.4	668.3	700
1088	1775	SR-1004	52.2	23.1	411.2	288.7	1800
1089	1775	SR-1004	52.2	31.4	477.2	318.2	3000
1090	1775	SR-1004	52.2	38.0	477.2	318.2	3000
1091	1775	SR-1004	52.2	61.1	477.2	318.2	3000
1092	1775	SR-1004	104.4	38.0	954.5	636.3	3000
1093	1775	SR-1004	52.2	126.3	477.2	318.2	3000
1094	1775	SR-1004	84.0	0.0	767.3	518.3	3000
1095	1775	SR-1336	71.8	145.9	419.1	419.1	600
1096	1775	SR-1336	71.8	82.6	437.7	437.7	600
1097	1775	SR-1336	72.6	83.8	465.9	465.9	600
1098	1776	SR-1415	79.3	95.0	1227.1	483.2	300
1099	1781	SR-1341	62.2	85.1	1092.5	379.1	700
1100	1785	SR-1415	109.8	106.0	1666.5	669.3	300
1102	1787	SR-1340	63.7	69.8	1133.4	382.6	700

# of Segment	# of Catchment	Road name	Road segment (m)	Length of flowpath (m)	DA (m^2)	Imp (m^2)	AADT (Vehicles/d)
1103	1787	SR-1340	63.9	44.2	1136.3	389.4	700
1104	1794	SR-1339	125.1	77.3	2232.8	755.9	700
1105	1794	SR-1339	62.6	37.2	1145.7	381.9	700
1106	1794	SR-1339	62.6	50.0	1145.7	381.9	700
1107	1794	SR-1339	62.6	43.0	1182.7	381.9	700
1108	1797	SR-1415	13.5	40.1	228.0	82.4	300
1110	1798	SR-1340	127.6	63.3	2297.6	771.4	700
1111	1798	SR-1340	64.3	32.7	1175.3	391.8	700
1112	1798	SR-1340	64.3	42.2	1175.3	391.8	700
1113	1798	SR-1340	64.3	58.6	1174.5	391.8	700
1114	1802	SR-1340	57.6	74.6	1054.9	351.4	700
1115	1802	SR-1340	114.8	109.1	2128.7	705.3	700
1116	1804	SR-1336	43.5	137.6	240.9	240.9	600
1117	1806	SR-1339	85.9	130.3	1683.5	556.8	700
1118	1828	SR-1341	12.6	128.2	262.7	76.9	700
1119	1832	SR-1339	13.4	0.0	91.2	48.3	700
1120	1835	SR-1340	17.4	0.0	351.2	106.3	700
1121	1839	SR-1339	152.5	0.0	2802.6	930.5	700

*DA = road drainage area;
Imp. = impervious area of road land use;
AADT = Average annual daily traffic. The shaded number is estimated.

APPENDIX G: PVBTWQM PROGRAM

To see the following three attachments:

a) PVbtWQM_HC.

b) PVbtWQM _TN.

c) PVbtWQM _TP.