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Development of a GIS-based Methodology to Estimate Stormwater Runoff Pollutant Loadings from North Carolina Highways

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16. Abstract

This report documents the development of a methodology to estimate pollutant loading from stormwater runoff from North Carolina. A summary of regression-based pollutant loading models developed for highway runoff from the literature is presented. The regression models based on average daily traffic (ADT) and percent impervious coverage (IMP) developed by Wu and Allan (2001) are applied to the I-40 corridor within NC. Multiple regression models based on traffic conditions, previous storm conditions, antecedent dry period and storm characteristics are developed for five NC highway sites and compared to similar regression models developed for highway sites near Austin, Texas. Finally, traditional digital elevation models (DEM) and Lidar topographic information is used in conjunction with the GIS-based NC sensitive water crossing point coverage to define highway drainage areas and their impervious cover characteristics for two case studies in eastern NC.

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Executive Summary

This report presents research findings pertaining to the development of statistical models to estimate pollutant loadings from highway stormwater runoff. The potential for implementing these models to estimate pollutant loadings within a GIS at the road segment or watershed scale is also examined. An extensive literature review was conducted to document previous efforts to develop statistically based models to predict pollutant-loading models for highway runoff and guide the development of such models from North Carolina field data.

The two most useful modeling approaches found in the literature were those that predicted roadway source pollutant loadings based on average daily traffic and percent impervious cover (Wu and Allan 2001) and multiple regression models based on current and previous event runoff characteristics, antecedent dry period, antecedent traffic counts and traffic counts during actual rainfall events (Irish et al. 1998).

A methodology was developed to apply Wu and Allan's model within a GIS using the NCDOT roadway database. Roadway attributes including number of lanes and width and median type and width were combined to estimate the independent variable, percent impervious cover and average daily traffic counts were directly available within the NCDOT database. The regression models for TSS, TDS, COD, TKN, NH_3-N, NO_3-N, TP, OP and Zn were applied to the I-40 corridor in North Carolina to generate an estimate of pollutant loading from these constituents along its entire length. The models appeared to perform reasonably well except where traffic volumes and impervious cover percentages exceeded the range of the values used to develop the original regression relationships.

A series of multiple regression models based on event and previous event runoff and precipitation characteristics, antecedent dry period, antecedent traffic counts and traffic counts during actual rainfall events were developed for six NC roadway sites examined in Wu and Allan's 2001 stormwater monitoring study. These sites represented drainage from completely impervious and mixed pervious/impervious roadway sites. A methodology is presented to develop the vehicles during storm (VDS) independent variable in the absence of actual real time traffic count data. Several highly significant regression relations were identified for each site but model form and the sign associated with various independent variables were inconsistent amongst sites and at odds with the variables most likely influence on the magnitude of the loading of a pollutant constituent. Regression models developed from multiple sites, classed either as impervious or mixed surface roadway sites generated for the most part a series of more consistent scientifically defensible loading equations. Such models could be applied within a GIS using real or synthetic precipitation data in conjunction with traffic data contained within the NCDOT road attribute database.

The final section of the report examines the utility of using Lidar and traditional Digital Elevation Model (DEM) topographic data to identify topographically defined drainage areas associated with sensitive water roadway crossing points. The accurate

identification of a particular crossing points specific drainage areas is necessary to accurately define the road surface and traffic conditions associated with that particular crossing. This data is necessary to apply the pollutant loading models identified and developed in this study. Case studies from eastern NC indicate significant potential to identify such small-scale drainage features with the Lidar data while traditional DEM data proved to be too coarse to identify these features. Incorporation of elevation data from the NCDOT bridge deck database and perhaps modification of the sensitive waters crossing point methodology remain to be worked out before the utilization of Lidar data to identify small drainage features can be fully realized.

Further research including site visits are required to determine the utility of Lidar topographic data in defining drainage areas for sensitive water crossing points. Multiple regression models from NC data and perhaps other studies need to be applied at the road segment scale and compared with other approaches used to estimate NPS pollutant loading to estimate the importance of stormwater runoff at the watershed scale. A ranking system needs to be developed to prioritize BMP installation at sensitive water crossing points. Such a system should be based on both the estimated magnitude of the pollutant loading at a crossing point as well as attributes associated with the receiving water such as whether it is a water supply source, Class 1 water, associated with an endangered species amongst others. Finally, additional field data should be collected for emerging pollutants of concern that may be associated with roadway runoff such as microbial organisms and organic contaminants.

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1. Introduction

UNC Charlotte researchers were contracted by NC DOT to monitor and characterize pollutants in highway runoff from several roadway sites across North Carolina as part of NC DOT's Nationwide Pollution Discharge Elimination System (NPDES) permit requirements (Wu and Allan 2001). This study was initiated in July 1999 and was completed in March 2001. The study involved the establishment of ten monitoring locations distributed throughout the Blue Ridge, Piedmont and Coastal Plain physiographic regions of the state. These sites represented different blends of pervious/impervious area ratios and traffic volumes and are exposed to different climatic regimes unique to each area of the state. The data collected at each location included precipitation volume, duration and intensity, bulk precipitation chemistry (for a select number of storms), runoff volume and distribution and volume weighted runoff chemistry. Chemical variables examined included total suspended solids (TSS), specific conductance, pH, chloride (Cl^-), ammonium nitrogen (NH_4-N), nitrate nitrogen (NO_3-N), total kjeldahl nitrogen (TKN), total phosphorous (TP), ortho phosphorus (ortho-P), chemical oxygen demand (COD), oil and grease (O&G), cadmium (Cd), nickel (Ni), copper (Cu), lead (Pb) and zinc (Zn).

Data from Wu and Allan (2001) are in fact point measurements and are best utilized to estimate average pollutant concentrations contained in runoff and annual pollutant loadings for the ten NC highway sites examined. A natural extension of the original highway runoff characterization involves the development of a methodology to estimate NPS pollutant loading from roadways on a watershed or highway segment scale. The ability to quantify NPS runoff pollutant exports from NC Highways with a scientifically defensible methodology will provide NC DOT and state regulators with a tool to assess the overall importance of highway source pollutants in relation to other pollutant sources in watersheds of concern. Once such a NPS loading methodology was established other pollutants not considered in the original runoff characterization study such as pathogens (e.g. fecal coliform), and organic contaminants could be assessed as concentration data and loading relationships became available. The development of a methodology to calculate NPS roadway source pollutants in combination with existing digital, GIS-based water quality and/or wetland sensitivity indices could also be used by NC DOT to help prioritize the installation of stormwater BMPs as required under the current NPDES permit. In this report we summarize the development of regression-based pollutant loading models for stormwater runoff from NC highways. Regression models developed for highway sites in NC are compared to models developed by Irish et al. (1998) for highway sites near Austin, Texas. Traditional photogrammetry-based digital elevation models (DEMs) and newly acquired Lidar digital topographic data are assessed as to their utility in defining road corridor drainage areas along the I-40 corridor in eastern N.C. A methodology of applying regression-based pollutant loading models within a GIS was investigated.

2 Literature Review

The issue of NPS pollutant loadings from highway runoff has become an important issue in this nation over the past twenty years. In the National Water Quality Inventory, 1990 Report to the Congress, states estimated about 30% of identified cases of water quality impairment were attributable to storm water discharges or nonpoint sources of pollution (NPS) (U.S. EPA 1990). Among the various nonpoint sources, agricultural runoff, urban runoff and mining drainage contribute over 90% of the pollution problems in assessed rivers. The several million miles of highway throughout the United States represent a known source of NPS pollution. Water-quality impacts due to highway runoff could be significant particularly in environmentally sensitive areas such as wetlands, groundwater recharge zones, and drinking water supply watersheds. The impact of highway runoff on water resources has traditionally been aggregated with urban runoff. In an effort to develop a comprehensive watershed management program, highway runoff must be considered as a separate component of the overall NPS accounting budget. Prompted by the Clean Water Act Amendments, the U.S. Environmental Protection Agency (EPA) was required to establish a NPDES for the stormwater permitting program to characterize storm water discharges and develop pollution prevention plans and best management practices (BMPs). While a considerable amount of monitoring data exists for stormwater runoff from urban areas (e.g. Wu and

Ahlert 1978, U.S. EPA 1983, Marsalek 1991, Novotny and Olem 1994, Makepeace et al. 1995, Robinson et al. 1996 and Wu et al. 1996), a limited amount of highway runoff data has recently been collected (Chui et al. 1982, Stotz 1987, Driscoll et al. 1990, Irish et al. 1995, Smith and Lord 1990, Wu et al. 1997, and Wu and Allan 2001).

For this study we conducted an extensive literature review to summarize research related to the simulation of highway runoff pollutant loads by statistical models.

2.2 Simulation of highway pollutant loads by statistical models

Kobriger et al. (1981) using data from two highway sites in Milwaukee, and individual sites from Denver, Pennsylvania and Nashville developed a characterization model for TS loading. These sites consisted of 100% impervious bridge deck sites, urban curb and gutter sites and rural highway sites with grassed swales. Each predictive model examined in this study was based on TS loading with TS loading modeled through a wash-off type model. The model applicability and predictive ability was not defined in this report. Mar and Horner (1982) developed a model for constituent loadings for Washington State. Pollutant loadings were determined from the product of the TSS loading and a proportionality constant. The TS loading was determined by the type of highway and ADT.

In the 1980's, Kerri et al. (1985) developed forecasting regression equations for estimating pollutant loads in runoff from highways in California. Data were collected during the wet seasons at completely paved urban highway sites in Redondo Beach, Walnut Creek, and Sacramento. Information was also obtained from a rural site near Placerville. Rainfall and runoff were monitored continuously. Bubbler flow meters were used in conjunction with automatic sequential samplers so that runoff samples could be collected to characterize entire storm events. The major constituents that were analyzed included boron (B), total Pb, total Zn, NH-N, NO_3-N , TKN, TP, ortho-P, O&G, non-filterable residue (NFR), filterable residue (FR), total Cd, and COD. The number of vehicles during a storm was evaluated and accepted as a satisfactory independent variable for estimating the loads of total Pb, Zn, FR, COD, and TKN. The total residue (TR) was evaluated and accepted as a satisfactory independent variable for estimating event loads of Zn, NFR, and COD. It was recommended that the use of these pollutant-loading equations should be limited to completely paved highway sites in semi arid regions (18”-24” annual rainfall) with average daily traffic of at least 30,000 vehicles. The number of dry days between storm events and the corresponding cumulative traffic volume before the storm were not found to be statistically significant for quantifying cumulative constituent loads. Apparently, traffic generated turbulence tended to prevent the accumulation of pollutant constituents on the paved traveled lanes and shoulders that were studied in this project.

No statistically significant correlations at the 5 percent level of significance were found with any of the independent variables examined in this study for the following constituent loads: B, Cd, NH_4-N, NO_3-N, TP, ortho-P, O&G. The following constituents exhibited a first flush pattern with relatively insignificant loads and concentrations: sulfate (SO_4^{2-}), iron (Fe), chromium (Cr), Copper (Cu), Manganese (Mn), Nickel (Ni), bicarbonate (HCO_3^-), carbonate (CO_3), calcium (Ca^{2+}), magnesium (Mg^{2+}), chloride (Cl^-), Mercury (Hg), molybdenum (Mb), potassium (K^+), silica (Si), and sodium (Na^+).

Because storm periods examined during this study included both the a.m. and p.m. peak traffic, the projected Average Daily Traffic (ADT) was used to compute constituent loads by using the following linear regression equations, which were evaluated and found to be acceptable predictors (t-test for significance of slope) for each chemical constituent.

$$Pb = 14.3\ 1- 0.00189(ADT) \qquad 2.1$$

$$Zn = 14.3 + 0.00060(ADT) \qquad 2.2$$

$$FR = 5360 + 0.140(ADT) \qquad 2.3$$

$$COD = 3590 + 0.221\ (ADT) \qquad 2.4$$

$$TKN = 150 + 0.00342\ (ADT) \qquad 2.5$$

Where Pb, Zn, FR, COD, and TKN are the cumulative loads in grams per storm. The intercepts represent initial dry loads in grams, and the slopes represent the washoff rate of constituent in grams per ADT during a storm. The relatively large intercepts for COD and FR indicate that a first flush of particulate matter can be expected to consist of some organic materials. To forecast an annual load, each of the daily loads is multiplied by the expected number of one-day events (events of at least 24 hours in duration), per year to arrive at an annual load.

A primary motive of this study was to develop a series of regression relationships to estimate event concentrations from a subset of water quality constituents that were relatively easy to measure in order to reduce the analytic costs of future runoff monitoring. The following linear regression equations were developed to use total residue to calculate constituent loads of Zn, COD and NFR in grams per storm:

$$Zn = 11.5 + 0.00064\,(TR) \qquad 2.6$$

$$COD = 3600 + 0.2\,14\,(TR) \qquad 2.7$$

$$NFR = 760 + 0.65\,(TR) \qquad 2.8$$

The intercepts represent the initial dry loads in grams, and the slopes represent the fraction of constituent found in the TR that is washed from the pavement during the storm. However, it should be noted that there were no correlation coefficients (R^2) reported by the authors, only that the equations were significant at a 5% significance level (Kerri et al. 1985).

Ellis et al. (1986) developed a predictive regression-based pollutant loading model utilizing precipitation and runoff parameters and that was able to reflect the variability of precipitation events. In their study ADP was found to be a significant predictive variable for EMC but not for mass loading for any precipitation event. Four statistical methods were presented by Barks (1995) to adjust regional regression equations to site-specific applications to estimate urban (including roadways) stormwater quality. The original regional regression equations were developed from the Nationwide Urban Runoff Program (NURP) and utilize easily measured physical, land use and climatic characteristics as explanatory variables (USEPA 1983, Driver et al. 1990).

Irish et al. (1998) used regression models to analyze highway storm water loading. In their study, storm-water data collected from an expressway in the Austin TX area were used to develop regression models for predicting loads for a number of constituents commonly found in highway runoff. Both natural and artificial rain events were examined. The goal of the model development was to identify the processes that affect the quality of highway runoff rather than simply predicting the total pollutant loading from a storm event. Multiple linear regression was selected as the most appropriate technique for analyzing the data because of its ability to identify constituent specific causal variables. The regression equations indicated that the majority of variations observed in highway storm-water loading could be explained by causal variables measured during the rainstorm event, the duration of the antecedent dry period (ADP), and the characteristics of the previous rainstorm event. Loads for each of the constituents were dependent upon a unique subset of the identified variables, indicating that processes responsible for the generation, accumulation, and wash off of storm-water pollutants are constituent specific. Loads of some constituents, such as TSS, were dependent on the characteristics of the current storm, ADP, and the preceding storm indicating the importance of buildup and wash off processes. The general form of the equation for TSS in the Irish et al (1998) study is:

$$\text{TSS (g/m}^2\text{)} = C + w\,(\text{Flow, L/m}^2) + x\,(\text{Intensity, L/m}^2\text{-min}) + y\,(\text{ADP, hours}) + z\,(\text{PINT, L/m}^2\text{-min}) \qquad 2.9$$

where: C = y-intercept

w, x, y, and z = model coefficients for their respective variables.

PINT = Intensity of Preceding Storm Event

ADP = Antecedent Dry Period

The predictive equation for the edge-of-pavement loading of TSS is determined using the coefficients shown in Table 1.1 (list of all coefficients for models). The predictive equation for TSS is therefore:

$$\text{TSS (g/m}^2\text{)} = 0.2556 + 0.3068*(\text{Flow}) + 2.0181*(\text{Intensity}) + 0.0037*(\text{ADP}) - 2.9865*(\text{PINT}) \qquad 2.10$$

Table 1.1 Summary of model coefficients (Irish et al. 1998)

1	2	3	4	5	6	7	8	9	10	11	12	13	14
Constituent (g/m^2)	N	S* (g/m^3)	R^2	C	Duration* (min)	Flow (L/m^3)	Intensity (L/m^3*min)	VDS	ADP (h)	ATC	POUR (min)	PFLOW (L/m^3)	PINT (L/m^3*min)
TSS	402	0.5482	0.93	0.2556		0.3068	2.0181		0.0037				-2.9865
VSS	401	0.063	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	6E-06			
BOD	398	0.0145	0.86	-0.0081		0.0035	0.0619	1.1E-05		2E-07			
Oil and grease	263	0.0054	0.94	-0.0004		0.003		0.00001					
Phosphorus	411	0.0005	0.9	-0.0005	3.3E-06	0.0002	0.0032			5E-09			
Nitrate	351	0.001	0.95	-0.0015		0.0006	0.0086			1E-08			
Iron	399	0.0084	0.92	-0.0028		0.0042	0.0282		2.3E-05				
Zinc	399	0.0007	0.92	0.0002	2.5E-06	0.0001				5E-09	-3.2E-06	0.0003	-0.0241
Lead	319	0.0004	0.68	0.0008		6.5E-05	-0.002	8E-08					-0.0023
Copper	398	8.1E-05	0.9	1.9E-05	3.8E-06	2.4E-05		-2E-07					

S = standard error of the estimate, Duration is length of the rain event, Flow is the runoff volume per unit area, VDS is the number of vehicles during the storm, ATC is the antecedent traffic count, POUR is the duration of the previous precipitation event, PFLOW is the runoff volume per unit area of the previous precipitation event.

The positive signs (+) preceding the coefficients of Flow, Intensity, and ADP indicate that an increase in the value of any of these variables will result in an increase in the load of TSS. Likewise, the greater the intensity of the preceding storm event (PINT), the less the resulting TSS load (i.e., there is less material remaining on the highway following a storm event of greater intensity). In fact, for a very small event preceded by a high-intensity event, the model predicts a negative TSS load. This type of phenomenon occurs when the equations are used for values outside the range of the original data. The linear relationship that has been assumed may be valid over the original data range but may be unlikely to remain so if extrapolated beyond it.

Other constituents, such as O&G, were dependent only on conditions during the current storm, such as Flow and VDS. The identification of constituent-specific explanatory variables suggests the type of mitigation that might be appropriate for each constituent in non-point-source pollution control. These researchers performed a detailed manual selection procedure that relied heavily on a scientific assessment of variable selection during their model development. The final models are all highly significant with adjusted R^2 values exceeding 0.9 (Table 1.1). Negative coefficients related to some of the predictive variables were attributed to undefined interactive effects between these variables. It should be noted that large sample sizes (N) reported from this study were developed from partial loads calculated during individual storm events which considerably inflates the N values presented in their study.

Thomson et al. (1997) developed relationships for predicting the impact of highway stormwater runoff. The predictive relationships are regression-based equations reflecting variations in the magnitude of the constituents of interest. The objective of their study was to identify a subset of constituents that could be used as surrogates for the remaining constituents as a means of decreasing the costs of collection and measurement of highway stormwater runoff quality data. The Minnesota highway stormwater quality database compiled in the late 1970's and early 1980's was employed in identifying the set of surrogate parameters. The findings indicated that TSS, TDS, total volatile solids (TVS), and TOC were effective surrogate parameters for numerous metals, ionic species, and nutrients. The findings also indicated that the developed ionic species constituent relationships were portable, while the metal and nutrient constituent relationships were limited to urban sites with similar environmental conditions. The general models from their study are shown as:

$$Cr = b1\ (TSS) + b2\ (TDS) \qquad 2.11$$

$$Cu = b1 + b2\ (TSS) \qquad 2.12$$

$$Fe = b1\ (TSS) + b2\ (TDS) \qquad 2.13$$

Where b1 and b2 are regression coefficients that differ between equations. Similar equations were generated for Pb, Zn, Ni, Cd, Al, Ar, Cl, Na, SO_4 by TN, COD, TKN, NO_{2+3}-N, and TP.

Wu and Allan (2001) presented research findings pertaining to the implementation of a comprehensive monitoring program for the characterization of North Carolina highway runoff. They examined ten monitoring sites distributed across the Piedmont (6 sites), Blue Ridge (2 sites) and Coastal Plain (2 sites), with contributing drainage areas ranging from 0.15 to 13.26 acres. Roadway imperviousness and traffic volumes ranged from 22% to 100% and 9,400 to 78,800 vehicles/day both directions, respectively. Rainfall-runoff data and composite storm water samples were obtained from 237 storm events. The effectiveness of vegetative best management practices

(BMPs) was assessed by comparing pollutant exports from three groups of paired monitoring sites. A database was established for estimation of seasonal and annual pollutant loads and event-mean-concentrations (EMCs).

Multiple regression analyses for site-averaged unit event loads for a variety of water quality constituents in the Piedmont were performed and are summarized below:

$TSS = -643.21 + 4.45 \times 10^{-3}$ (ADT) + 19.64 (Imp)	$R^2 = 0.87$	2.14
$TDS = 346.33 + 4.25 \times 10^{-3}$ (ADT) + 3.12 (Imp)	$R^2 = 0.87$	2.15
$COD = 111.62 - 0.90 \times 10^{-3}$ (ADT) + 6.88 (Imp)	$R^2 = 0.84$	2.16
$TKN = 3.72 - 0.025 \times 10^{-3}$ (ADT) + 0.244 (Imp)	$R^2 = 0.89$	2.17
$NH_3\_N = -3.21 + 0.019 \times 10$ (ADT) + 0.132 (Imp)	$R^2 = 0.79$	2.18
$NO_{3+2}\_N = -2.03 + 0.049 \times 10^{-3}$ (ADT) + 0.094 (Imp)	$R^2 = 0.89$	2.19
$TP = 2.65 - 0.025 \times 10^{-3}$ (ADT) + 0.021 (Imp)	$R^2 = 0.77$	2.20
$OP = 2.55 - 0.025 \times 10^{-3}$ (ADT) + 0.003 (Imp)	$R^2 = 0.70$	2.21

where ADT is the average daily traffic (both directions) at a site and Imp stands for percentage of impervious drainage area for each site.

EMCs for Cd, Cr and Ni were generally found to be below method detection limits (MDLs) at all sites. Pb was typically at or slightly above MDLs. Zn was consistently well below the secondary drinking water standard of 5 mg/L. Site average EMCs for COD, NH_3-N, TKN, OP and TP were generally within the North Carolina urban runoff concentration ranges. All monitoring sites exhibited site median EMCs ranging from 10% to 25% below the national rural highway runoff concentrations. TKN was found to be 25% below the national urban highway runoff average concentration. The annual runoff loadings expressed as lb/ac-yr for COD, TKN, NH_3-N, NO_{3+2} -N and TP in North Carolina highway runoff were found to be within the lower percentiles (10-30%) of the national highway runoff data, when the reported national data range is linearly scaled between its upper and lower values.

Pervious vegetated shoulders and medians were found to be effective in reducing TSS and its associated pollutants. However, pervious roadside surfaces were sometimes found to export higher runoff loadings of COD, P and N when compared to equivalent impervious surfaces. The reduction of pollutant export in highway runoff could largely be attributed to infiltration losses as runoff moves over the pervious surfaces and efforts to maximize infiltration capacity of these surfaces should be encouraged.

In their 2001 study the authors compared loading totals for TN based on their highway runoff database with export functions for total nitrogen (TN) derived from North Carolina urban watersheds using Schueler's "Simple Method"(Schueler 1987).

$$TN\ (lb/ac\text{-}yr) = [\ (P)\ (Pi)\ (Rv)\ /\ 12]\ (C)\ (2.72) \qquad 2.22$$

Where P = annual rainfall, inches

Pi = correction factor for excluding storms without measurable runoff (0 to 1).

Rv = Runoff Coefficient

C= Flow weighted mean concentration of TN, mg/L

When the coefficients P, Pi, Rv and C were adjusted to data derived from Wu and Allan's (2001) study nitrogen loading estimates based on the Simple Method were as much as 0.68 times lower for Blue Ridge and Piedmont highway sites than for model outputs for urban areas based on the "New Development Scenario". TN loadings derived for coastal plain highways deviated significantly from Piedmont and Mountain sites and were approximately 67% those estimated for the other regions of the state for highway surfaces with 100% impervious cover.

3 Methodology

3.1 The application of a GIS to identify highway crossing points of sensitive waters

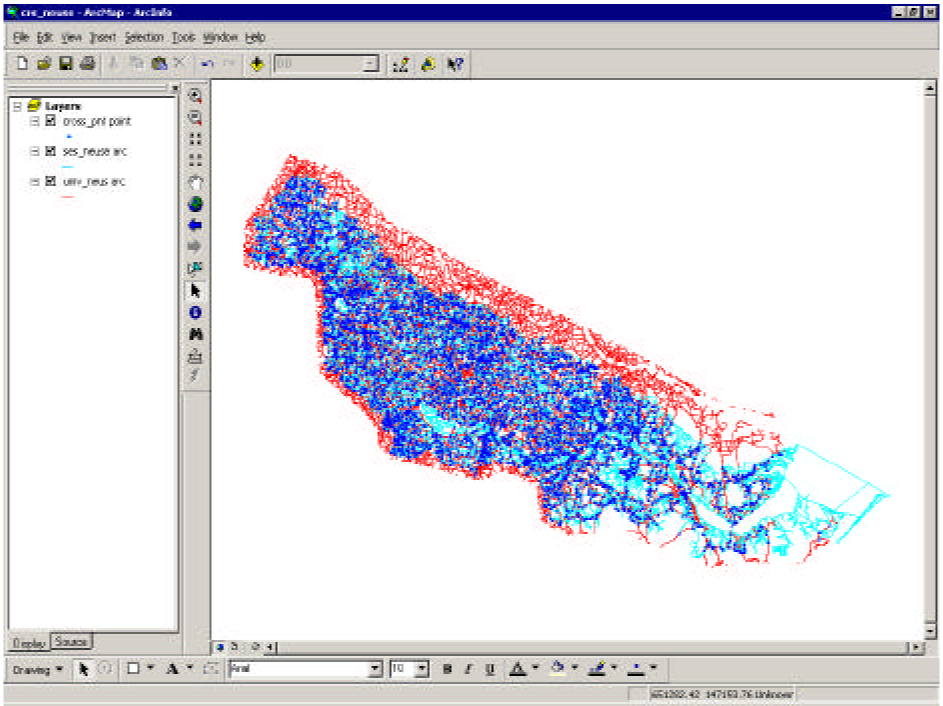
The locations of the most concern with regard to highway runoff are the intersections of highways and streams. Of particular concern are those crossing points identified close to sensitive waters. An study has been completed to implement a GIS-based methodology to automate the identification of these crossing points (Wu 2003). In order to study highway runoff outfalls at these intersections, GIS was used to overlay stream and highway layers, creating a point at each crossing. These crossing points were linked to both the stream and highway databases. In this project, a digital coverage of sensitive waters defined as High Quality Water/Outstanding Resource Waters and Anadromous Fish Spawning Areas represented the stream layer. The digital transportation system file supplied by NCDOT was comprised of four types of roads: interstate, US and NC highways, and secondary roadways. Other information such as road surface, median, left and right shoulder conditions and widths, type of improvement, number of lanes, route number, mile post, and inventory control was also provided. After creating crossing points for the entire state, crossing points based on discrete basins and NCDOT operational divisions were derived. The crossing point coverage for the Neuse River watershed is presented in Figure 3.1

In this study all crossing points were linked with attribute information from the associated stream and roadway. This provides a foundation upon which future analysis can be built. Of particular relevance to this study are the traffic and roadway attributes that can be used as inputs to statistical loading equations.

3.2 Integrated GIS with Wu and Allan's pollutant loading models for North Carolina Highways

The application of GIS into a highway environmental project is a relatively new approach. GIS, with its data visualization capabilities, provides a useful and objective tool to better understand and quantify the contribution of Non Point Source highway pollutant loadings across the state. This has the potential to facilitate management decisions through the utilization of the NCDOT GIS database, which contains information including right of way, highway width and type, highway widths and types of left and right shoulders, average number of vehicles, etc..

Figure 3.1 Crossing Points in Neuse River Basin (Total 5223 crossing points)



Wu and Allan's (2001) annual pollutant loading relationships (Eq. 2.11-2.18) between site-averaged annual load (mg/m^2) and Average Daily Traffic (ADT) and a site's Imperviousness (Imp, %) represent a simple and practical methodology that can be applied within a GIS. In the current NC DOT GIS database, Average Daily Traffic is readily available. Although some of this data might be slightly out of date for some sites, it can be used as a reference so that at least an approximate range of pollutant loadings from highways can be estimated. The percentage of imperviousness in Wu and Allan's study was directly surveyed in the field and included the surface area of the highway as well as pervious areas flowing into the collection point. Aside from the ten sites from the previous NC DOT project, there is no percent impervious cover variable available in the current highway databases. As an initial proxy, we have attempted to use variables in the existing database such as lane width, number of lanes, type of right of way, width and type of shoulder, and width and type of median to calculate the percentage of imperviousness in the GIS environment through a process we have called the imperviousness variable derivation (IVD).

3.2a Imperviousness Variable Derivation in GIS

The principle of impervious variable derivation is to calculate the percentage of imperviousness of the area of highway surface as compared to the total area of the right of way for a unit length of highway. The highway variable in the data set is generally composed of the width of the hard surface (specific types may vary), left and right shoulder width, and median width. The right of way usually covers all of the above surfaces and land extending from the shoulders to the edge of the highway right of way. In most cases, these extensions are grass or vegetated land and for this study it was assumed that the edge of shoulder to edge of roadway margins were hydraulically pervious.

In the GIS roadway database, Inventory Control (ICNTRL) records data in each direction of travel in order to indicate unbalanced conditions where they might exist. This column will be used to indicate the method of inventory and also to indicate common cards (A card that provides one or more user traffic interfaces (lines) is called a **line card**; a card that does not offer user traffic interfaces is called a **common card)** or gap card for which inventory data is included elsewhere. The codes will be as follows:

Both directions of travel	1
Northbound only	2
Southbound only	3
Eastbound only	4
Westbound only	5
Common card	6
Gap card	7

For the I-40 Interstate in N.C., there are only two conditions that are separated: Inventory Control equal to 1 and not equal to 1, which indicate if travel is in two directions or only one direction. The median types are distinguished into grass with curb, positive barrier or paved mountable. If the median type is grass it will be coded as the number five. It is important to distinguish whether the median is grassed or not because the grassed median will be assigned as a pervious surface and other two median types will be assigned as impervious. All left and right shoulders on I-40 are paved bituminous which are considered impervious. In summary, the situation on I-40 can be simplified as two types of conditions:

1. If the highway is two directions (ICNTRL = 1), which means two separate lanes, under two types of median conditions, the calculations are:

If "ICNTRL" = 1 and "MEDTYP" = 5:

Then Imperviousness = ([SURFWID] + [RSWIDTH] + [LSWIDTH])/([ROWNO]*10/2)

If "ICNTRL" = 1 and "MEDTYP" <> 5:

Then Imperviousness = ([SURFWID] + [RSWIDTH] + [LSWIDTH] + [MEDWIDTH])/([ROWNO]*10/2)

Where: ICNTRL represents Inventory Control, MEDTYPE is median type. SURFWID is the surface width. RSWIDTH and LSWIDTH are the right shoulder width and left shoulder width respectively. ROWNO represents width of the highway right of way. As defined in the NCDOT database description file, if the inventory is in two directions, half the total is coded for each direction. If there is sufficient right of way beside a two-lane section to construct parallel lanes, this is indicated with a number. The multiplication by 10 and division by 2 is a transfer of units because the code of the right of way is most representative of the record to the nearest ten feet.

2. If the highway is one direction and with divided highway there will be two types of median conditions. The calculations are:

If "ICNTRL" <> 1 AND "MEDTYP" = 5

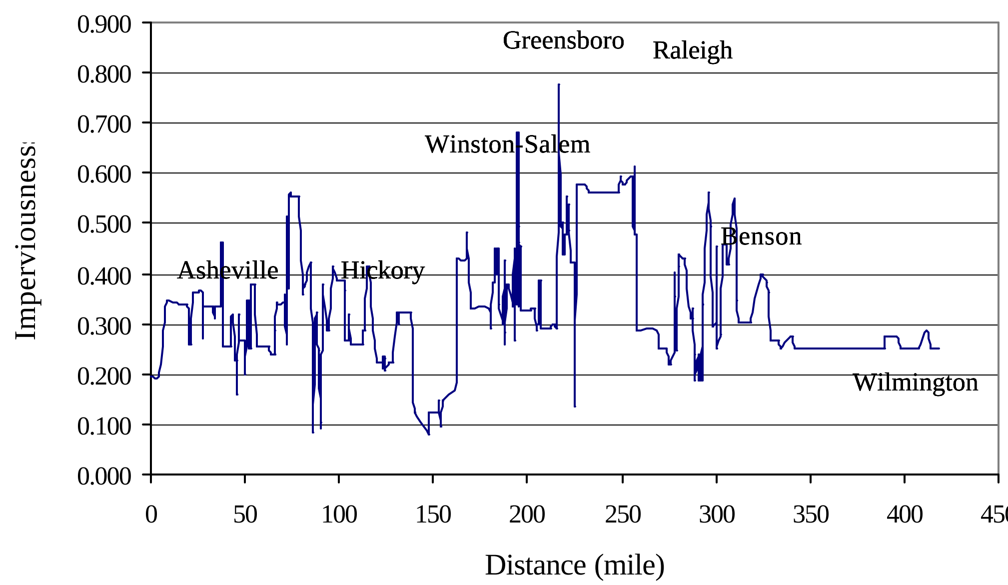
Then Imperviousness = ([SURFWID] + [RSWIDTH] + [LSWIDTH])/([ROWNO]*10)

If "ICNTRL" <> 1 AND "MEDTYP"<> 5

Then Imperviousness = ([SURFWID] + [RSWIDTH] + [LSWIDTH] + [MEDWIDTH])/([ROWNO]*10)

Based on the above four conditions, the entire distribution of “imperviousness” along the I-40 corridor within NC can be calculated in the ArcGIS environment as performed in a GIS attribute table. The results can then be converted to a dbase or Microsoft Excel worksheet to generate longitudinal plots of highway and traffic attributes as illustrated in Figure 3.2. This graph shows that regions of consistently high impervious cover are located near Greensboro while a minimum exists between Hickory and Winston Salem.

Figure 3.2 Imperviousness along I 40



3.2b Pollutant Loading along NC I-40

Since the estimate of the percent impervious cover has been calculated and daily average traffic (ADT) is available in the GIS database, pollutant loadings based on the regression models from Wu and Allan (Eq. 2.11-2.18) can be used. Graphically the data might be presented as a top view of the I-40 corridor with loading values for specific highway segments defined by the size of a symbol (e.g. Figures 3.4 or 3.5 for TDS and COD, respectively). Note that the loading for only some roadway segments is presented for clarity of the loading symbols. Alternatively, more traditional and continuous scatter plots might be utilized (e.g. Figures 3.6– 3.12). The second panel included with Figures 3.6 to 3.12 is the frequency distribution of the pollutant loading for each constituent along the I-40 corridor. In the second panel the x-axis is arbitrarily scaled into pollutant loading levels defined by the range of loading values. The magnitude of these values is defined as the average loading value of that particular loading level (negative values are explained in the following section). In the upper panels pollutant loading is represented on the x-axis and the frequency of each loading level is given on the y-axis. It should be stated here that these results should be viewed as preliminary representations of pollutant loading distributions rather than quantitative pollutant loading values. In some sections along I-40 negative loading values for TSS, NH_4-N, TP and ortho-P are evident. Both TSS and NH_4-N have negative intercepts -643 and -3.21, respectively and negative loading rates are generated when traffic counts approach 20,000 ADT and Imp is <40%. Wu and Allan specifically state that the minimum criteria for the application of these regression models are ADT values of 30,000 vehicles/day and imperviousness percentages of at least 50%. To extend the use of the relationships for all stormwater constituents (including those with non negative loading rates) it is suggested that additional runoff monitoring data be collected for sites with lower ADT counts and impervious coverage percentages. As mentioned earlier the regression relationships developed in this and other studies are only accurate for the combinational (ADT and Imp) data ranges used to derive the original relationships.

Figure 3.3 TDS Loading Distribution along I-40 Highway in North Carolina

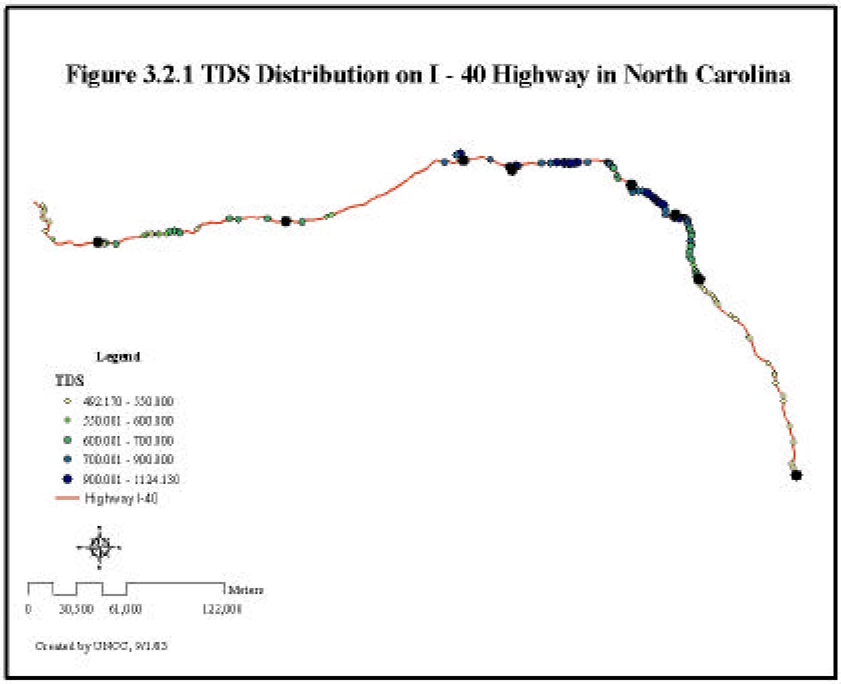


Figure 3.4 COD Loading Distributions along I-40 Highway in North Carolina

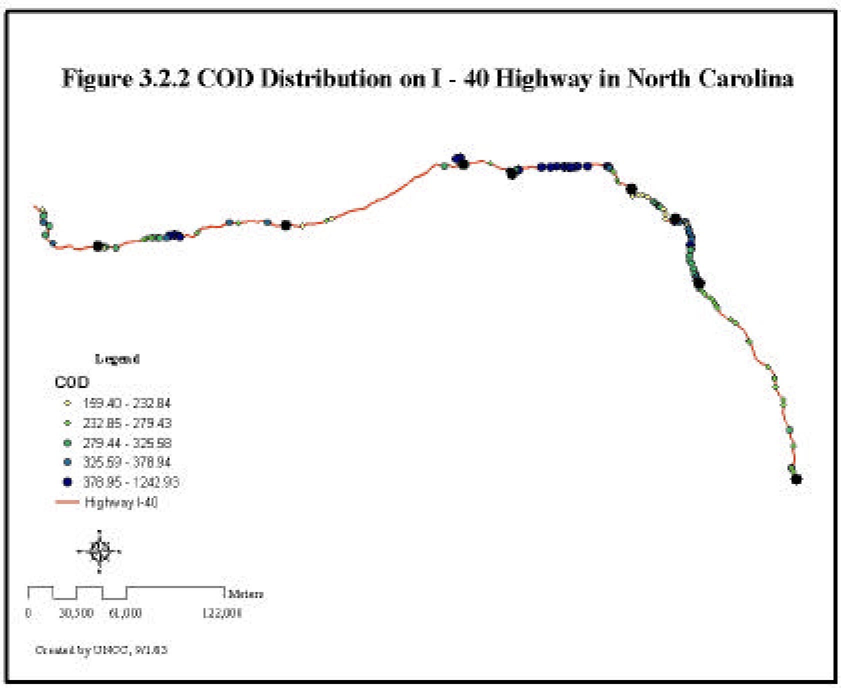
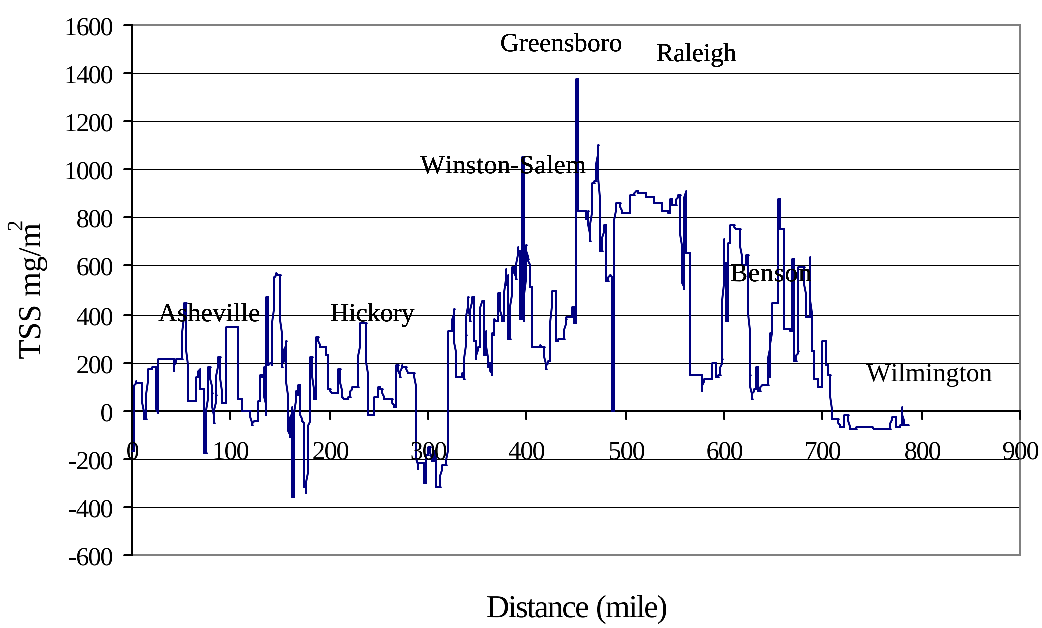
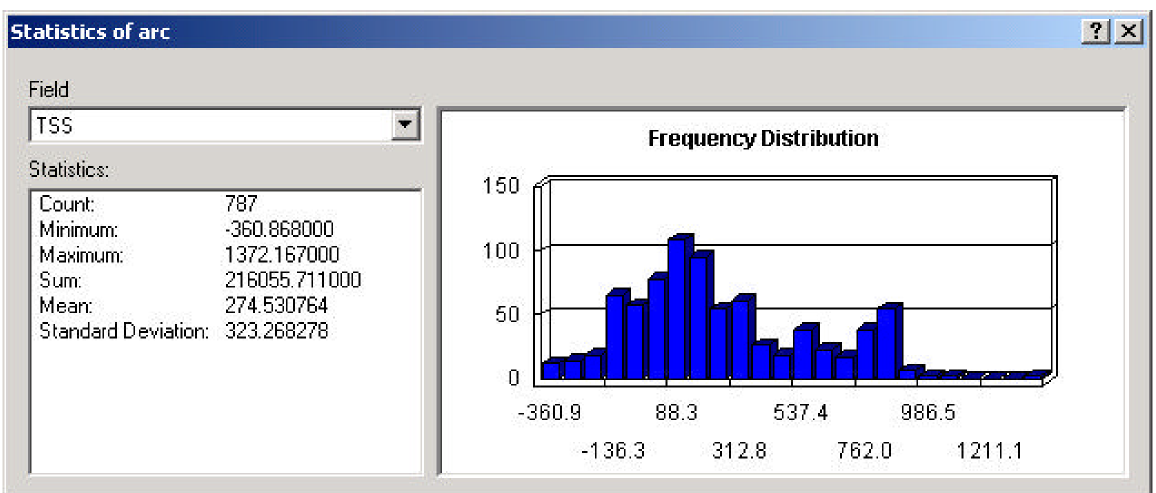


Figure 3.5 TSS along I 40



-643.21+0.00445 * [ADT] +19.64 * [IMP] *100



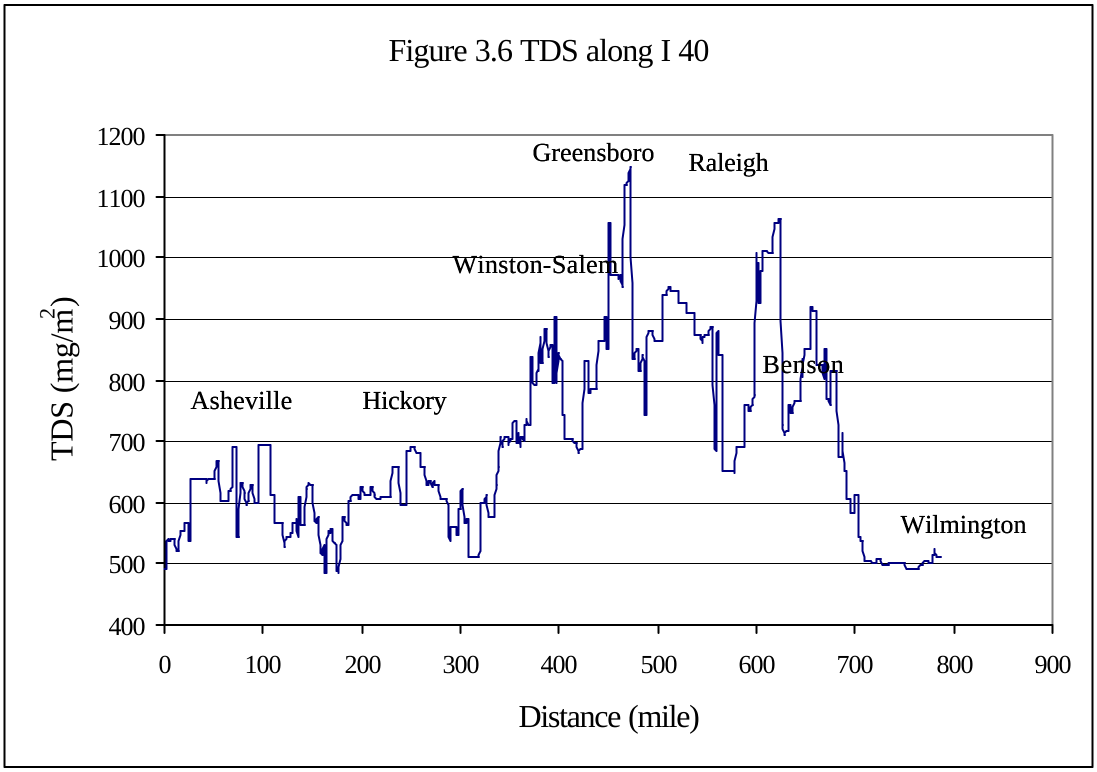
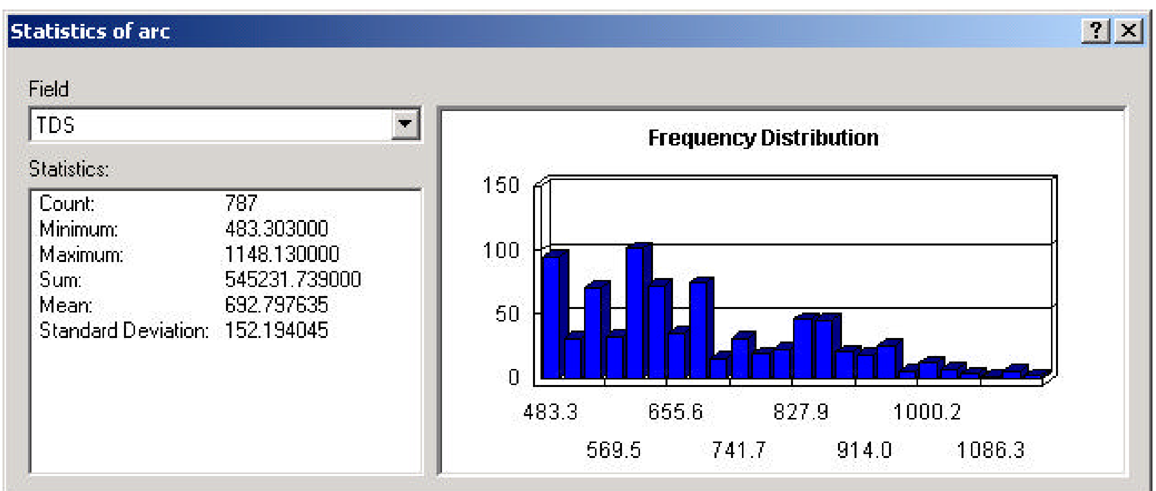
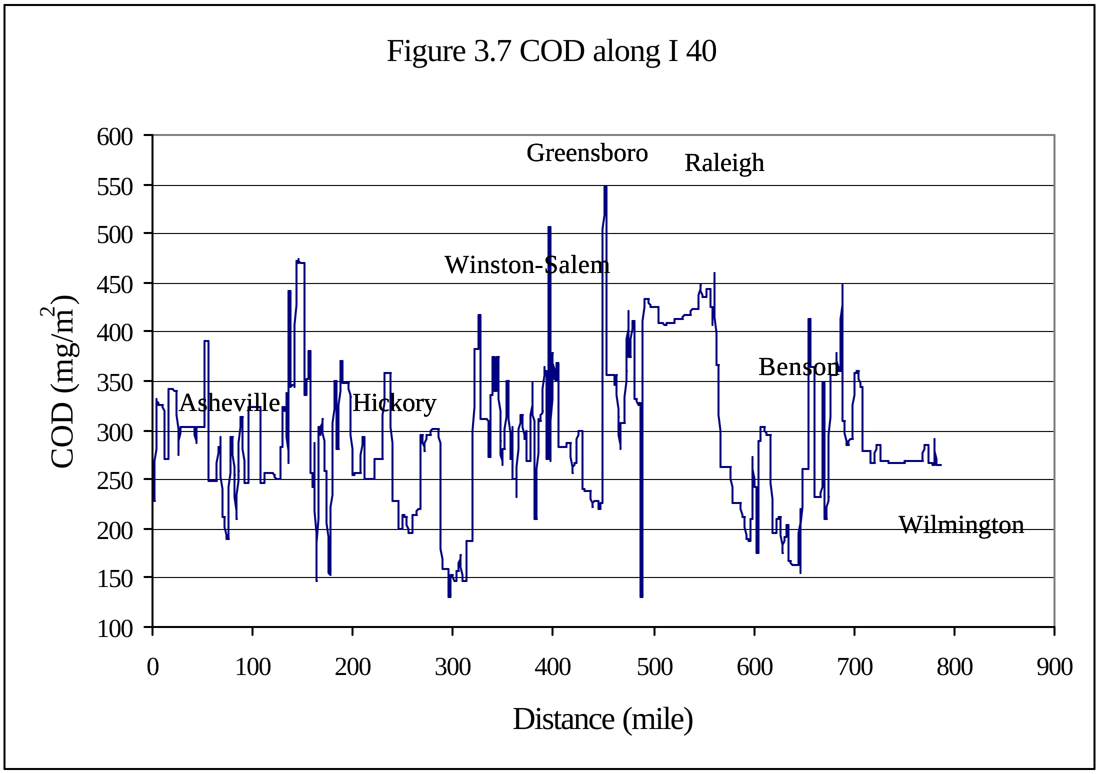


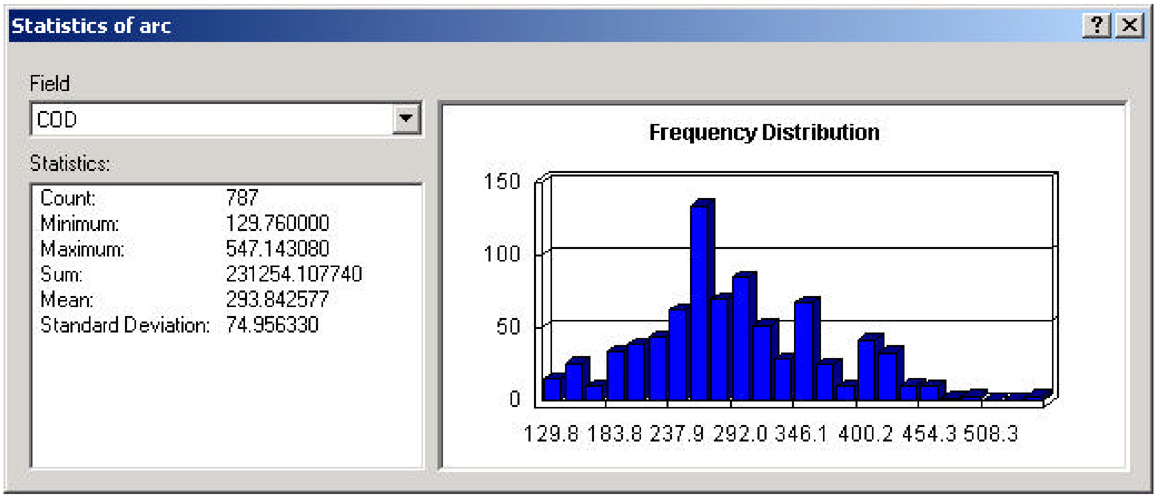
Figure 3.6 TDS along I 40

$$346.33+0.00425 * [ADT] +3.12 * [IMP]*100$$





111.62 - 0.0009 * [ADT] + 6.88 * [IMP]*100



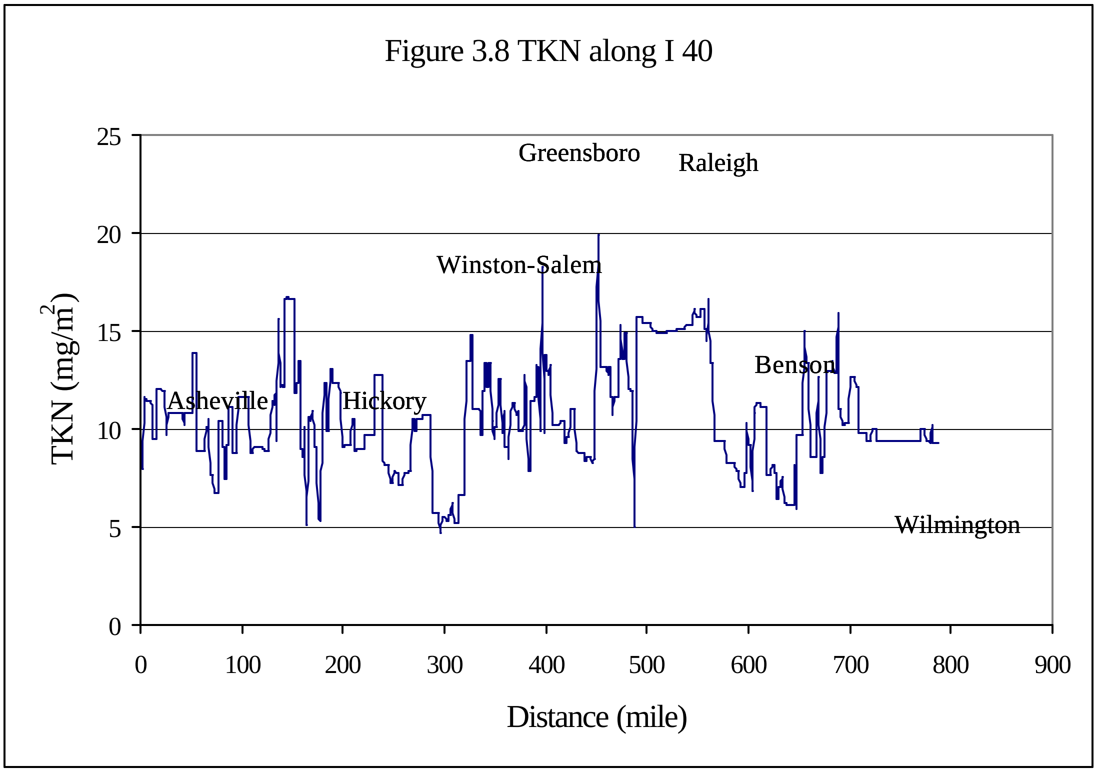
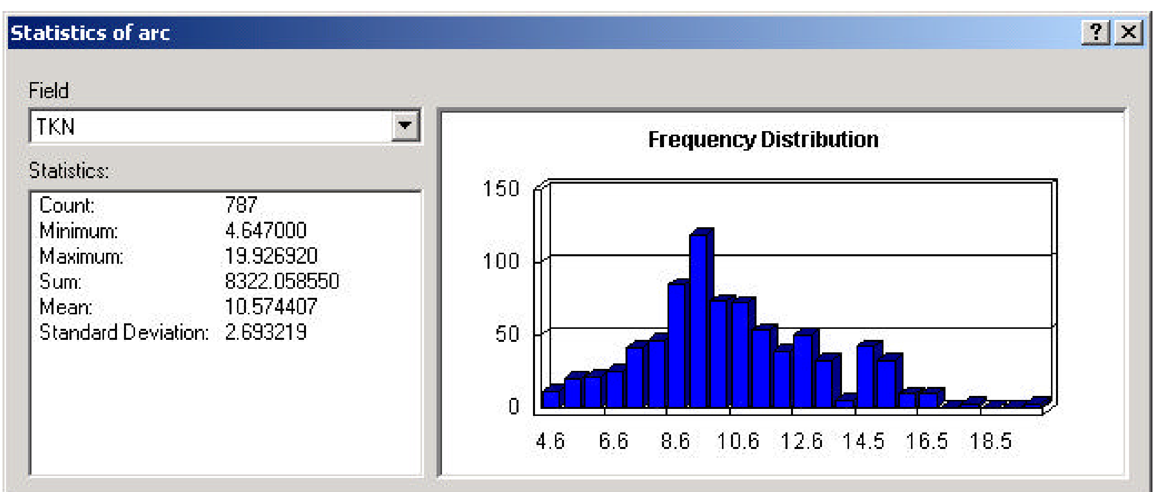
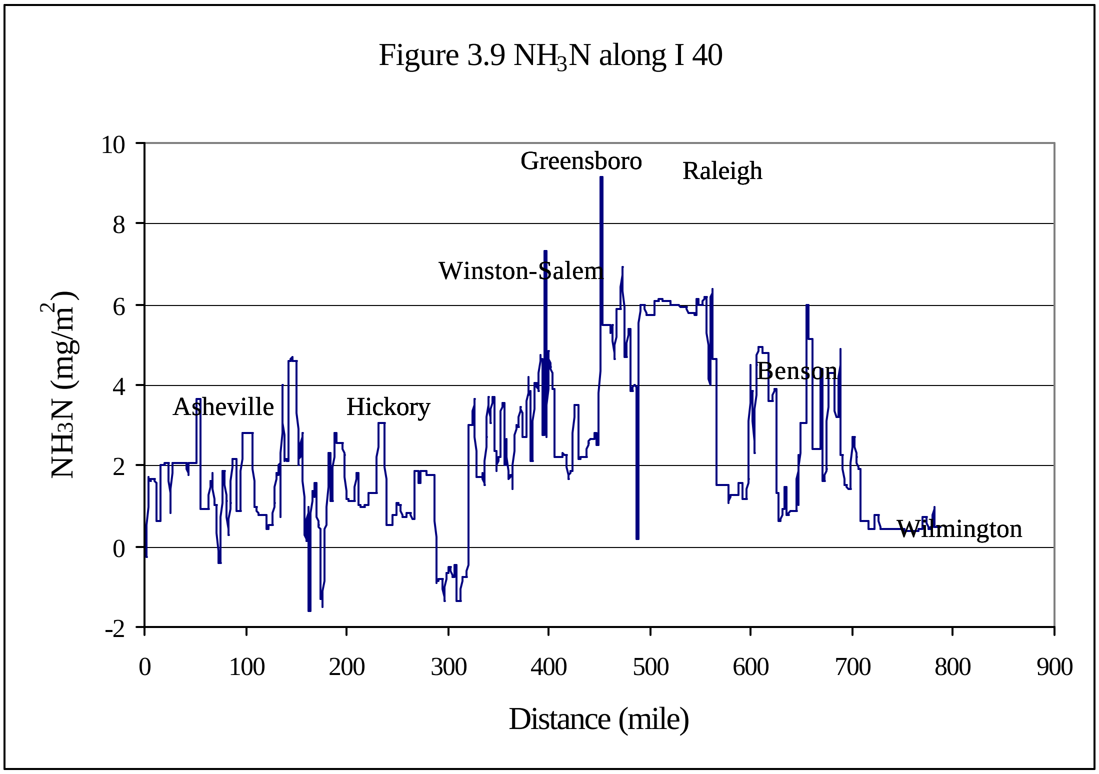


Figure 3.8 TKN along I 40

1.72 - 0.000025 * [ADT] + 0.244 * [IMP]*100





-3.21+0.000019* [ADT] +0.132 * [IMP] *100

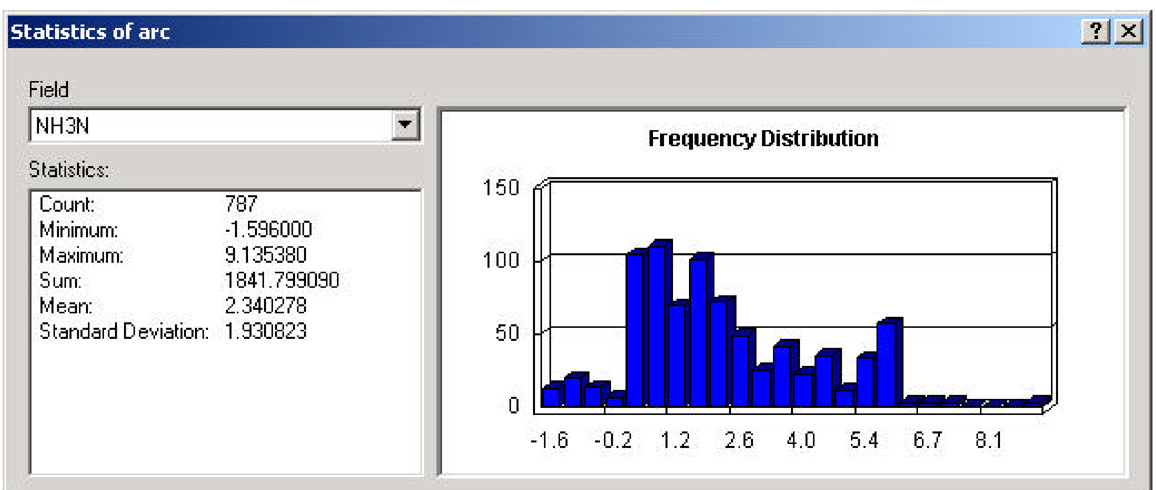
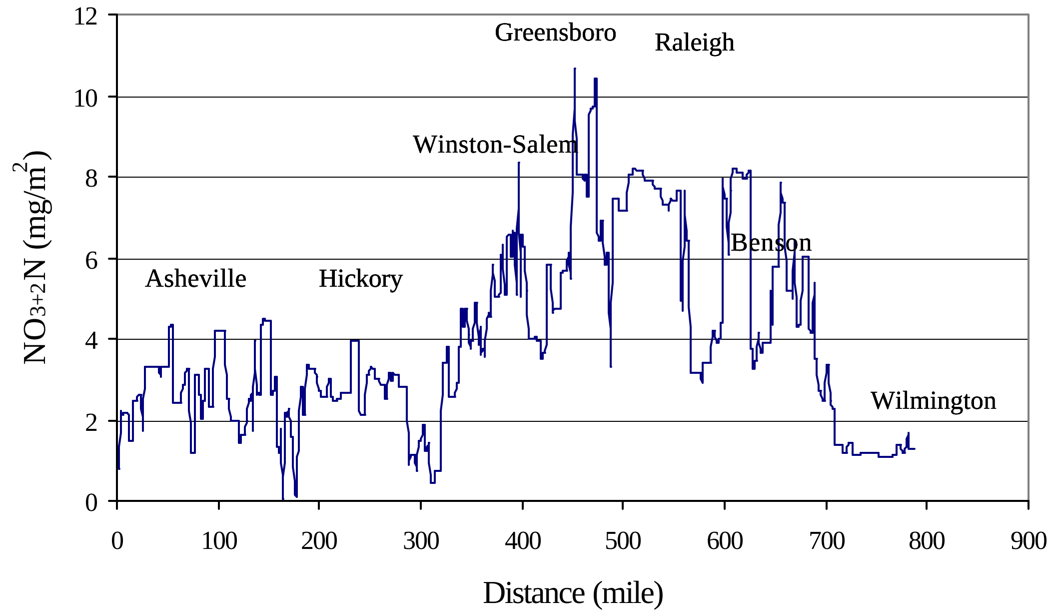


Figure 3.10 $NO_{3+2}N$ along I 40



$$-2.03 + 0.000049^* [ADT] + 0.094 * [IMP] *100$$

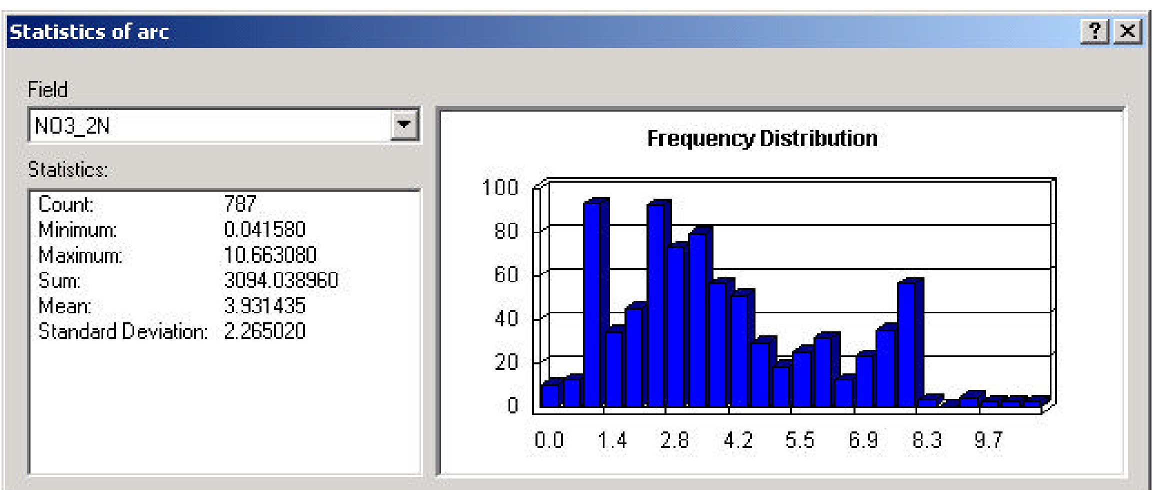
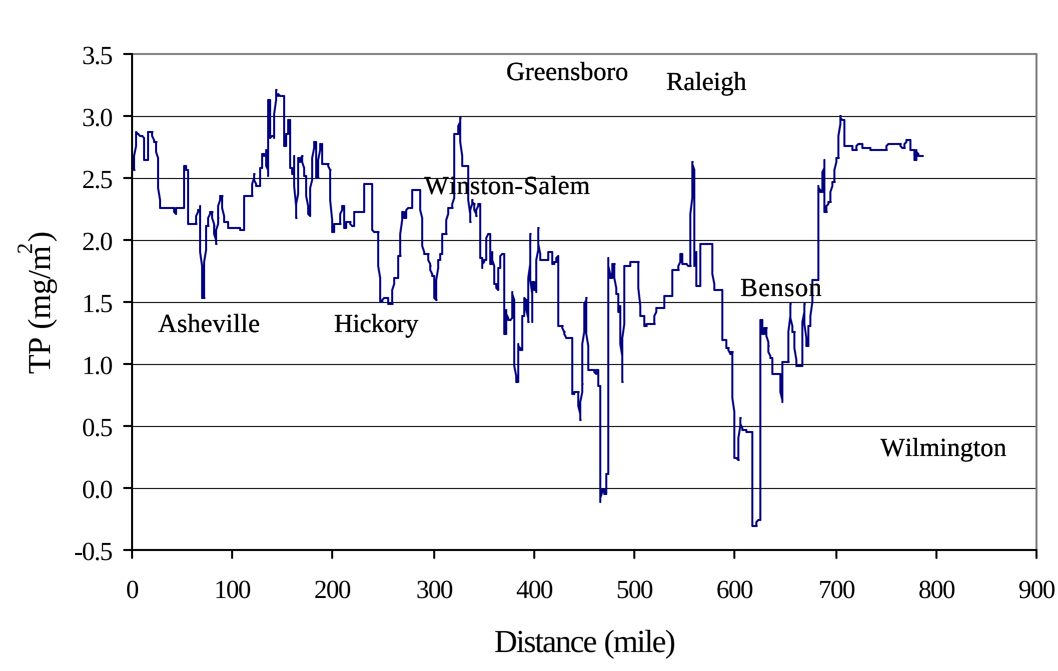


Figure 3.11 TP along I 40



2.65 - 0.000025 * [ADT] + 0.021 * [IMP] *100

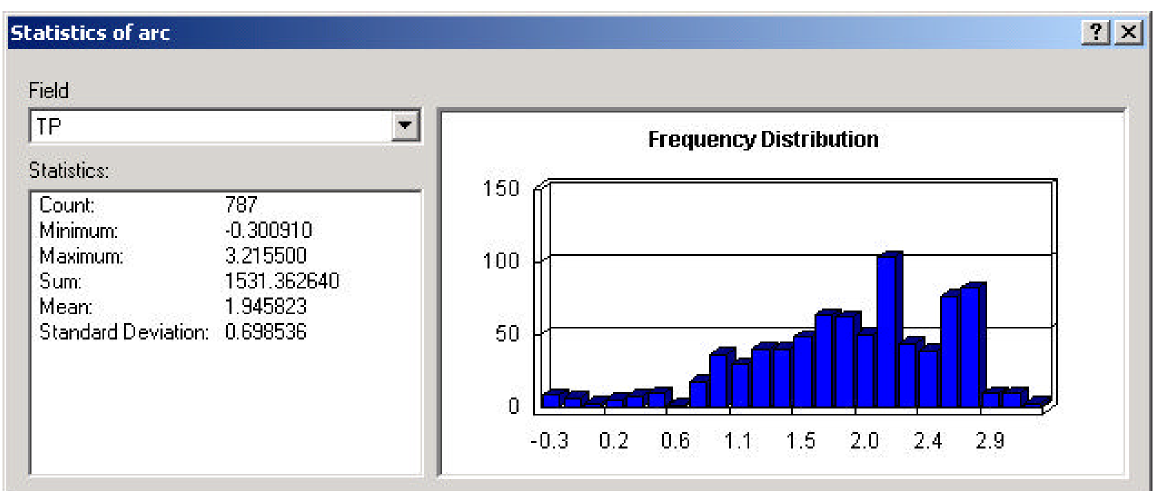
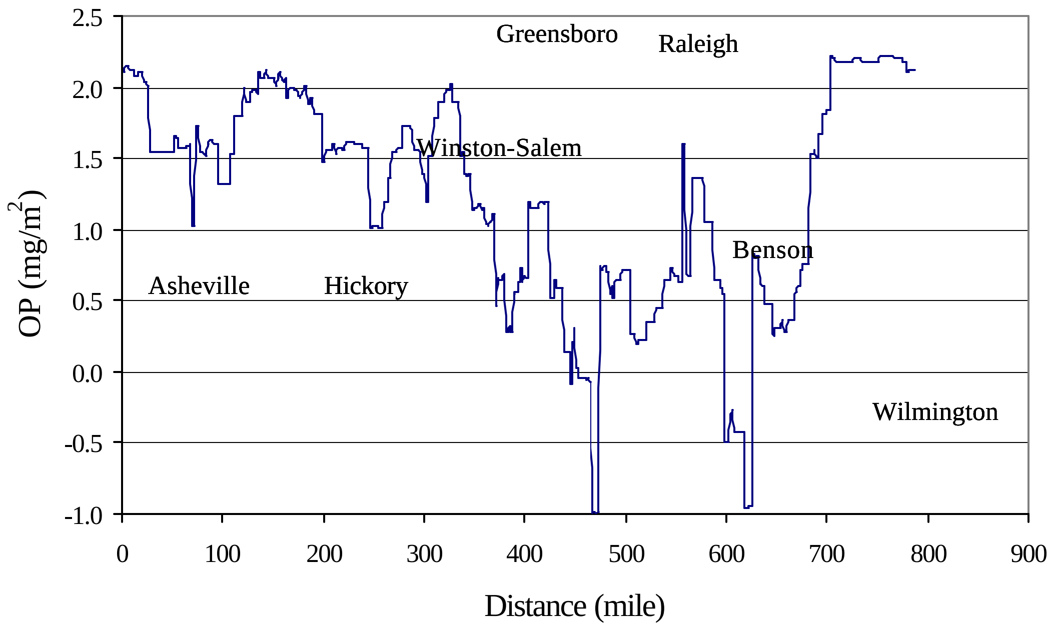
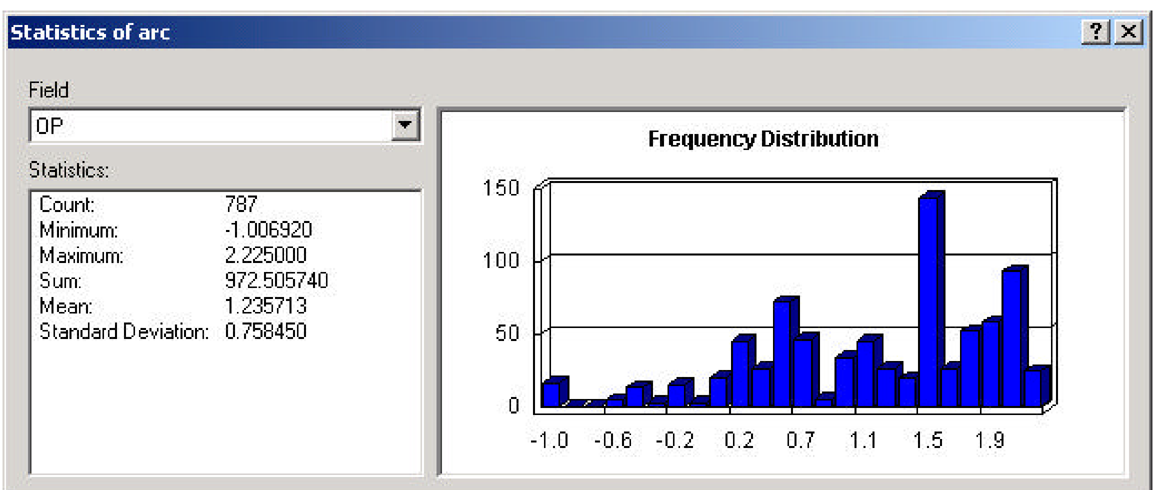


Figure 3.12 OP along I 40

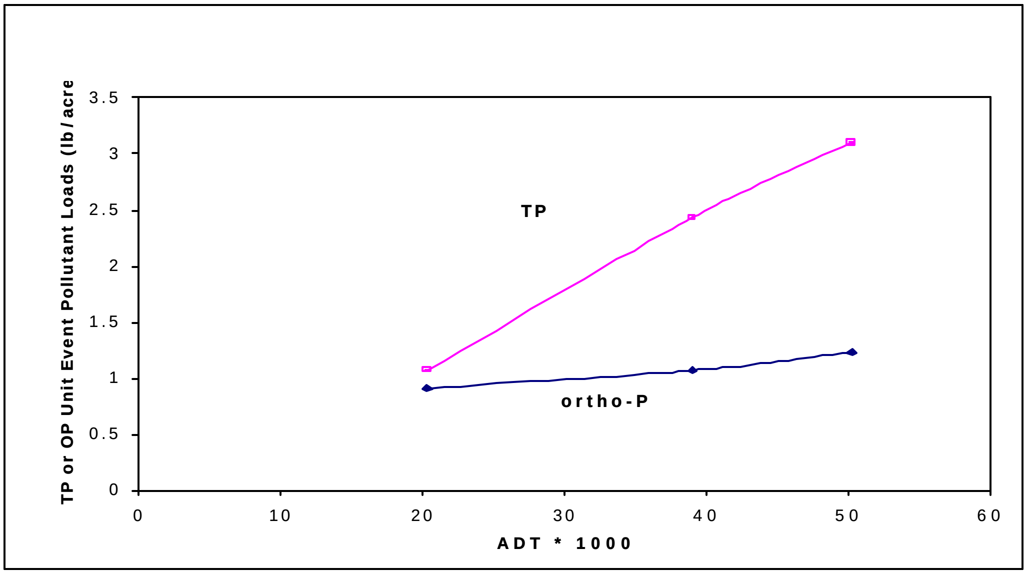


2.55 - 0.000025 * [ADT] + 0.003 * [IMP] *100



The loading relationships developed for both ortho-P and TP are more problematic in that both have negative regression coefficients associated with ADT variable. It should be noted that several of the regression relationships developed by Wu et al. (2001), Kerri et al. (1985) and Irish et al. (1998) also contain negative regression coefficient values. When applying Wu and Allan (2001) regression equations to the I-40 corridor negative pollutant loadings are generated where ADT >120,000 and Imp <40%. The regression loading equations using only ADT and Imp as predictive variables do not appear to capture the complexity of the interaction between the pervious and impervious surfaces as source areas for P. This becomes readily apparent when one examines the meant unit event pollutant loads plotted against ADT for the three impervious sites monitored during Wu and Allan's (2001) study (Figure 3.13). From their monitoring data it is clearly evident that for 100% impervious surfaces the loading of phosphorus in highway stormwater runoff is positively correlated with ADT. In Wu et als. 1996 study for a limited number of highway sites in the Charlotte area it was found that pervious highway shoulders and medians could act as a source for phosphorus. In the regression relationships under consideration small positive regression coefficients are associated with the Imp model parameter. Given the lack of a clear scientific reason for the sign of both regression coefficients and the empirical evidence contradicting the present form of these relationships the authors suggest that more complex models utilizing additional predictive variables may be required for estimating quantitative TP and ortho-P loadings in highway runoff. However, the present regression relationships are likely still useful in ranking P loading for roadway sites, particularly for the range of Imp conditions and ADT volume upon which the regressions were originally based.

Figure 3.13 Relationship between TP and ortho-P Loading and ADT for 100% Impervious Surfaces



3.3 Development of Multiple Regression Loading Models

The statistical pollutant loading models developed by Wu and Allan 2001 (Equations 2.11-2.18) predict the unit event pollutant load for North Carolina Highways based on the per cent impervious cover of a drainage area and average daily traffic volume. In this section of the report a series of multiple regression models are developed to predict pollutant loadings from highway runoff based on precipitation and runoff characteristics as well as the length of the antecedent dry period, time of year and traffic volume during storm events. These models could be used to examine the factors that explain the runoff loading for individual pollutant constituents. Such data could then be used to guide management practices to control their export from highway corridors. This form of regression equation is directly comparable to those developed by Irish et al. (1998) for Texas roadways.

3.3a <u>Variable Selection Methodology for Multiple Regression Models</u>

Multiple regression models were developed using the SPSS, v. 12.0 statistical analysis software package. This package allows for easy data entry (it will accept Excel, dbase and Access files), it has efficient syntax and analysis for hierarchical regression, and it has a professional quality output presentation. Linear multiple regression was chosen for the analysis using the backwards regression procedure. In the backward selection procedure, the initial model includes all effects specified to be included in the analysis. The initial model for these methods is therefore the largest or overfit model. Variables with the least explanatory power in the model are deleted during each model iteration. The F probability for variable entry and removal from the model was set at 0.05 and 0.10, respectively.

The variables relating to rainfall characteristics of an individual storm event included precipitation total in millimeters (Precipitation), duration of the storm event in minutes (Duration) and maximum five minute precipitation intensity in millimeters/hour (P5). Regression variable related to flow characteristics included runoff depth in millimeters/square meter (Flow) and average runoff rate in millimeters/square meter-minute (Intensity). Variables related to the rainfall event immediately preceding a monitored rainfall event included the duration of the previous rainfall event in minutes (PDUR), the runoff depth from the previous precipitation event in millimeters/square meter (PFLOW) and the average runoff intensity of the preceding rainfall event in millimeters/square meter-minute (PINT). As runoff hydrographs were not available for several unmonitored events from the (Wu and Allan 2001) study, the PFLOW total was estimated from the rainfall/runoff relationships developed by Wu and Allan and PINT was calculated as PFLOW/PDUR. Other variables included in the regression model development were day number (Day), the number of vehicles during the storm per lane of traffic (VDS), the length of the antecedent dry period in hours (ADP) and the antecedent traffic volume per lane (ATC). Units for the regression analysis were chosen to match those presented by Irish et al (1998). The dependent variables (pollutants) examined in the analysis were TSS, TDS, COD, TKN, NH_3-N, NO_3-N, TP, OP and Zn. Event mean concentrations of other chemical constituents examined in Wu and Allan's (2001) study including O&G, Cd, Cr, Pb, Cu and Ni were generally near detection levels of the analytical methodology and were excluded from this analysis. Units for the dependent variables were all milligrams/meter squared.

3.3b Development of the Variable - Traffic During Storm

During rain events solids, metals, O&G petroleum residues and other lubricants may be washed from vehicles and transported in stormwater runoff. Therefore, an accounting of the vehicle traffic during the storm is a very important variable that should be included in multiple regression pollutant-loading models. However, in-storm traffic data are generally not available and it is time and labor consuming to directly measure in-storm traffic counts. An analysis of site-specific traffic data supplied by NC DOT for the Wu and Allan (2001) study revealed consistent traffic patterns for weekends and weekdays. These site-specific traffic patterns were used to generate traffic during storm data for the monitored runoff events. The individual steps used to generate the variable 'vehicles during storms ' (VDS) follow.

3.3b1 Traffic patterns on weekdays and weekends

Since vehicle traffic during individual storms was not always available at each study site during each monitoring event, it was necessary to develop a unique model to calculate traffic during storms. For this study we utilized the traffic data collected by the Traffic Survey Unit, NC DOT during the Wu and Allan (2001) study. Traffic counts were collected on a quarterly basis with a minimum of seven days of data collected per quarter. Data at each of the ten sites monitored by Wu and Allan (2001) was collected for at least four quarters. Where possible permanent traffic volume monitoring sites were utilized. All traffic volume counts were collected using inductance loops. No post processing of the data was required. A vehicle classification count was also collected once for each site. Data was provided for each lane and summarized by direction and two-way total. For this study we used data collected from the ten study sites from the 1st October to 31st of December in 1999.

It was found that daily traffic exhibited specific patterns on weekdays and weekends. Usually, the pattern was a double peak curve on weekdays from Monday to Friday and single peak curve on weekends (Saturday and Sunday). Figures 3.14, 3.15 and 3.16 present examples of these double and single peak curves at three locations on highway I-40.

Figure 3.14 represents the weekday and weekend traffic pattern of the Highway 49 site with the city of Charlotte (CLT1) as described in Wu and Allan (2001). This site is located near UNC Charlotte and represents an urban environment so the double traffic peak is very discernable on weekdays. The first peak was in the range of 700 – 900 hours and the second peak was between 1600 – 2000 hr, corresponding with the two daily "rush hours". On weekends, only one peak was evident, lasting from 1000– 2100 hours. The greatest traffic occurred at approximately 1800 hours in both directions on this highway. The traffic volume for the I-40 site near Wilmington (Wilmington 6, Wu and Allan (2001)), was much lower than that depicted for the Charlotte site (Figure 3.15). The double rush hour traffic peaks are plainly evident with the first traffic peak corresponding to the same time period as the Charlotte site (Figure 3.14). But the second peak ranged from 1600 – 2100 hr, which was one hour longer than that exhibited by the Charlotte site. Figure 3.16 depicts the I-40 traffic pattern near Asheville (Asheville 8, Wu and Allan (2001)). This site exhibited an increasing traffic volume corresponding to the early rush hour period but traffic volume remains relatively constant until a second much higher rush hour peak. This pattern is even more evident on Friday's as tourists utilize the I-40 corridor to visit the Tennessee and N.C. mountains. Data from other Fridays were checked to confirm these results.

Although the examples presented represent only three sites, they can be considered to be representative of most typical daily traffic patterns. These data can be used to estimate traffic volume during individual storms, as will be described below.

3.3b2 Average Daily Traffic

Table 3.1 lists average daily traffic on weekdays and weekends for the Charlotte, Wilmington and Asheville sites. Weekend traffic was usually lower than weekday traffic for the Charlotte and Wilmington sites. This was especially obvious for the city of Charlotte. Asheville weekend traffic totals were generally higher than for weekdays likely as a result of tourist traffic.

Figure 3.14 Charlotte Highway 29, Traffic Distribution

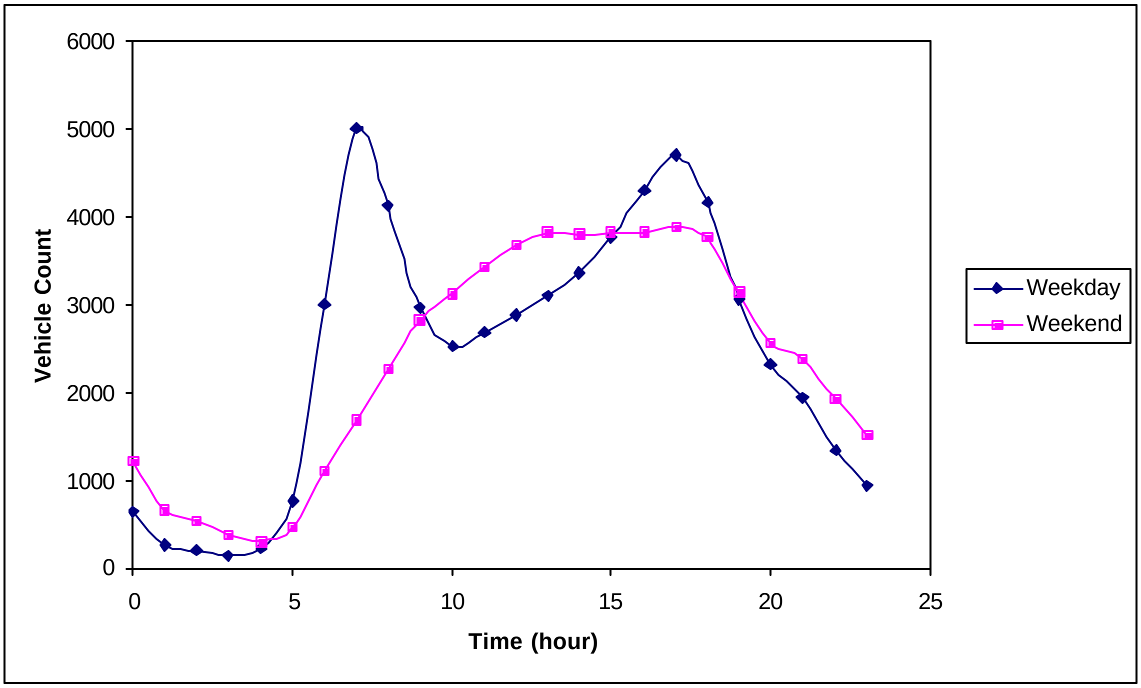


Figure 3.15 Wilmington I-40, Traffic distribution

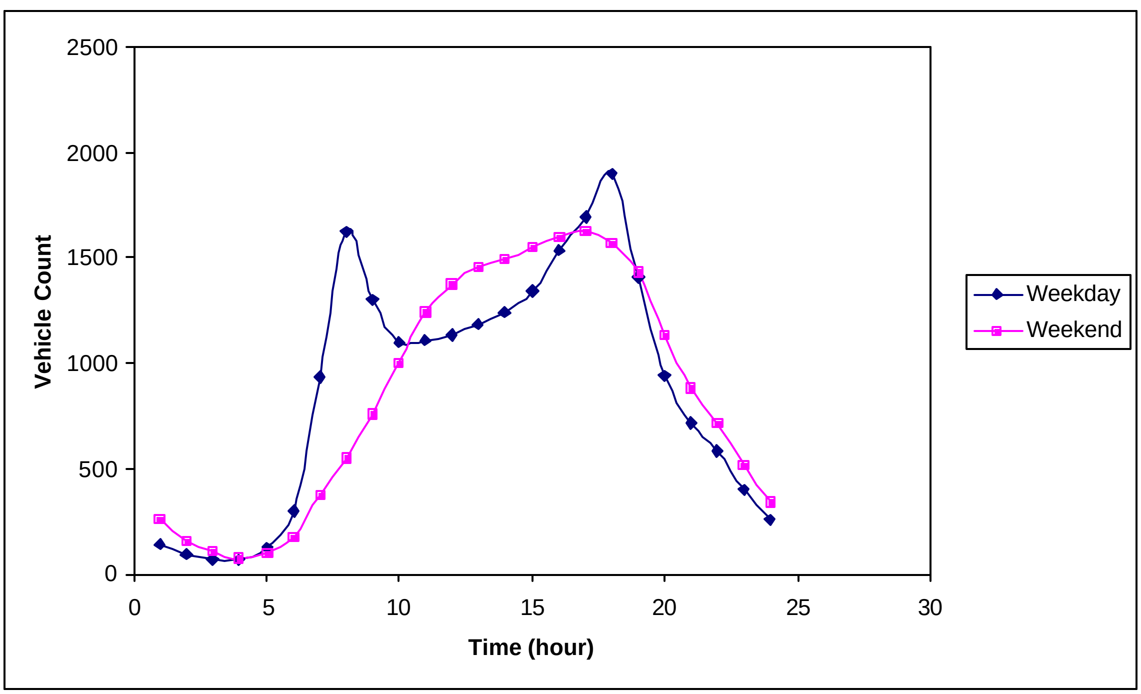


Figure 3.16 Asheville I-40, Traffic Distribution

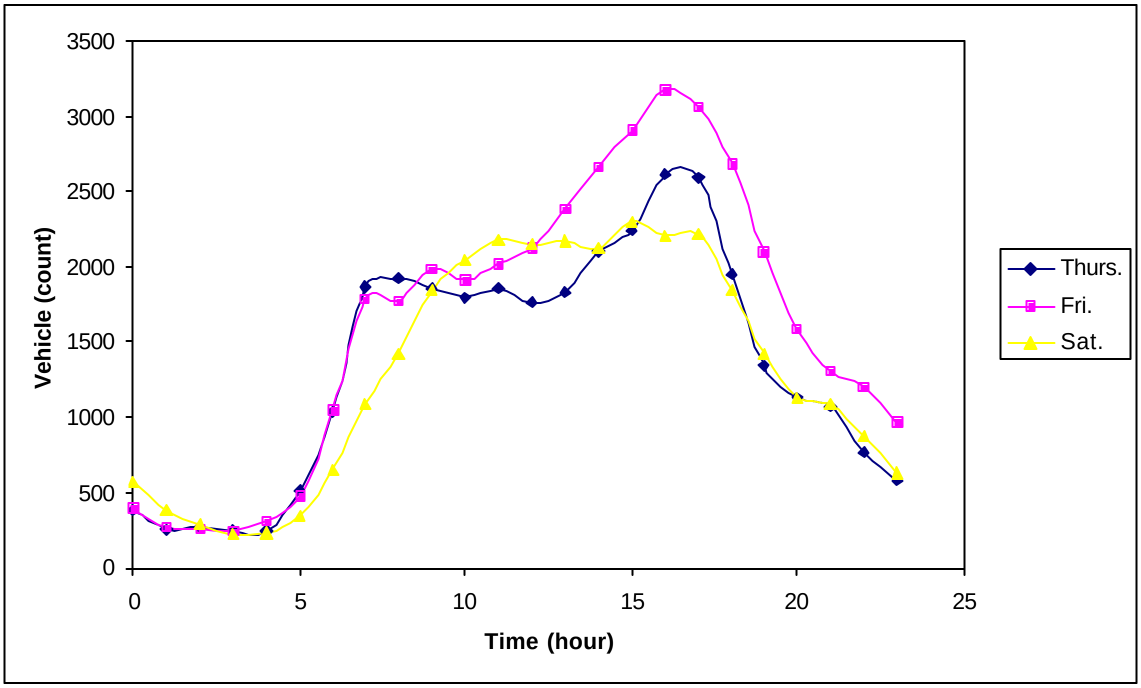


Table 3.1 Average traffic volume comparison

Site	Charlotte, Hwy 29		Wilmington, I-40		Asheville, I-40	
	Weekday	Weekend	Weekday	Weekend	Weekday	Weekend
Days Sampled	4	2	52	21	21	8
Average Daily Traffic Volume*	59,442	49,910	21,186	20,489	30,015	33,210

Traffic counts are the total vehicle counts for both directions and all lanes. Sample period from Oct 1 – Dec 31, 1999

3.3b3. Cumulative daily traffic models

An average daily cumulative traffic curve was developed for both weekend and weekdays for each site. A polynomial regression was used to model each of the three sites. Figures 3.17 and 3.18 are examples from the Wilmington I-40 site. Polynomial traffic models for Charlotte Hwy 29, Wilmington I-40, and Asheville I-40 are as follows:

Charlotte Hwy. 29

Weekday $y = -295.91x + 256.06x^2 - 2.7355x^3 - 0.1267x^4$ $\quad R^2 = 0.9972$ $\quad$ 3.1

Weekend $y = 872.17x - 134.88x^2 + 24.134x^3 - 0.691x^4$ $\quad R^2 = 0.9989$ $\quad$ 3.2

Wilmington I-40

Weekday $y = -117.05x + 76.614x^2 + 1.083x^3 - 0.1066x^4$ $\quad R^2 = 0.9981$ $\quad$ 3.3

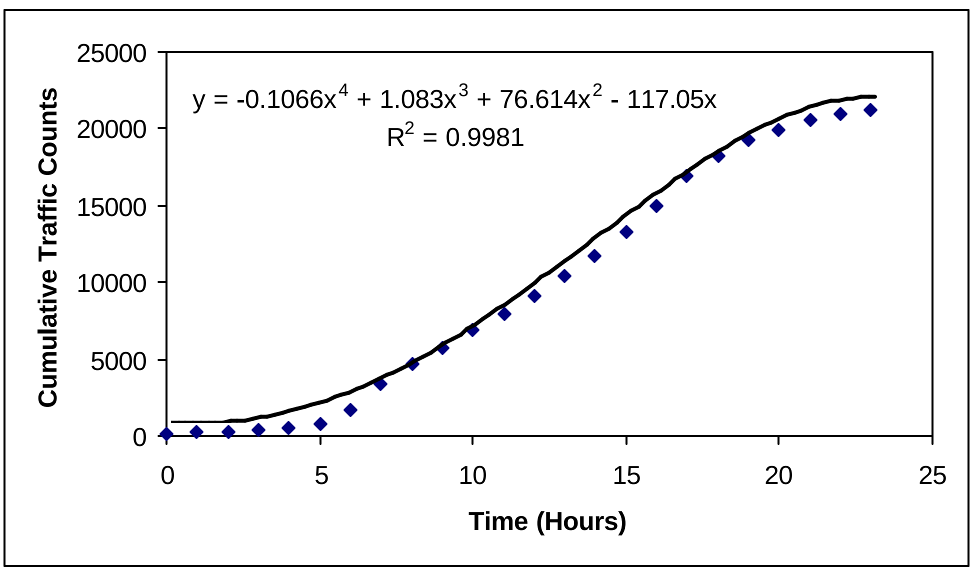
Weekend $y = 121.4x - 23.964x^2 + 8.7832x^3 - 0.2746x^4$ $\quad R^2 = 0.9993$ $\quad$ 3.4

Asheville I-40:

Weekday $y = 51.92x + 56.822x^2 + 4.9277x^3 - 0.2198x^4$ $\quad R^2 = 0.9993$ $\quad$ 3.5

Weekend $y = 258.13x - 47.804x^2 + 15.099x^3 - 0.4715x^4$ $\quad R^2 = 0.9986$ $\quad$ 3.6

Figure 3.17 Daily Cumulative Traffic (Weekday) for Wilmington I-40



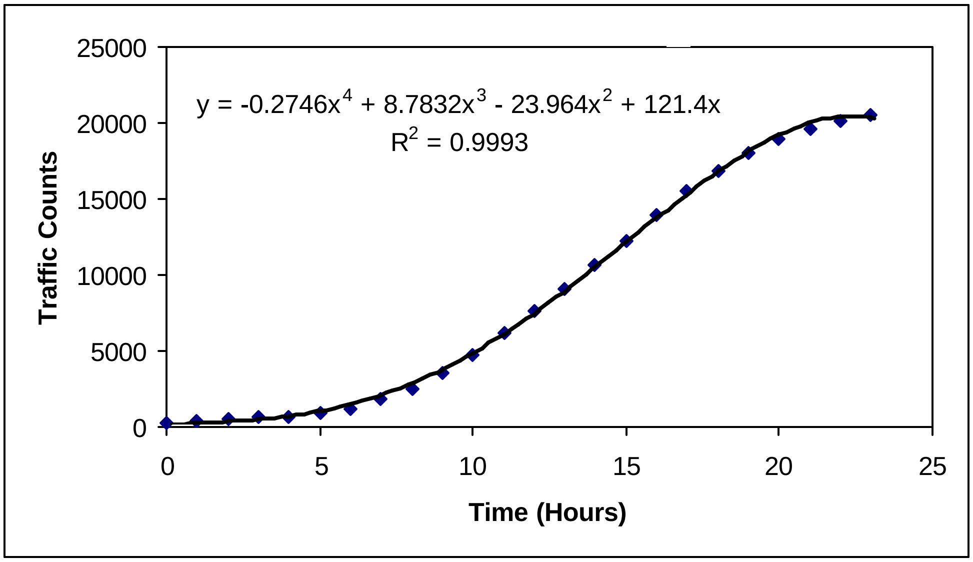


Figure 3.18 Daily Cumulative Traffic (Weekend) for Wilmington I-40

3.3b4. Calculation of Traffic During Storm

Once the accumulated daily traffic models were derived, the traffic during any precipitation event could be calculated by inserting the time period of storm and subtracting the cumulative traffic that occurred before the event began. The traffic volumes generated by this methodology reflect the average traffic volumes associated with these sites for times associated with each storm event. It is most likely that these "in storm" traffic volumes are over estimates as motorists might decide to delay or forgo discretionary travel during inclimate weather conditions. For this study we have chosen not to apply a coefficient to arbitrarily reduce traffic volumes during storm periods.

3.3c Multiple Regression Pollutant Loading Models

The pollutant loading models developed from the Wu and Allan (2001) study are summarized in tables 3.2, 3.3 and 3.4 for the Charlotte Hwy 29, Wilmington I-40 and Asheville I-40 sites. These three sites are characterized by 100% impervious coverage so that the land cover conditions were identical between each site and only traffic, deposition and climatic conditions varied between the three sites. The data from these three sites is also comparable to the Austin, Texas study (Irish et al. 1998). Regression models were also developed for three mixed cover sites US Highway 74 (50% impervious, 9,300 ADT), I-40 near Winston Salem (48 % impervious, 52,500 ADT), and I-40 near Garner (33% impervious, 78,800 ADT), Tables 3.5, 3.6, 3.7, respectively. Pollutant loading from these sites is likely to depend on site-specific variables such as slope, and pervious cover characteristics in addition to traffic, deposition and climatic conditions.

3.4 Regression Results and Analysis

3.4a North Carolina Multiple Regression Pollutant Loading Models

The multiple regression pollutant loading models display a marked lack of consistency between the North Carolina roadway sites (Tables 3.2-3.7). For example the correlation coefficient for the TSS loading regression is relatively good (0.839) for the Charlotte Hwy. 49 site, relatively poor for the Wilmington I-40 site (0.218) and no significant relationship was found for the Asheville I-40 site. Even where correlation coefficients were relatively good amongst the three impervious sites, for example for the OP loading relationships, 0.885, 0.915 and 0.702, for the Charlotte, Asheville and Wilmington sites, respectively. The independent predictive variables for the loading regressions vary between sites. The independent variables selected for the OP loading relationships were P5, Flow, Intensity, PFLOW, PINT and Day for the Charlotte site, only Flow was selected for the Asheville site and Precipitation and PINT were selected for the Wilmington loading relationship. Finally, in several instances the sign of an independent variable appears to be counter intuitive as to its effect on the independent variable. For example several instances of negative Precipitation values were entered for various sites when it would be expected that higher pollutant loads would result from higher precipitation totals. Perhaps surprisingly, the correlation coefficients for the mixed land cover sites (Tables 3.5, 3.6 and 3.7) are relatively higher for most constituents as compared to the 100% imperious sites, despite land cover and drainage path differences between sites. However, as with the 100% impervious sites considerable inter site differences in the selection of independent predictive variables are apparent. The reasons for the lack of consistency in model form between roadway sites is most likely due to the small sample sizes used to develop the regression relationships

Table 3.2 Summary of Pollutant Loading Model Coefficients for Charlotte Hwy 29 Site

Constituent (mg/m^2)	N	S (g/m^2)	R^2	C	Duration (min)	Precipitation (mm)	P5 (mm)	Flow (L/m^2)	Intensity (L/m^2-min)	VDS	ADP (hours)	ATC	PDUR (min)	PFLOW (L/m^2)	PINT (L/m^2-min)	Day
TSS	27	617	.839	-751.92	-3.91	31.99	16.828		1096.44	.28		.004	2.173	-26.067		3.179
TDS	27	430.7	.469	537.86	-2.029			26.108		.165						
COD	27	255.6	.784	238.13	-2.53			30.188		.164		.001	.884	-12.597		
TKN	27	4.927	.905	7.501	-.045			.81	7.352	.004		.000023	.015	-.175		
NH_3-N	27	3.277	.564	6.889	-.008			.142		.002						
NO_3-N	27	3.061	.430	6.043	-.010			.122		.001						
TP	26	.936	.894	-1.483	-.008		.028	.109	1.69	.00046		.000007	.005	-.060		.006
OP	27	0.438	.885	-.024			.025	.032	.694					-.011	-2.545	.003
Zn	25	.991	.604	.793	-.002		.036			.00032						

N= number of events, S = standard error of the estimate, R^2= correlation coefficient adjusted for degrees of freedom, C= regression constant.

Table 3.3 Summary of Pollutant Loading Model Coefficients for Asheville I-40 Site

Constituent (mg/m^2)	N	S (g/m^2)	R^2	C	Duration (min)	Precipitation (mm)	P5 (mm)	Flow (L/m^2)	Intensity (L/m^2-min)	VDS	ADP (hours)	PDUR (min)	PFLOW (L/m^2)	PINT (L/m^2-min)	Day
TSS	19	-	-	-	-	-	-	-	-	-	-	-	-	-	-
TDS	19	274.5	.463	572		-39.558		43.707		.094					-1.67
COD	19	-	-	-	-	-	-	-	-	-	-	-	-	-	-
TKN	19	18.377	.156	22.22			-.215		75.457						
NH_3-N	19	3.40	.126	8.783								.012	-.194		-.016
NO_3-N	19	2.828	.118	3.898					9.095						
TP	19	-	-	-	-	-	-	-	-	-	-	-	-	-	-
OP	19	0.181	.915	.148				.046							
Zn	14	4.42	.488	.509	.006				125.515			-.058	1.032	-179.404	

N= number of events, S = standard error of the estimate, R^2= correlation coefficient adjusted for degrees of freedom , C= regression constant.
- No significant model was found between dependent and independent variables.

Table 3.4 Summary of Pollutant Loading Model Coefficients for Wilmington I-40 Site

Constituent (mg/m^2)	N	S (g/m^2)	R^2	C	Duration (min)	Precipitation (mm)	P5 (mm)	Flow (L/m^2)	Intensity (L/m^2-min)	VDS	ADP (hours)	ATC	PDUR (min)	PFLOW (L/m^2)	PINT (L/m^2-min)	Day
TSS	22	213.28	.218	55.175		4.984										
TDS	21	148.5	.952	17.468	-.59			40.477		.156			.578			
COD	21	116.4	.725	37.072	-.238		1.674			.168			-.217			
TKN	22	4.66	.600	3.129				.354								
NH_3-N	22	1.16	.623	2.315				.108	11.643	-.000619		-.000024				-.006
NO_3-N	22	2.16	.523	-.531			.045			.001						
TP	21	.605	.644	.303		.016	.01		-8.784						3.378	
OP	21	.537	.702	-.111		.019									3.726	
Zn	19	.213	.854	-.117		.012				.000108			.001	-.01	1.183	

N= number of events, S = standard error of the estimate, R^2= correlation coefficient adjusted for degrees of freedom, C= regression constant.

Table 3.5 Summary of Pollutant Loading Model Coefficients for Hwy 74 Site

Constituent (mg/m^2)	N	S (g/m^2)	R^2	C	Duration (min)	Precipitation (mm)	P5 (mm)	Flow (L/m^2)	Intensity (L/m^2-min)	VDS	ADP (hours)	ATC	PDUR (min)	PFLOW (L/m^2)	PINT (L/m^2-min)	Day
TSS	26	53.59	.968	31.402		-10.254	2.722	12.994	5194.52	.07						
TDS	26	329	.706	-15.828	.861			30.002								
COD	26	150.7	.836	-65.873	.485		2.448	17.22								
TKN	26	4.21	.900	0.76	.015		.13	.643					-.015			
NH_3-N	26	.688	.799	-.227	.003				28.45							
NO_3-N	26	.573	.918	-.06			.024	.044	16.972					-.158	53.996	
TP	26	1.63	.820	-1.139	.008	.084	.049			-.002				-.114		
OP	26	1.51	.766	-1.374	.006	.201		-.12		-.003				-.102		
Zn	22	.156	.509	.026		.009						-.000004				

N= number of events, S = standard error of the estimate, R^2= correlation coefficient adjusted for degrees of freedom, C= regression constant.

Table 3.6 Summary of Pollutant Loading Model Coefficients for Winston Salem I-40 Site

Constituent (mg/m^2)	N	S (g/m^2)	R^2	C	Duration (min)	Precipitation (mm)	P5 (mm)	Flow (L/m^2)	Intensity (L/m^2-min)	VDS	ADP (hours)	ATC	PDUR (min)	PFLOW (L/m^2)	PINT (L/m^2-min)	Day
TSS	19	23.5	.919	98.874		-7.131	2.112	30.469				-.000295			-2358.988	
TDS	21	397	.676	824.44		-59.834		257.36								
COD	21	39.6	.946	61.739		-5.241	.67	52.247				-.000197				
TKN	21	1.62	.921	2.120		-.278	.056	1.792		.00042		-.000008				
NH_3-N	21	.253	.800	.072		-.017	.007	.135								
NO_3-N	19	.625	.438	.374	.002							.000002			27.278	-.003
TP	19	.660	.888	-.344		-.042	.015	.387							32.23	
OP	21	.593	.847	-.346	-.002			.393								.003
Zn	19	.114	.552	.131	.001			.038		-.00007			-.000279		-6.564	

N= number of events, S = standard error of the estimate, R^2= correlation coefficient adjusted for degrees of freedom, C= regression constant.

Table 3.7 Summary of Pollutant Loading Model Coefficients for Garner I-40 Site

Constituent (mg/m^2)	N	S (g/m^2)	R^2	C	Duration (min)	Precipitation (mm)	P5 (mm)	Flow (L/m^2)	Intensity (L/m^2-min)	VDS	ADP (hours)	ATC	PDUR (min)	PFLOW (L/m^2)	PINT (L/m^2-min)	Day
TSS	20	105	.675	-62.525	-1.001	31.971			-14579.9							-.598
TDS	13	452.6	.808	-537.7		34.608			67315	-.346			1.603			-4.208
COD	20	115	.757	-20.82	-.677	24.989										-.705
TKN	13	1.49	.995	-11.962	-.044	.684		3.077	-2225.793			-.000053	.101	-1.353	213.141	
NH_3-N	20	.889	.361	-.609		.092				-.00022						
NO_3-N	13	1.14	.873	-.685		.090			195.033				.006		23.937	-.022
TP	20	.998	.537	-.695	-.005	.153										
OP	20	.604	.508	-.286	-.003	.088										
Zn	20	.389	.179	-.198		.02										

N= number of events, S = standard error of the estimate, R^2= correlation coefficient adjusted for degrees of freedom, C= regression constant.

and missing independent variables such as application of deicing compounds and bulk precipitation chemistry. The lack of road maintenance information could be expected to be particularly important in the Blue Ridge region of the state and may help explain the relatively poor relationships developed for the Asheville site.

The initial multiple regression analysis of the individual roadway sites generated pollutant loading models that were site specific and contained in some instances independent variables whose influence or sign appeared to have little scientific relevance to the magnitude of the predicted independent variable. In an effort to generate more general relationships that might be applied to a variety of roadway settings the individual databases were pooled into impervious and mixed cover sites (Tables 3.8 and 3.9). It was found that the inclusion of the Asheville I-40 data resulted in poor or non-significant loading relationships for all chemical constituents except OP (Table 3.8). Therefore all loading relationships except OP presented in Table 3.8 are based on the Wilmington I-40 and Charlotte Hwy 49 datasets.

3.4b Comparison of Multiple Regression Model Results for North Carolina Impervious and Mixed Land Cover Sites and those Developed During the Austin, Texas Study.

The pooling of the road site data into impervious and mixed land use classes did not result in uniformly higher correlation coefficients for most chemical constituents (Table 3.8 and 3.9). The average adjusted R^2 for the impervious sites was 0.69 and excluding NO_3-N was 0.60 for the mixed land cover sites. Applying a decision rule of an adjusted R^2 at least equal to 0.7 it would appear that these pooled regressions should only used to estimate relative pollutant loads for TSS, COD, TKN, NH_3-N and TP (impervious) and TSS, COD, TP (mixed land use) roadway sites. At best the remainder of the regressions except for NO_3-N (mixed land use) should only be used to rank order pollutant load for a site rather than predict the quantitative value of the loading for a particular site.

Table 3.8 Summary of Pollutant Loading Model Coefficients for Impervious Sites

Constituent (mg/m^2)	N	S (g/m^2)	R^2	C	Duration (min)	Precipitation (mm)	P5 (mm)	Flow (L/m^2)	Intensity (L/m^2-min)	VDS	ADP (hours)	ATC	PDUR (min)	PFLOW (L/m^2)	PINT (L/m^2-min)	Day
TSS	49	653.1	.767	95.112	-1.423	16.397			1854.4	.202	-1.965	.005				
TDS	49	415.8	.551	353.27	-.912	23.603				.140						
COD	48	262.46	.719	204.84	-.695	8.214			441.21	.121		.001		-6.017		
TKN	49	5.502	.872	7.975	-.018			.494	13.238	.004	-.024	.00005		-.100		
NH_3-N	48	2.868	.765	4.243	-.008	-.163		.360		.002	-.014	.000024	.005	-.075		
NO_3-N	49	2.967	.538	4.346	-.006			.115		.001	-.011	.000014				
TP	49	1.287	.720	.130	-.002			.069	3.081	.00032		.000005				
OP	68	.604	.657	.051				.047	1.256			.000001				
Zn	45	.853	.638	.137	-.001	.017			1.525	.00025		.000004				

N= number of events, S = standard error of the estimate, R^2= correlation coefficient adjusted for degrees of freedom, C= regression constant.

Table 3.9 Summary of Pollutant Loading Model Coefficients for Mixed Land Cover Sites

Constituent (mg/m^2)	N	S (g/m^2)	R^2	C	Duration (min)	Precipitation (mm)	P5 (mm)	Flow (L/m^2)	Intensity (L/m^2-min)	VDS	ADP (hours)	ATC	PDUR (min)	PFLOW (L/m^2)	PINT (L/m^2-min)	Day
TSS	67	102.2	.777	7.685	-.258			7.730	4683.245	.024						
TDS	66	570.4	.428	241.29				61.849	-6538.327							
COD	58	133.4	.793	31.472	.214	4.337		18.091	-3440.149	-.026			-.178			
TKN	58	9.23	.565	-2.079				.936					.018			
NH_3-N	67	.702	.652	-.201		.043			15.116	-.000074						
NO_3-N	67	5.39	.048	.304		.091										
TP	57	1.561	.721	-.607		.172				-.000486				-.098		
OP	58	1.378	.662	-.668	.003	.113				-.001				-.069		
Zn	62	0.259	.205	-.045		.01										

N= number of events, S = standard error of the estimate, R^2= correlation coefficient adjusted for degrees of freedom, C= regression constant.

The pooling of the data into the two roadway site classes did result in the generation of a more uniform and in most instances scientifically defensible series of predictive relationships for the impervious data set (Table 3.8). The variables included most often for the impervious sites were precipitation duration (negative), vehicles during the storm (positive) and antecedent traffic counts (positive). Precipitation (positive with one exception), Flow (positive) and Intensity (positive) were kept for five of the nine relationships. The duration of the antecedent dry period (negative) was kept for four relationships. The negative signs for this variable likely reflect cross correlations with the variable ATC, which is strongly related to the length of the antecedent dry period. Increasing pollutant loadings could then be expected for short duration high magnitude precipitation and runoff events with pollutant loadings generally increasing with higher in-storm traffic volumes and in part due to the build up of pollutants associated with high traffic volumes during antecedent dry periods. The influence of previous storm characteristics, the magnitude of the previous precipitation event (PFLOW) negatively influenced the pollutant loading relationships of COD, TKN and NH_3-N.

For the mixed land cover site data, precipitation and/or runoff magnitude (positive) were included in every final loading relationship. Flow intensity and vehicle counts during the storm were included in for four and five relationships, respectively. Unlike for the impervious sites, the signs all variables loaded except precipitation and flow were a mixture of positive and negative values. The opposing signs for runoff intensity could be explained by increased contact times (negative values) and lower contact times (positive values) that could serve to remove pollutant constituents from pervious surfaces and reduce the retention of road source pollutants, respectively. The negative values associated with vehicles during a storm are likely the result of inter correlations with other variables and likely do not have any physical meaning. Characteristics of the preceding precipitation events (PDUR- COD and TKN; and PFLOW- TP and OP) also were loaded with inconsistent signs for these mixed land cover sites.

The results of this multiple regression analysis are not directly comparable to the Irish et al (1998) Austin, Texas study because of the inclusion of the precipitation variables: Precipitation, duration and P5 in the analysis of the NC data. Results derived from the Austin, Texas study involved both natural and artificial rainfall events and precipitation variables were excluded from their analysis. Significant variation in the form of the equations are evident in the comparison of the TSS relationships developed in this and Irish et als 1998 study (Equations 3.7, 3.8, and 3.9).

NCIMP

$$95.112 + -1.423(\text{Duration}) +16.397 (\text{Precipitation}) +1854.4 (\text{Intensity}) + .202 (\text{VDS}) – 1.965(\text{ADP}) + .005(\text{ATC})= \text{TSS (mg/m}^2) \quad 3.7$$

NCMIX

$$-.258 + 7.730(\text{Precipitation}) + 4683.245 (\text{Intensity}) + .024 (\text{VDS}) = \text{TSS (mg/m}^2) \quad 3.8$$

TX*

$$255.6 + 306.8(\text{Flow}) + 2018.1(\text{Intensity}) + 3.7(\text{ADP}) - 2986.5(\text{PINT})= \text{TSS (mg/m}^2) \quad 3.9$$

Correlation coefficients generated from the NC dataset were generally lower than those reported by Irish et al. (1998). One obvious difference is the much greater number of observations used to generate the Texas loading models (Table 3.5). In their study Irish et al. (1998) calculate multiple partial event loadings per storm rather than one single total event loading per storm. The use of partial loads during each event considerably inflates the N values used to generate their regression equations. Such an analysis could not be attempted with the NC data set owing to the collection of volume weighted composite samples rather than multiple discrete samples during each rainfall event. Data from Wu et als. 1997 study suggests that the incorporation of bulk deposition data could be expected to improve model performance, in particular for nitrogen species. As for any other regression modeling approach the user should only apply the regression relationship for the range of data from which the relationship was originally derived.

The application of any of the above multiple regression pollutant loading approach within a GIS environment is a relatively straight-forward procedure. Precipitation inputs to the model (Duration, Precipitation, ADP and P5) could be generated from actual or synthetic series of precipitation data. Flow parameters (Flow, Intensity, PDUR, PFLOW and PINT) could be generated from real or synthetic precipitation inputs using standard engineering runoff approaches for small watersheds such as TR55 or rainfall/runoff regression approaches such as those developed by Wu and Allan (1998). Traffic volumes for roadways of concern are generally available in most state DOT databases and can be used to develop the ATC variable. An approach for generating the VDS variable was outlined in section 3.3 above.

Chapter 4 GIS based Drainage Basin Delineation

In the final section of this report we examined the utility of using Lidar and DEM digital topographic data to define drainage areas of interest along North Carolina Highways. The goal of this portion of the study was to define highway drainage areas associated with highway/river crossing points defined in the NC Crossing Point Study (Wu 2003). Once the drainage area for a specific crossing point is defined then the highway database can be queried to define the roadway, shoulder, and median and traffic attributes of the drainage area. This information would allow the calculation of the IMP variable and along with the ADT data would allow the use of the pollutant loading models developed by Wu and Allan (2001), Equations 2.11 to 2.18. Data generated from the pollutant loading models could then be used to rank the potential roadway stormwater impacts on sensitive waters within a watershed or NC DOT jurisdiction to better target stormwater BMP implementation.

4.1 Application of Lidar

Lidar stands for Light Detection and Ranging. It uses the same principle as Radar except that a laser instead of radio waves is utilized. Lidar is a relatively new technology that consists of a scanning laser, Global Positioning System (GPS) and an Inertial Measuring Unit (IMU). The system is mounted on the underside of a fixed wing aircraft and measures distances from the scanning laser to the terrain surface. The other two components of the system, the GPS and IMU ascertain the precise in-flight position of the aircraft and laser sensor in relation to known ground control points.

The Lidar instrument maps a surface by transmitting light out to a target. The transmitted light interacts with, and is changed by the target/ground. Some of this light energy is reflected/scattered back to the instrument where it is analyzed. The change in the properties of the light enables some properties of the target to be determined. The time for the light to travel out to the target and back to the instrument is used to determine the distance to the target. A more complete explanation of the theory and application of Lidar can be obtained from NASA's Lidar tutorial page at http://www.ghcc.msfc.nasa.gov/sparcle/sparcle_tutorial.html.

One of the advantages of Lidar digital data over conventional photogrammetry is improved mapping definition and precision in vegetated and otherwise obscured areas. Lidar is better able to define and map bare earth elevations in forested or vegetated areas than other methods because only a single laser pulse needs to be able to penetrate the vegetative canopy to measure the ground elevation. Lidar can ‘see through the tree canopy’ so that precise ground elevations can be determined after "filtering" out the trees and buildings. Lidar also has a much higher resolution than traditional mapping methods. For example, the Lidar data from eastern North Carolina used in this study has a nominal measurement spacing of approximately 3 meters, whereas older methods typically acquire data points spaced at 10 to 30 meters. Lidar is also considerably less expensive than digital data created from traditional methods, especially when automated post-processing is used to generate Lidar bare earth elevation data. However, there are some limitations associated with Lidar data. In particular is the somewhat reduced accuracy in identifying streams, shorelines or ridgelines that are more visible on photographic images.

The Lidar data used in this study covered a small section of eastern North Carolina. The sections of interest used in this study overlapped with the I-40 corridor between Garner and Wilmington (Figure 4.1).

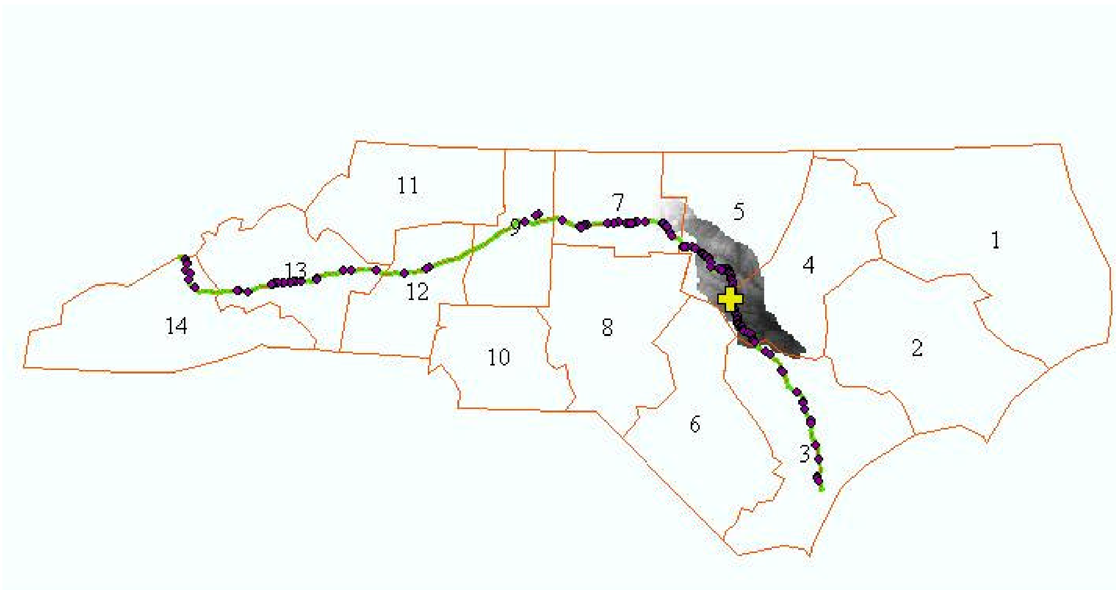


Figure 4.1 Lidar Coverage

Details regarding the source of DEM and the processing of the Lidar in ArcGIS to delineate the case study drainage areas along I-40 are presented in Appendix 1.

4.2 Comparison of Watershed Delineation from Lidar and DEM

The increasing availability of Lidar data is critical to the automated delineation of small drainage areas such as those associated with highways. The topographic data contained in a DEM is simply too coarse to define small drainage areas associated with highway/water crossings. The watershed delineation tool described in Appendix 1 was used to define the drainage area associated with an I-40 bridge crossing in the Neuse River watershed in eastern North Carolina (Figure 4.2). The pour points (green crosses) selected to generate the contributing watershed were two sensitive water crossing points generated from the NC DOT GIS ‘Crossing Point’ project (Wu 2003).

The watershed generated from the Lidar data produces a much more realistic drainage area for the highway crossing point (shown as the blue area in Figure 4.2). The watershed generated from the DEM data appears as the much larger pink area in Figure 4.2.. It is apparent that the lower resolution of the DEM, 30x30 meters, is insufficient to define the drainage area of the two highway crossing points for this case study. In this case, the highway width is 6 – 12 meters and certainly cannot be identified in DEM. The three-meter resolution of the Lidar data allows a much better definition of the case study watershed.

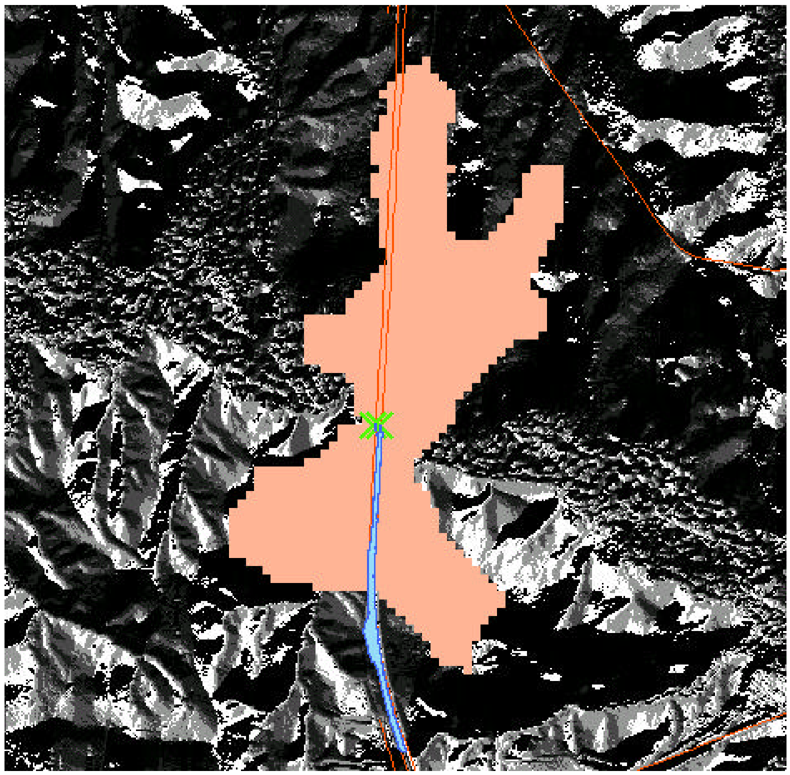


Figure 4.2 Watershed delineation based on cross points

4.3 *Uncertainties in Current Drainage Pattern Mapping Using GIS "Crossing Point" Coverage's and Lidar Data*

Although the utilization of digital topographic data derived from Lidar represents a significant improvement over standard DEM's in the delineation of small, low relief features upon close inspection of this I-40 bridge crossing reveals that there are still problems associated with the development of an automated highway drainage area delineation (Figure 4.3). Lidar data cannot capture narrow ground features when they are cam-flashed with the background ground elevation measurements. One problem occurs when a stream has certain width (wide) and the bridge structure of the highway is divided (narrow) into two parts. One partial width of the bridge structure is approximately four meters. Unfortunately, the three-meter resolution of the current Lidar field mapping instrumentation does not appear to be sufficiently dense to capture topographic information from highway bridge structure. The lack of representation of Lidar topographic data for the bridge crossing is plainly evident in Figure 4.3. As a result, the GIS algorithm that draws the contours fails in these cases. Figure 4.4 illustrates the absence of contour lines representing the bridge crossing above the stream.

Figure 4.3 Absence of Bridge Crossing Topography in Lidar

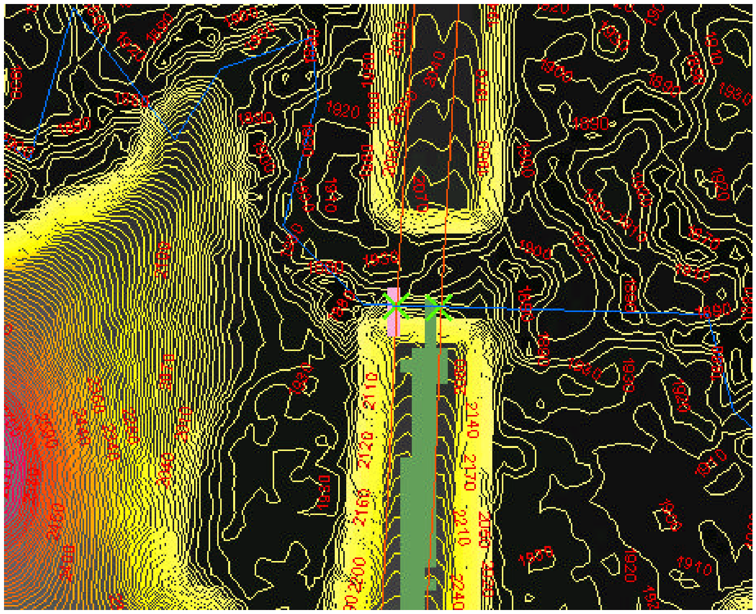


Figure 4.4 Lidar contour data for highway bridge case study

The lack of bridge crossing topographic representation is problematic for the automatic delineation of drainage areas at highway crossing points. The capture of the stream valley rather than the bridge deck results in only one half of the drainage area been delineated. A possible workaround for this problem could be to refine the GIS crossing point methodology to generate four rather than two crossing points at each bridge crossing. The GIS software would then draw separate watersheds for each side of the bridge crossing. Data for watersheds of crossing points within a small, specified radius could then be merged and Wu and Allan's (2001) or other pollutant loading relationship could be applied to the combined watersheds land cover and traffic characteristics. Alternatively, elevation data from NCDOT bridge crossing database could be used in association with the Lidar coverage prior to defining the basin within the GIS. It is possible that once the Lidar coverage is modified at these crossing points the complete drainage basin might be defined correctly.

A second crossing point case study from this area of the NC coastal plain is presented in Figure 4.5. In this instance the lack of any topographic relief in the immediate vicinity of the two bridge crossing results in the delineation of watersheds defined by only one or two grid cells. In areas of low relief such as the NC coast plain a site visit might be required to confirm the contributing drainage areas to crossing points of special interest.

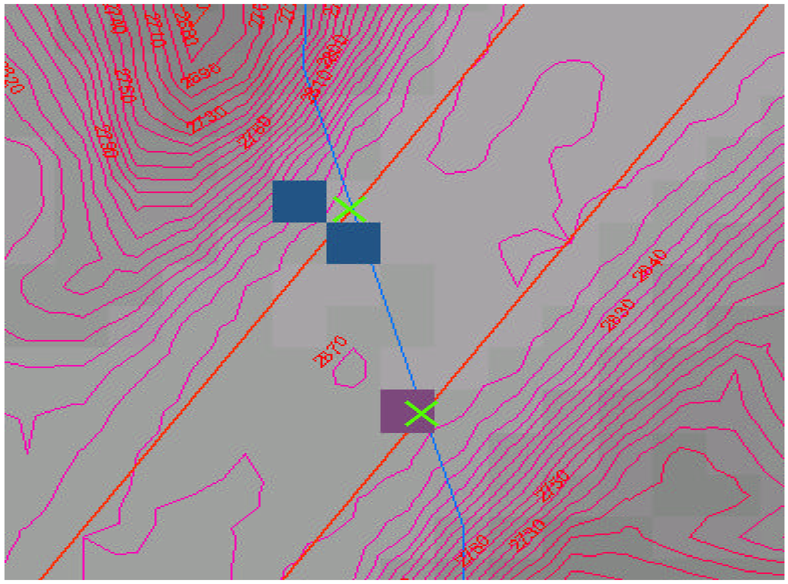


Figure 4.5 Case Study 2, Watershed Drainage Area Delineation

Chapter 5 Study Conclusions

Regression equations developed by Wu and Allan (2001) that predict average event unit loadings of pollutants from average daily traffic volumes and the percentage of impervious cover for a highway drainage area appear to be a practical tool to asses NPS loadings from highway stormwater runoff. At present these equations should be applied to the NC Piedmont and Blue Ridge portions of the state. Data from Wu and Allan's (2001) study indicate that different statistical relationships might be necessary for the coastal plain region of the state. The use of these equations should also be confined to ADT values of >30,000 vehicles/day and for road corridor areas with >50% impervious cover. Additional monitoring data from roadways with low ADT counts and lower percent impervious cover would help extend these relationships. The ADT/IMP based statistical loading relationships for TP and ortho-P appear problematic in that the factors controlling phosphorus transport from roadways is not entirely dependent upon the ADT and IMP variables.

Multiple regression relationships developed for single sites to predict storm event pollutant concentrations from the variables: length of antecedent dry days, vehicle counts during storm periods and precipitation and runoff conditions appear to be site specific with limited predictive power for most pollutant constituents. Regression models developed from multiple sites, classed either as impervious or mixed surface roadway sites generated for the most part a series of more consistent scientifically defensible loading equations. Such models could be applied within a GIS using real or synthetic precipitation data in conjunction with traffic data contained within the NCDOT road attribute database.

Delineation of roadway drainage areas using traditional photogrammetrically-based DEMs does not appear to be practical, particularly in low relief areas such as the NC coastal plain. Lidar derived topographic data appears to have the spatial resolution necessary to define small low relief drainage areas. However, the current GIS crossing point coverage will have to be modified or bridge deck elevations included where the elevation of the bridge deck surface is not captured during Lidar data acquisition.

It is recommended that as Lidar data becomes available for more areas of the state that the crossing point/watershed delineation data be applied to a variety of highway/stream crossing scenarios to develop confidence in the methodologies for subsequent applications at the watershed scale. After the watershed delineation methodology is finalized a ranking methodology should be developed to prioritize crossing sites for stormwater BMP retrofits.

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Appendix 1 DEM and Lidar Processing Methodology

A1 Source and Conversion of Digital Elevation Data (DEM)

The DEM data from the directory the DEM data for Wayne County, NC used in this study was obtained from the website: http://download.geocomm.com. to overlap with the LiDAR coverage supplied by NC DOT. The next step in the development of the DEM was to obtain a translator for the STDS DEM files. The translator, sdts2dem was obtained from the web page http://www.cs.arizona.edu/topovista/sdts2dem.html. Documentation for the translator program was found at the same site. Each of the original DEM files was downloaded and unzipped into a separate directory. The sdts2dem translator program was copied to each directory and the program run to convert the DEM files from the STDS format to the USGS DEM format.

The next stage in the process was to convert the USGS DEM format to Grid in the ESRI ARCGIS software. The command steps for this are: Launch ArcToolBox, then double click "Conversion Tools / Import to Raster / DEM to Grid" to convert the USGS DEM to Grid. The output grids were then placed into the same directory, and the following workspace is defaulted to the DEM directory. The final step in the preparation of the DEM was to define the projection for Grid data. In the ArcToolBox, "Data Management Tools / Projections / Project Wizard (coverage's, grids)" was selected to project the Grid data. Use "Project my data to match existing data", then select one of data sets in the DEM/Grid database with State Plane NAD83 and units in meters. The converted output grids were then placed in a common directory.

A.2 Delineation of Drainage Areas in ArcGIS

The Hydrology Model from ArcGIS was downloaded from the ESRI website under Arc Objects online (http://arcobjectsonline.esri.com/). The purpose of the Hydrology Modeling Tool is to introduce some of hydrology modeling methods available through Spatial Analyst Objects and demonstrate how to develop a complex application using Spatial Analyst Objects in the ArcGIS environment. The Hydrology Modeling Tool provides interfaces for creating flow directions, flow accumulation, filling sinks, creating watersheds and stream networks.

Steps Used in the Hydrology Modeling Tool

<u>Flow direction</u>

One of the keys to deriving hydrologic characteristics of a surface is the ability to determine the direction of flow from every cell in the grid. This is done with the Flow Direction dialog. To access the dialog select Flow Direction from the Hydrology dropdown menu.

This dialog takes a surface as input and outputs a raster showing the direction of flow out of each cell. If ‘Create drop’ is selected, an optional output raster is created displaying a ratio of the maximum change in elevation from each cell along the direction of flow, to the path length between centers of cells. This slope is expressed in percent. If ‘Force flow at edge’ is selected then all cells at the edge of the surface grid will flow outward from the surface grid.

There are eight valid output directions, relating to the eight adjacent cells into which flow could travel from a central cell.

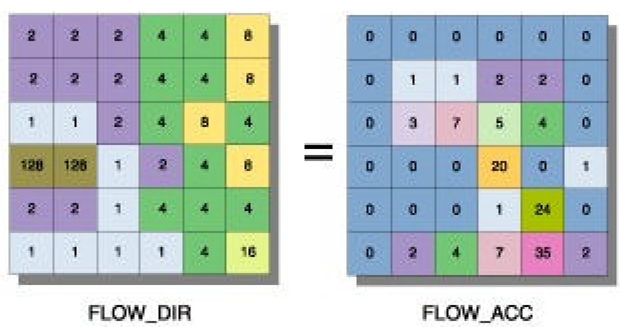
32	64	128
16		1
8	4	2

The direction of flow is determined by finding the direction of steepest descent, or maximum drop, from each cell. This is calculated as

maximum drop = change in z value / distance A.1

The distance is determined between cell centers. Therefore if the cell size is 1, the distance between two orthogonal cells is 1 and the distance between two diagonal cells is 1.414216, the square root of 2. If the descent to all adjacent cells is the same, the neighborhood of cells is enlarged until the steepest descent is found.

When a direction of steepest descent is found, the output cell is coded with the value representing that direction.



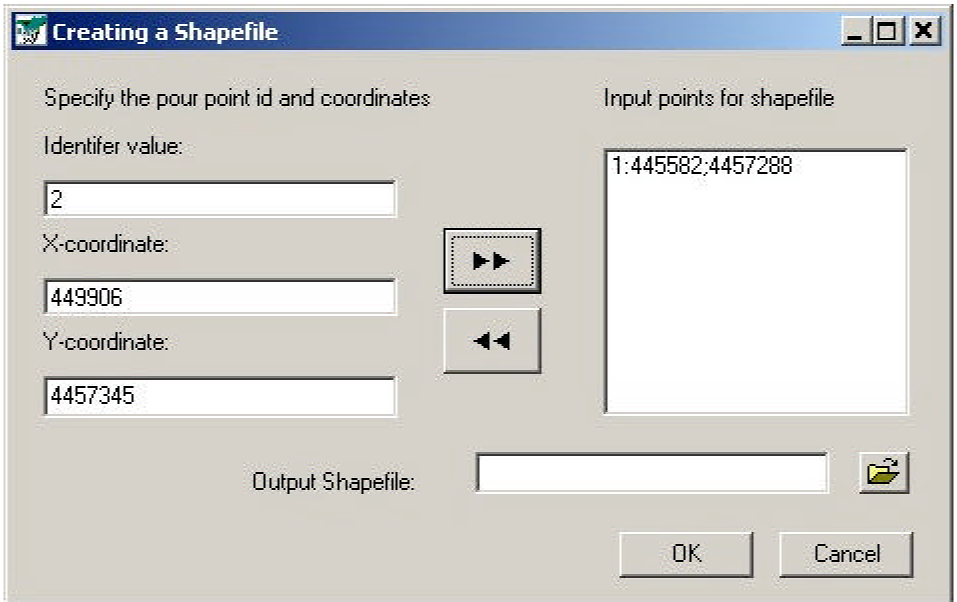
If all neighbors are higher than the processing cell, the processing cell is a sink, and has an undefined flow direction. Cells with undefined flow direction can be flagged as sinks using the Identify Sinks dialog. To obtain an accurate representation of flow direction across a surface, all sinks should be filled. Information pertaining to the filling of sinks is found in the section 'Creating a depressionless DEM'.

Watershed delineation

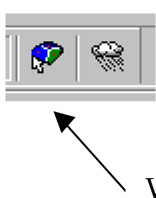
A watershed is the up slope area contributing flow to a given location. The watershed is also referred to as a basin, catchment, subwatershed, or contributing area. A subwatershed is simply part of a hierarchy implying that a given watershed is part of a larger watershed. Watersheds can be delineated from a DEM by computing the flow direction and using it in the Watershed dialog. The Watershed dialog is accessed by selecting the Watershed option from the Hydrology menu. This routine uses a raster of flow direction to determine contributing area.

The watershed can be delineated for junctions in a stream network or for individual pour points. The input to the Watershed dialog defining how the watersheds will be delineated is either by a flow accumulation threshold or pour points in a shapefile. When the threshold is used to define a watershed the pour points for the watershed will be the junctions of a stream network derived from flow accumulation. Therefore, a flow accumulation raster must be specified as well as the minimum number of cells that constitute a stream.

When a shapefile is used to define a watershed, the shapefile identifies the pour points (the cells above which to find the contributing area). A shapefile can be easily created using the Creating a Shapefile dialog that is accessed from the Watershed dialog.



An alternative for creating a watershed raster is to interactively identify the pour points and delineating the watershed using the Watershed tool on the sample extension tool bar. The process is described in the 'Interactive Tools' section.



Watershed tool

Instructions for Using the Hydrologic Modeling Tool:

1. Register DLL: Click Tool/Customize, click Add from file button in the Customize dialog, navigate to the file esrihydrology.dll, and click OK button. Click Toolbars tab in Customize dialog, check Hydrology Modeling, then the Hydrology modeling toolbar appears.

2. Using VB Project: To use VB project, make three folders: class, form, module. Copy all class file (*.cls) into folder class, copy all form files into folder form, copy resource file hydro.res and module file utilmodule.bas into the folder module, leave the VB project file in the same level as the three folders.

3. To active the watershed and rain drop buttons, set up flow accumulation and flow direction from the Properties dialog in the Hydrology toolbar.

4. The working directory for Hydrology Modeling is implemented through Spatial Analyst. To set up the working directory (include other environment settings except output spatial reference), click Options dialog in Spatial Analyst, and type the path in the working directory combo box.

5. The results are temporary rasters by default. To save the results, use ‘Make Permanent’ in the Context Menu.

6. Additional information can be found under HydrologyAnalysis.doc.

Appendix 2 NC Multiple Regression Data

Table A2.1 Regression Data for Hwy. 29 Charlotte, NC

Day	Duration (min)	Precipitation (mm)	P5 (mm/hr)	Flow (mm)	Intensity (mm/hr)	VDS	ADP (hours)	ATC	PDUR (min)	PFLOW (mm)	PINT (mm/hr)
139	174	6.9	6.1	6.4	0.022	417	449	469579	558	25.9	0.046
146	72	6.4	6.1	6.4	0.015	972	173	180929	174	5.6	0.032
160	72	4.6	6.1	3.3	0.006	940	335	350354	72	5.1	0.071
166	114	9.7	24.4	7.9	0.018	1743	144	150600	72	3.5	0.049
171	342	6.6	3.0	5.6	0.003	1028	87	90988	408	20.8	0.051
192	78	10.7	15.2	9.1	0.019	276	128	133867	84	29.1	0.346
205	96	20.6	79.2	18.0	0.097	1323	300	313750	78	9.1	0.116
236	138	11.7	21.3	9.4	0.036	1747	111	116088	18	6.8	0.376
248	186	34.0	12.2	30.2	0.033	2766	2	2092	96	18.0	0.188
252	54	14.2	33.5	12.7	0.085	828	94	98308	186	30.3	0.163
264	84	5.1	6.4	3.8	0.010	1232	289	302246	54	12.3	0.228
282	1188	85.3	31.2	77.0	0.056	3891	144	150600	126	4.0	0.032
306	294	17.0	36.6	14.7	0.047	2362	542	566842	468	96.3	0.206
315	126	29.7	61.0	26.4	0.155	1924	354	370225	294	11.8	0.040
330	42	21.6	36.6	18.8	0.035	641	4.5	4706	126	26.3	0.209
344	96	17.8	21.3	15.2	0.118	1341	331	346171	42	19.0	0.452
353	210	6.1	7.1	4.6	0.054	576	255	266688	96	15.5	0.162
4	120	10.2	35.3	8.6	0.054	1159	312	326300	210	8.1	0.039
43	228	16.8	15.2	14.5	0.030	4678	572	598217	78	2.6	0.034
49	114	7.9	6.1	7.1	0.539	41	130	135958	228	14.6	0.064
65	168	6.1	12.2	4.8	0.019	2577	162	169425	114	10.0	0.088
71	90	7.1	3.6	5.6	0.031	887	148	154783	168	5.0	0.030
76	192	43.2	94.5	38.6	2.323	7498	119	124454	90	1.9	0.021
98	150	23.1	67.1	20.1	0.085	1879	529	553246	192	38.5	0.201
115	564	19.1	33.5	16.5	0.015	8623	205	214396	108	5.4	0.050
118	192	12.4	9.1	10.2	0.446	348	75	78438	564	16.7	0.030
141	34.8	6.1	27.4	4.3	0.030	258	105	109813	192	10.7	0.056

Blanks are missing data.

Table A2.1 Regression Data for Hwy. 29 Charlotte, NC (contd.)

TSS (mg/m^2)	TDS (mg/m^2)	COD (mg/m^2)	TKN (mg/m^2)	NH_3-N (mg/m^2)	NO_3-N (mg/m^2)	TP (mg/m^2)	OP (mg/m^2)	Zn (mg/m^2)
1079.5	336.6	412.8	15.2	7.0	5.7		0.6	
1187.5	692.2	920.8	30.5	17.8	9.2	2.3	1.5	
1188.7	1221.7	673.6	25.4	9.2	9.1	1.9	0.5	1.8
1094.5	669.3	519.7	15.0	4.8	3.7	2.0	0.7	1.5
139.7	625.9	363.2	11.2	5.3	6.0	0.7	0.4	0.7
795.5	859.5	475.5	12.8	4.5	6.2	1.8	0.5	2.2
3534.7	1785.4	1154.2	36.1	8.5	15.0	6.7	2.9	5.0
667.3	422.9	347.7	15.0	8.8	6.7	1.5	0.5	0.9
392.9	1541.5	695.2	30.2	11.8	10.0	2.1	1.5	1.2
1155.7	533.4	419.1	19.1	10.0	12.2	1.8	0.6	2.0
339.1	266.7	240.0	10.3	5.7	5.6	1.2	0.3	0.4
692.7	615.7	384.8	38.5	14.6	7.7	3.8	3.8	0.8
1826.8	883.9	73.7	20.6	9.3	3.1	2.5	0.7	1.5
4120.9	1981.2	1373.6	42.3	16.6	14.0	8.7	4.0	4.0
1503.7	1033.8	695.5	22.6	11.3	8.8	2.8	0.9	0.9
3139.4	609.6	1188.7	30.5	15.2	7.6	4.3	0.8	3.7
534.9	233.2	251.5	9.1	5.0	2.3	0.8	0.4	0.7
1200.4	457.7	500.9	19.0	11.2	5.7	1.6	0.4	0.8
4082.8	2302.0	1940.1	44.9	17.4	13.6	6.9	0.9	4.3
199.1	355.6	177.8	10.7	6.3	7.9	0.6	0.4	0.7
641.9	270.3	419.9	18.8	7.7	3.8	0.9	0.5	1.0
681.7	413.5	508.5	19.6	7.8	4.5	1.4	0.6	1.1
6949.4	2007.6	2509.5	84.9	20.8	14.7	13.1	5.4	6.6
2167.1	702.3	1163.8	38.1	12.0	10.8	4.2	1.8	2.6
1651.0	1139.2	825.5	39.6	21.5	18.2	2.8	1.0	2.6
1524.0	680.7	751.8	22.4	12.2	7.9	1.8	0.6	1.9
1230.6	319.5	470.7	14.7	5.6	6.0	2.3	1.1	1.3

Blanks are missing data.

Table A2.2 Regression Data for I-40 near Asheville, NC

Day	Duration (min)	Precipitation (mm)	P5 (mm/hr)	Flow (mm)	Intensity (mm/hr)	VDS	ADP (hours)	ATC	PDUR (min)	PFLOW (mm)	PINT (mm/hr)
293	1650.0	12.7	14.4	7.6	0.018	1428	220	89375	270.0	6.0	0.022
305	870.0	37.1	100.8	33.5	0.100	2995	288	117000	105.0	9.1	0.087
329	1308.0	55.9	49.8	49.3	0.052	6877	80	32500	535.2	29.2	0.055
344	90.0	5.6	50.4	3.6	0.030	626	327	132844	625.2	44.7	0.072
348	1410.0	51.8	86.4	29.5	0.039	7470	64	26000	79.8	3.2	0.041
10	1290.0	34.8	54.6	7.9	0.044	6462	637	258781	184.8	41.4	0.224
43	465.0	24.9	64.8	23.4	0.063	2400	787	319719	394.8	27.5	0.070
45	172.2	17.0	64.8	15.2	0.069	193	37	15031	285.0	19.2	0.067
72	210.0	36.1	86.4	33.3	0.142	801	158	64188	169.8	12.7	0.075
79	696.0	47.8	36.0	41.9	0.164	1736	64.5	26203	330.0	28.4	0.086
104	1230.0	42.7	52.7	24.6	0.079	7131	242	98313	110.0	7.0	0.064
119	555.0	23.4	15.6	21.6	0.103	3025	44	17875	115.2	17.5	0.152
144	810.0	21.1	24.6	15.0	0.150	2521	607	246594	475.2	17.9	0.038
157	75.0	18.0	222.0	8.6	0.192	635	230	93438	30.0	4.1	0.136
210	60.0	19.6	144.0	9.7	0.124	525	80	32500	4.0	0.3	0.078
215	1560.0	20.6	72.0	15.2	0.034	8574	61	24781	60.0	14.8	0.246
220	52.2	22.4	184.2	21.8	0.628	332	95	38594	160.2	15.6	0.097
244	570.0	16.3	44.6	10.2	0.057	2751	245.5	99734	195.0	7.4	0.038
269	435.0	7.2	35.4	3.0	0.022	3506	600	243750	64.2	10.8	0.168

Blank data are missing

Table A2.2 Regression Data for I-40 near Asheville, NC (contd.)

TSS (mg/m^2)	TDS (mg/m^2)	COD (mg/m^2)	TKN (mg/m^2)	NH_3-N (mg/m^2)	NO_3-N (mg/m^2)	TP (mg/m^2)	OP (mg/m^2)	Zn (mg/m^2)
129.5	144.8	53.3	6.1	2.1	1.1	0.4	0.4	1.1
0.0	0.0	167.6	16.8	2.0	2.7	1.7	1.7	3.0
98.6	739.5	345.1	29.6	7.9	4.4	2.5	2.5	3.9
152.9	46.2	110.2	2.8	1.6	1.2	0.4	0.2	1.0
294.6	29.5	412.5	11.8	5.6	3.2	1.5	1.5	4.1
78.7	7.9	86.6	4.7	2.4	1.1	0.4	0.4	1.0
3762.2	1191.8	1939.5	23.4	8.2	6.8	4.0	1.2	5.6
91.4	91.4	76.2	6.1	2.6	1.7	0.8	0.8	1.2
299.5	798.6	366.0	29.9	15.0	10.0	1.7	1.7	5.3
4400.6	293.4	544.8	21.0	1.7	2.5	5.4	2.1	25.1
3005.8	221.7	1059.4	32.0	7.4	5.4	4.9	1.2	5.9
7901.9	798.8	2374.9	79.9	7.6	6.5	13.6	1.1	8.6
704.3	494.5	734.3	59.9	10.8	7.6	3.4	0.7	4.5
60.5	224.5	103.6	10.4	5.1	3.4	0.6	0.4	2.1
48.4	241.9	106.5	8.7	3.9	7.7	0.8	0.5	
61.0	944.9	213.4	7.6	4.0	9.3	0.8	0.8	
131.1	21.8	349.5	19.7	7.6	9.0	1.1	1.1	
1833.4	20.4	346.3	15.3	5.3	7.1	2.4	1.2	
116.9	59.9	89.9	3.0	1.2	2.5	0.7	0.6	

Blank data are missing

Table A2.3 Regression Data for I-40 near Wilmington, NC

Day	Duration (min)	Precipitation (mm)	P5 (mm/hr)	Flow (mm)	Intensity (mm/hr)	VDS	ADP (hours)	ATC	PDUR (min)	PFLOW (mm)	PINT (mm/hr)
181	549.6	8.1	33.5	4.3	0.051	1765	100	21146			
192	375.0	30.5	88.4	20.8	0.077	2371	124	26221	60.0	11.8	0.197
220	19.8	7.1	39.6	2.8	0.111	135	357	75491	49.8	11.8	0.237
223	100.2	6.4	125.0	4.6	0.186	620	69.7	14739	19.8	5.4	0.271
237	120.0	11.7	85.3	9.4	0.035	734	103.5	21886	70.2	12.1	0.172
290	1170.0	83.3	61.0	63.2	0.056	2889	407	86064	19.8	11.1	0.561
306	180.0	39.4	42.7	31.2	0.106	1684	370	78240	409.8	77.1	0.188
340	390.0	7.1	6.1	6.6	0.019	504	219	46309	199.8	10.6	0.053
344	160.2	9.1	6.1	4.8	0.028	925	100	21146	175.2	5.4	0.031
4	280.2	9.1	24.4	4.1	0.029	400	358	75702	225.0	16.1	0.072
9	960.0	15.0	27.4	9.9	0.037	2578	119	25164	105.0	2.5	0.024
22	1440.0	90.4	18.3	40.6	0.031	7105	300	63438	154.8	12.8	0.083
30	495.0	15.2	21.3	4.8	0.080	2710	129	27278	1440.0	83.8	0.058
46	138.0	16.5	54.9	10.7	0.059	516	344.5	72847	195.0	3.0	0.015
103	45.0	5.3	24.4	2.3	0.041	220	93	19666	214.8	9.0	0.042
106	1158.0	40.1	33.5	25.1	0.030	3137	67	14168	45.0	3.7	0.082
116	90.0	5.1	15.2	1.3	0.014	413	152	32142	145.2	13.5	0.093
142	49.8	16.8	88.4	6.9	0.194	235	540	114188	64.8	4.2	0.064
146	432.0	56.1	170.7	43.7	0.186	740	81.5	17234	45.0	14.5	0.321
158	640.2	19.1	30.5	15.2	0.073	2698	227	48001	150.0	51.5	0.344
237	525.0	28.4	73.2	19.6	0.071	1884	189.5	40071	45.0	5.8	0.130
241	189.6	6.9	21.3	2.5	0.028	666	52	10996	55.2	25.5	0.461

Blanks are missing data

Table A2.3 Regression Data for I-40 near Wilmington, NC (contd.)

TSS (mg/m^2)	TDS (mg/m^2)	COD (mg/m^2)	TKN (mg/m^2)	NH_3-N (mg/m^2)	NO_3-N (mg/m^2)	TP (mg/m^2)	OP (mg/m^2)	Zn (mg/m^2)
30.2	492.3	336.8	4.3	0.4	1.9	0.4	0.2	0.4
270.8	1187.2	374.9	10.4	0.8	3.7	1.2	1.0	0.4
25.1	229.1	103.4	3.6	1.5	2.2	0.2	0.1	0.2
32.0	301.8	182.9	5.0	1.9	3.0	0.3	0.2	0.2
103.4	469.9	319.5	0.0	0.6	3.2	1.5	1.0	0.1
63.2	2403.3	316.2	19.0	3.2	3.8	3.2	3.2	1.9
31.2	1437.1	156.2	12.5	1.2	1.9	1.6	1.6	0.3
46.2	455.7	178.3	6.6	1.8	1.6	0.5	0.3	0.5
48.3	308.9	135.1	2.9	0.3	1.4	0.3	0.2	0.3
8.1	117.9	52.8	1.6	0.3	0.4	0.2	0.2	0.1
79.2	455.7	217.9	6.9	1.7	3.6	0.7	0.5	0.4
772.2	2072.6	1016.0	20.3	1.6	9.8	2.0	2.0	2.0
48.3	1211.3	67.6	3.4	1.6	2.5	0.2	0.2	1.0
362.7	693.4	288.0	10.7	3.1	2.5	1.5	0.5	0.6
230.9	196.6	118.9	4.3	1.5	2.2	0.3	0.1	0.1
100.6	528.1	125.7	7.5	1.3	1.5	1.3	1.3	0.5
16.5	90.2	43.2	1.0	0.2	0.6	0.1	0.1	0.1
75.4	308.6	123.4	4.8	0.5	2.3	0.3	0.3	0.3
436.9	1791.2	480.6	21.8	9.2	11.4	2.6	2.2	0.9
152.4	838.2	381.0	13.7	2.0	7.3	0.8	0.8	0.8
880.1	665.0	430.3	25.4	2.9	10.0	1.8	1.0	
25.4	94.0	22.9	1.3	0.3	1.3	3.5	3.4	

Blanks are missing data

Table A2.4 Regression Data for Hwy. 74 near Forest City, NC

Day	Duration (min)	Precipitation (mm)	P5 (mm/hr)	Flow (mm)	Intensity (mm/hr)	VDS	ADP (hours)	ATC	PDUR (min)	PFLOW (mm)	PINT (mm/hr)
192	460	25.9	11.9	3.3	0.004	1139	115	11141	60.0	0.0	0.000
235	455	50.0	82.3	17.3	0.026	270	353	34197	195.0	0.0	0.000
264	275	27.2	57.7	1.5	0.006	700	704	68200	454.8	25.5	0.056
277	355	21.1	9.7	5.3	0.013	724	135	13078	90.0	0.0	0.000
283	1070	52.1	12.2	26.7	0.030	2543	137	13272	354.0	7.9	0.022
305	240	34.3	12.2	16.8	0.035	279	282	27319	100.2	0.0	0.000
329	350	40.4	15.2	13.2	0.010	2044	557	53959	520.2	12.7	0.024
339	275	10.4	6.1	1.0	0.002	59	235	22766	349.8	11.1	0.032
344	100	4.6	6.1	0.3	0.002	233	127	12303	276.0	0.0	0.000
347	245	20.8	39.6	12.2	0.012	343	66	6394	102.0	0.0	0.000
9	415	35.3	27.4	24.9	0.020	737	10.5	1017	252.0	6.4	0.026
18	135	10.7	6.1	2.3	0.004	133	188	18213	195.0	8.5	0.044
86	55	5.6	12.2	1.3	0.002	167	361	34972	239.4	6.1	0.026
64	60	2.0	3.0	0.3	0.001	172	133.5	12933	25.2	0.0	0.000
71	40	2.0	9.1	0.8	0.003	5	157	15209	60.0	0.0	0.000
76	465	33.0	33.5	26.2	0.025	1228	127	12303	40.2	0.0	0.000
80	330	61.0	61.0	46.2	0.071	286	201	19472	465.0	13.7	0.029
93	215	28.7	24.4	14.2	0.027	150	309.5	29983	330.0	21.7	0.066
104	290	12.2	6.1	2.8	0.004	383	238.5	23105	175.2	5.5	0.031
115	270	24.1	21.3	7.1	0.014	696	213	20634	345.0	7.1	0.021
144	125	8.4	6.1	0.5	0.002	158	620	60063	318.0	3.9	0.012
157	120	10.2	9.1	0.3	0.001	301	291	28191	124.8	0.0	0.000
194	345	37.6	76.2	6.6	0.014	782	130	12594	120.0	0.0	0.000
205	105	74.9	155.4	44.2	0.227	20	264	25575	345.0	13.2	0.038
262	280	15.0	9.1	0.8	0.004	668	978	94744	145.2	0.0	0.000
266	865	43.7	17.8	23.4	0.013	452	63.5	6152	280.2	2.7	0.010

Blanks are missing data

Table A2.4 Regression Data for Hwy. 74 near Forest City, NC (contd.)

TSS (mg/m^2)	TDS (mg/m^2)	COD (mg/m^2)	TKN (mg/m^2)	NH_3-N (mg/m^2)	NO_3-N (mg/m^2)	TP (mg/m^2)	OP (mg/m^2)	Zn (mg/m^2)
13.2	310.4	151.9	5.6	0.1	0.3	0.9	0.7	0.6
51.8	1070.9	518.2	22.5	1.7	3.5	12.6	11.7	0.2
6.1	108.2	89.9	3.0	0.1	0.7	1.9	1.8	0.0
21.3	373.4	186.7	5.9	0.5	0.3	2.0	1.7	0.1
80.0	1253.5	826.8	29.3	2.7	1.3	4.8	4.0	0.3
83.8	1374.6	452.6	20.1	1.0	1.0	3.9	3.0	0.2
79.2	805.7	369.8	13.2	2.2	0.7	3.7	2.8	0.1
1.0	79.2	34.5	1.0	0.2	0.3	0.4	0.4	0.0
1.8	16.3	11.7	0.3	0.0	0.1	0.1	0.1	0.0
134.1	499.9	329.2	12.2	0.7	1.3	2.9	1.7	0.1
273.8	746.8	348.5	17.4	1.2	2.5	4.2	3.2	0.2
18.3	84.6	91.4	3.4	0.5	1.4	0.5	0.3	0.0
11.4	118.1	78.7	1.9	0.1	0.8	0.2	0.1	0.0
1.8	18.0	11.7	0.3	0.0	0.4	0.0	0.0	0.0
7.6	86.9	39.6	1.1	0.1	0.5	0.1	0.0	0.0
418.6	1805.2	1072.6	36.6	3.1	4.2	6.0	3.1	0.3
554.7	878.3	785.9	27.7	1.8	3.2	4.2	2.8	0.9
99.6	810.8	426.7	14.2	1.4	1.8	1.6	0.9	0.1
19.6	176.0	95.0	4.2	0.3	0.7	0.4	0.2	0.0
71.1	440.9	263.1	9.2	0.4	0.9	1.1	0.4	0.1
5.6	33.0	14.2	0.5	0.0	0.2	0.0	0.0	0.0
2.3	15.7	11.7	0.4	0.0	0.2	0.0	0.0	0.0
79.2	627.4	501.9	22.5	2.6	1.5	5.3	3.9	
1458.5	1591.1	1237.5	48.6	6.6	9.7	12.4	8.0	
3.0	45.7	30.5	1.1	0.1	0.1	0.3	0.3	
93.5	2033.0	1098.3	30.4	3.3	1.9	11.7	10.0	

Blanks are missing data

Table A2.5 Regression Data for I-40 near Winston Salem, NC

Day	Duration (min)	Precipitation (mm)	P5 (mm/hr)	Flow (mm)	Intensity (mm/hr)	VDS	ADP (hours)	ATC	PDUR (min)	PFLOW (mm)	PINT (mm/hr)
167	400.2	29.5	15.2	3.8	0.003	4683					
211	25.2	10.9	85.3	1.8	0.008	359	193	105547			
226	150.0	24.9	82.3	2.5	0.008	1128	141	77109	25.2	1.2	0.047
237	390.0	51.6	73.2	15.2	0.016	2157	119	65078	115.2	9.6	0.083
248	745.2	47.8	27.4	11.7	0.005	3488	248	135625	390.0	11.5	0.029
258	1040.0	39.6	18.3	9.1	0.006	10732	236	129063	745.2	10.5	0.014
271	565.2	29.0	24.4	3.6	0.003	5274	133	72734	90.0	0.0	0.000
283	550.2	20.8	12.2	1.3	0.001	6616	137.5	75195	75.0	0.0	0.000
293	235.2	13.5	9.1	1.5	0.001	1714	211	115391	550.2	3.7	0.007
306	210.0	9.7	15.2	0.3	0.001	2165	302	165156	235.2	1.8	0.008
330	559.8	46.2	128.0	9.7	0.014	7032	572	312813	210.0	0.9	0.004
340	300.0	7.1	6.1	0.5	0.001	792	237	129609	559.8	10.1	0.018
5	120.0	15.0	33.5	3.3	0.004	1708	709	387734	100.2	0.0	0.000
11	379.8	25.9	9.1	5.6	0.004	4143	116	63438	120.0	2.2	0.019
20	295.2	20.1	12.2	1.5	0.002	2552	215	117578	379.8	5.0	0.013
46	79.8	7.1	9.1	6.6	0.008	252	597	326484	295.2	3.5	0.012
50	150.0	9.4	9.1	1.0	0.001	1125	96	52500	79.8	0.2	0.003
77	409.8	19.8	70.1	6.1	0.006	4243	123.5	67539	184.8	0.0	0.000
81	390.0	26.7	27.4	7.4	0.007	4612	201	109922	409.8	3.4	0.008
96		22.6		3.3							
102		16.3		1.5							
104	199.8	17.5	15.2	1.3	0.002	2337	113	61797			
121	525.0	20.6	9.1	2.8	0.004	6176	68.5	37461	90.0	0.0	0.000
143	229.8	26.9	88.4	2.3	0.006	1325	531	290391	525.0	3.6	0.007

Blanks are missing data.

Table A2.5 Regression Data for I-40 near Winston Salem, NC (cont'd)

TSS	TDS	COD	TKN	NH_3-N	NO_3-N	TP	OP	Zn

(mg/m^2)	(mg/m^2)	(mg/m^2)	(mg/m^2)	(mg/m^2)	(mg/m^2)	(mg/m^2)	(mg/m^2)	(mg/m^2)
41.9	491.5	152.4	3.4	0.2	4.3	0.6	0.4	0.2
14.2	124.5	76.5	3.4	0.6	1.6	1.4	1.1	0.1
20.3	210.8	86.4	3.0	0.4	2.0	1.2	0.1	0.1
137.2	1234.4	640.1	19.8	2.0	2.6	8.4	6.7	0.2
46.7	1016.5	397.3	11.7	1.1	2.3	2.9	2.8	0.6
54.9	768.1	283.5	10.1	0.4	2.1	1.7	1.3	0.1
14.2	181.4	106.7	2.8	0.1	1.2	0.7	0.5	0.2
3.8	119.4	25.4	0.9	0.1	0.9	0.1	0.1	0.1
9.1	160.0	35.1	2.0	0.1	0.9	0.2	0.1	0.0
1.8	29.5	2.8	0.2	0.0	0.2	0.0	0.0	0.0
231.6	637.0	328.2	14.5	1.7	2.1	3.3	2.0	0.4
0.5	64.0	11.2	0.3	0.1	0.5	0.0	0.0	0.0
39.6	251.0	99.1	4.0	0.4	1.4	0.6	0.3	0.1
78.2	810.3	139.7	5.6	0.7	3.2	0.6	0.3	0.2
9.1	525.8	35.1	2.1	0.6	0.6	0.2	0.1	0.2
145.3	3150.1	323.6	9.2	0.9	2.2	2.0	1.7	0.3
18.3	393.2	43.7	1.4	0.1	0.6	0.2	0.1	0.0
292.6	1152.1	359.7	16.5	1.5	1.4	2.9	1.4	0.5
140.0	906.0	353.6	11.0	0.4	1.0	1.8	1.3	0.1
85.9	449.1	165.1	6.3	0.5	0.9	0.8	0.5	0.1
18.3	224.0	57.9	2.4	0.2	0.5	0.3	0.2	0.0
90.2	119.4	39.4	1.7	0.1	0.5	0.2	0.2	0.0
33.5	357.6	170.4	5.6	0.3	0.6	0.5	0.2	0.1
68.6	233.2	91.4	2.7	0.4	1.9	1.1	0.9	0.0

Blanks are missing data.

Table A2.6 Regression Data for I-40 near Garner, NC

Day	Duration (min)	Precipitation (mm)	P5 (mm/hr)	Flow (mm)	Intensity (mm/hr)	VDS	ADP (hours)	ATC	PDUR (min)	PFLOW (mm)	PINT (mm/hr)

167	385.0	32.5	2.8	13.0	0.013	3590	75.3	41224			
221	205.0	11.9	0.8	1.5	0.004	2507	1063.7	582062	40.2		
238	55.0	22.1	8.4	10.9	0.025	578	124.4	68084	49.8	6.9	0.139
252	50.0	18.3	0.8	8.4	0.015	600	88.1	48201	222.0	8.6	0.039
264	185.0	15.0	4.1	2.3	0.003	464	144.3	78982	1428.0		
291	835.0	46.7	1.5	23.4	0.021	8902	156.8	85777	105.0	0.3	0.003
294	460.0	30.5	2.3	15.7	0.009	3128	54.0	29550	835.2	18.9	0.023
306	85.0	16.5	3.3	4.1	0.013	1183	321.1	175704	460.2	11.8	0.026
340	115.0	9.1	0.8	1.3	0.004	1587	814.2	445530		17.9	
344	20.0	2.8	0.8			296	97.5	53354	115.2	2.3	0.020
5	175.0	16.3	2.5	4.8	0.008	2159	603.3	330112		1.8	
11	355.0	31.2	1.0	26.7	0.032	3262	11.0	6019	105.0	0.0	0.000
46	105.0	31.2	2.8	20.6	0.033	671	37.3	20430	378.0	8.0	0.021
50	260.0	12.4	0.8	6.6	0.008	1197	104.0	56911	105.0	12.1	0.116
60	165.0	10.4	2.8	1.8	0.003	1452	230.5	126135	258.0	3.7	0.015
78	305.0	37.6	6.1	18.8	0.015	4127	420.7	230198	165.0	2.8	0.017
89	85.0	13.5	2.3	3.0	0.006	909	246.2	134708	304.8	15.0	0.049
104	190.0	10.9	0.5	1.3	0.003	2731	111.2	60833		8.3	
121	465.0	23.6	0.8	3.6	0.004	6441	81.6	44644	192.0	3.1	0.016
143	115.0	18.0	4.8	3.3	0.011	180	558.5	305624	465.0	8.7	0.019
241	285.0	21.8	4.6	1.5	0.008	3185	53.4	29231	60.0		

Blanks are missing data.

Table A2.6 Regression Data for I-40 near Garner, NC (cont'd)

TSS (mg/m^2)	TDS (mg/m^2)	COD (mg/m^2)	TKN (mg/m^2)	NH_3-N (mg/m^2)	NO_3-N (mg/m^2)	TP (mg/m^2)	OP (mg/m^2)	Zn (mg/m^2)
375.7	1774.7	647.7	33.7	4.7	43.7	5.4	3.5	1.9

18.3	213.4	97.5	2.3	0.1	1.2	0.5	0.3	0.0
32.8	786.4	294.9	0.0	0.4	3.6	1.3	1.1	0.1
25.1	620.3	217.9	7.5	0.7	1.1	1.6	1.3	0.2
6.9	93.7	41.1	1.8	0.1	0.5	0.2	0.2	0.0
93.5	1472.2	280.4	14.0	0.9	2.1	1.6	1.2	0.2
15.7	1307.1	189.0	78.7	0.6	3.1	0.0	0.8	0.2
32.5	426.7	117.9	5.3	0.2	0.2	2.1	1.7	0.0
10.2	127.0	6.4	1.0	0.1	0.1	0.3	0.3	0.0
29.0	328.2	106.2	4.3	0.4	3.6	0.9	0.6	0.0
133.4	2267.0	586.7	16.0	1.3	8.3	2.4	1.3	0.3
349.8	3826.8	637.8	24.7	2.7	11.5	3.1	2.1	0.4
13.2	911.4	244.3	4.6	0.7	5.7	0.6	0.4	0.1
28.4	215.1	71.1	1.4	0.1	1.8	0.2	0.1	0.1
751.8	1672.8	751.8	30.1	1.5	4.5	4.3	1.7	0.6
24.4	347.5	103.6	2.7	0.1	1.2	0.3	0.2	0.1
67.3	119.4	39.4	1.4	0.1	0.9	0.2	0.2	0.0
39.1	348.5	106.7	3.6	0.3	1.7	0.4	0.2	0.1
33.0	237.7	122.2	5.9	1.1	2.5	1.0	0.7	0.0
53.3		16.8	1.1	0.3	0.7	1.3	0.3	

Blanks are missing data.