CHARACTERIZATION AND POLLUTANT LOADING ESTIMATION FOR HIGHWAY RUNOFF

By Jy S. Wu,[1] Member, ASCE, Craig J. Allan,[2] William L. Saunders,[3] and Jack B. Evett,[4] Member, ASCE

ABSTRACT: Three highway segments typical of urban, semiurban, and rural settings in the Piedmont region of North Carolina were monitored to characterize the respective runoff constituent concentrations and pollutant discharge or export loadings. Runoff from the impervious bridge deck (Site I) carried total suspended solids (TSSs) concentrations and loadings that are relatively higher than typical urban highways, whereas nitrogen and phosphorus loadings are similar to agricultural runoff. Site II included a pervious roadside shoulder with traffic volume equal to that of Site I. Site III was a nonurban highway having lower traffic counts and imperviousness due to the presence of a roadside median. The existing roadside shoulder and median appeared to attain at least 10–20% hydrologic attenuation of peak runoff discharges, more than 60% reduction of event mean concentration of TSSs, and attenuation of the first-flush concentrations for most pollutant constituents. Bulk precipitation data collected at the bridge deck site indicated that 20% of TSS loadings, 70–90% of nitrogen loadings, and 10–50% of other constituent exports from the roadway corridors might have originated from atmospheric deposition during dry and wet weather conditions. The long-term highway pollutant loadings have been derived to provide a basis for comparing highway runoff with other categories of nonpoint sources (NPSs).

INTRODUCTION

According to the National Water Quality Inventory, 1990 Report to the Congress, states estimated that 30% of identified cases of water quality impairment are attributable to storm water discharges or nonpoint source (NPS) pollution (U.S. EPA 1990). Among the various NPSs; agricultural runoff, urban runoff, and mine drainage create over 90% of the pollution problems in assessed rivers. NPS pollution resulting from silvicultural and construction activities may be substantial but are usually localized. The several million miles of highway throughout the United States represent a known but unquantified source of NPS pollution. Water quality impact due to highway runoff could be significant particularly in environmentally sensitive areas such as wetlands, ground-water 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, the impact of highway runoff must be treated 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 National Pollution Discharge Elimination System for the storm water permitting program to characterize storm water discharge and develop pollution prevention plans and best management practices. While a considerable amount of monitoring data exists for runoff from urban areas (Wu and Ahlert 1978; U.S. EPA 1983; Marsalek 1991; Novotny and Olem 1994; Makepeace et al. 1995; Robinson et al. 1996; Wu et al. 1996), only a limited amount of highway runoff data has been collected (Chui et al. 1982; Stotz 1987; Driscoll et al. 1990; Smith and Lord 1990; Irish et al. 1995). Highway runoff data are generally not available for the southeast region of the United States.

Most states including North Carolina have developed guidelines, best management practices, and policies pertaining to the planning, design, construction, and maintenance of the state highway systems (e.g., N.C. DOT 1997). To properly address the issues of highway runoff and its control and management practices, state officials must rely on a comprehensive database by which the export of highway pollutants can be estimated. Consequently, a study was initiated to examine and characterize highway runoff from different highway surface types and traffic conditions. The study included a field monitoring program to collect storm water quantity and quality data from three segments of highway settings. This paper summarizes the monitoring data and evaluates the exports of highway runoff pollutant loads that are representative of roadway conditions in the southeast United States. Additional research findings pertaining to statistical modeling and watershed monitoring and management issues from this data set will be reported in forthcoming articles.

METHODOLOGY

Three highway sites located inside the city of Charlotte, in the Piedmont region of North Carolina, were selected for monitoring during the period of August 1995–July 1996 (see Figs. 1 and 2 for site layout). Table 1 summarizes the physical characteristics and other pertinent information of these monitored sites. Two sites exhibited similar average daily traffic (ADT) counts, expressed as vehicles per day, but differed in their percentage of impervious cover. The third site was a nonurban highway and had lower traffic counts and imperviousness. This study was aimed at developing a strategic sampling protocol to characterize highway runoff as related to roadway imperviousness and traffic conditions.

Site Description

Site I (W. T. Harris Blvd.): This section of the W. T. Harris Blvd. carries an average traffic of 25,000 vehicles/day and is a major artery around the north and east sides of the city of Charlotte, extending from I-77 on the north to U.S. 74 on the southeast. The highway segment that was sampled was located

[1]Prof., Dept. of Civ. Engrg., Univ. of North Carolina at Charlotte, Charlotte, NC 28223.
[2]Asst. Prof., Dept. of Geography and Earth Sci., Univ. of North Carolina at Charlotte, Charlotte, NC.
[3]Res. Assoc., Dept. of Civ. Engrg., Univ. of North Carolina at Charlotte, Charlotte, NC.
[4]Prof., Dept. of Civ. Engrg., Univ. of North Carolina at Charlotte, Charlotte, NC.

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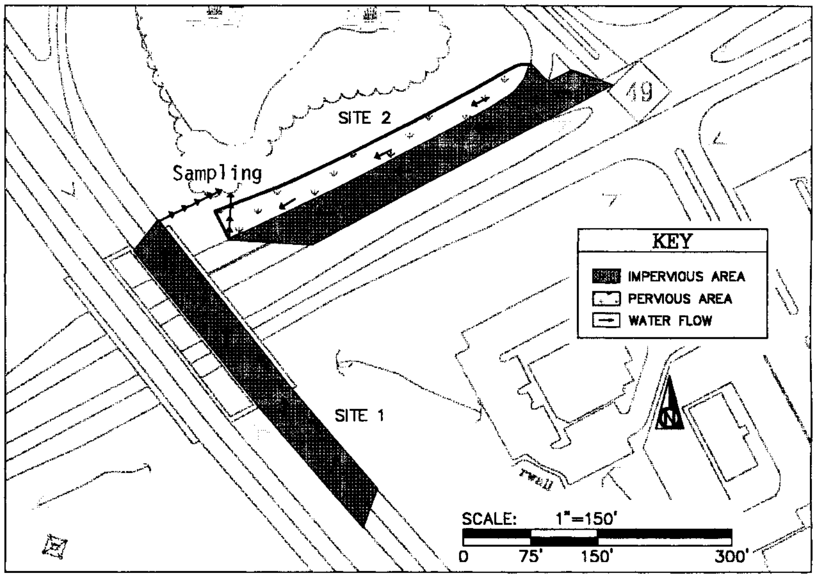

FIG. 1. Highway Runoff Sampling Sites I and II (W. T. Harris Blvd. and N.C. 49)

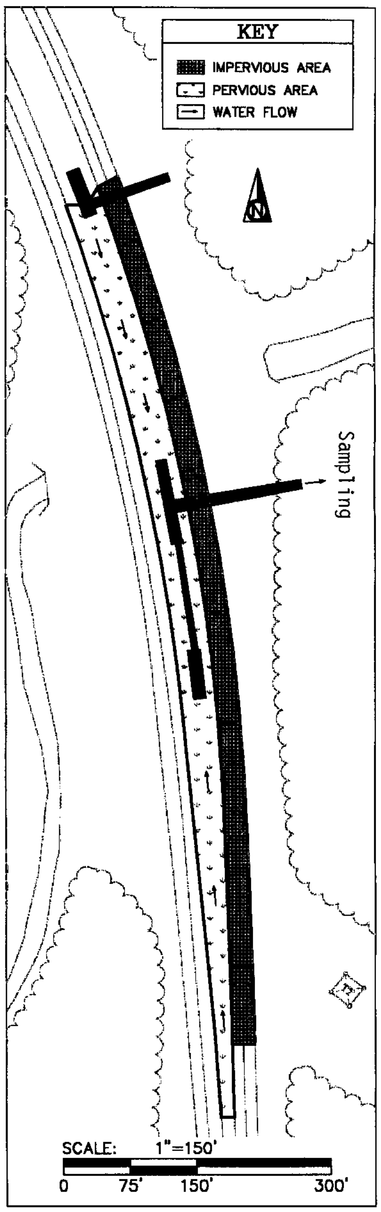

FIG. 2. Highway Runoff Sampling Site III (I-85 and U.S. 29 Connector)

TABLE 1. Physical Characteristics of Highway Runoff Monitoring Sites

Characteristics (1)	Site I (2)	Site II (3)	Site III (4)
Drainage area[a]			
m^2	1,497	2,307	4,452
acres	0.37	0.57	1.10
Road surface material	Concrete/asphalt	Asphalt	Asphalt
Imperviousness (%)	100	61	45
Average daily traffic	25,000	21,500	5,500
Number of lanes	3	3	2
Lane-ft	1,125	1,100	1,560
Surrounding land use (%)			
Woods	69	69	73
Residential	24	24	17
Heavy commercial	6	6	—
Light commercial	<1	<1	<1
Industrial	<1	<1	2
Others	—	—	7

[a]Including road surface and grassy shoulders and medians.

on a three-lane concrete bridge with a posted speed limit of 89 km/h (55 mi/h). Runoff enters a pipe located at the northeast corner of the bridge, then flows through the pipe under the bridge, and discharges into a vegetated area.

Site II (N.C. 49 at W. T. Harris Blvd. Overpass): The average traffic at the overpass is 21,500 vehicles/day. N.C. 49 is a state highway connecting Charlotte and Raleigh. The highway segment that was sampled was located along a three-lane asphalt section and included a mixed impervious and pervious runoff contributing area. The posted speed limit is 81 km/h (50 mi/h). Runoff at this site drains to a catch basin located at the north edge of the grassy shoulder, then flows through an underground pipe into a vegetated area. Runoff may occasionally bypass the pervious area and flow directly into the catch basin from the impervious roadside.

Site III (I-85 and U.S. 29 Connector): This is a four-lane, divided highway with light traffic volume and a mixed impervious and pervious runoff area. The highway section that was sampled was located on a curve in the connector roadway, which carries a daily traffic of 5,500 vehicles/day between U.S. 29 and I-85. The posted speed limit is 89 km/h (55 mi/h). All highway runoff at this site flows into a grassy median and discharges at the foot of an embankment through a pipe under the north roadway.

Monitoring Program

The monitoring program included the collection of rainfall and runoff volumes, bulk precipitation, traffic counts, and discrete and composite storm water samples.

Tipping bucket and nonrecording rain gauges were installed at each monitoring site. Each tipping bucket rain gauge recorded rainfall amounts on five-min intervals and stored the data in either a Campbell Scientific CR-10 Data Logger or with an American Sigma 800SL water sampler.

A rectangular channel made of plywood was installed at the outlet of each drain pipe at Sites I and II. Flow through the rectangular channel passes through a 60° V-notch weir and finally discharges into a natural ditch into a vegetated area. An ISCO or American Sigma automatic sampler was installed to continuously record flow stages that were subsequently converted to flow rates. Each weir was volumetrically gauged over a wide range of discharge to develop stage-discharge curves.

An elliptical flow divider, made of relatively inexpensive materials, was installed at the end of the drain pipe to collect composite samples of Site III. The divider provides accurate diversion for a fixed fraction of runoff, proportional to the flow rate, to pass through and drain into a holding tank of 48 × 47 × 36 in. capacity. The liquid level in the holding tank was continuously recorded by a potentiometric water-level recorder logged with Campbell Scientific CR-10 Data Logger and converted into flow rates. The flow divider has been shown to be an ideal device for collecting composite samples when event-based pollutant loads of highway runoff are the primary data to be collected.

Bulk precipitation was collected using two 19-L (5-gal.) plastic-lined collectors at each site. Each collector was mounted at least 12 m from the road edge and 2 m above the ground surface to ensure that visible objects within 20 m would not exceed 30° from the horizontal.

Depending on the duration of the runoff event, each automatic sampler was programmed to collect discrete samples at a preset time increment to ensure the collection of at least 6–8 samples within a storm event. Composite sampling was accomplished by taking a fixed amount of sample at equal flow intervals during a storm. Composite samples from Site III were obtained directly from the holding tank as previously described. Both discrete and composite samples were collected at Sites I and II, whereas only composite samples were obtained at Site III.

Traffic counts were conducted during nonstorm and nonholidays including weekdays and weekends, between 6 a.m. and 8 p.m. and 10 p.m. to 1 a.m. Since the traffic data were used primarily for site characterization, traffic counts during a storm event were estimated by adjusting the nonstorm data by a correction factor of 0.6% reduction for each 0.25 mm (0.01 in.) increase in rainfall (Riles 1981).

Runoff samples were taken to the Environmental Research Laboratory at the University of North Carolina at Charlotte. Water quality constituents analyzed included pH, specific conductance, salinity, total dissolved solids (TDS), total suspended solids (TSS), nitrate plus nitrite (NO_{3+2}-N), ammonia (NH_3-N), total Kjeldahl nitrogen (TKN), ortho-phosphorus (OP), total phosphorus (TP), oil and grease (O&G), chromium (Cr), nickel (Ni), copper (Cu), cadmium (Cd), and lead (Pb). Nutrients and COD were analyzed using Hach methods (*Water* 1992). Solids and O&G were determined following procedures described in Standard Methods (*Standard* 1992). Metals samples were preserved with nitric acid, and the supernatant portions of the settled samples were withdrawn for analysis by an atomic absorption spectrophotometer equipped with controlled temperature furnace atomizer. Whenever the measured concentrations of metal species were less than the method detection limit of 5 parts per billion (ppb), typically observed in the range of 1–5 ppb, a value of half the detection limit or 2.5 ppb was used for numerical calculations. Appropriate probes were used to measure pH, specific conductance and salinity. All analyses were performed in accordance with the EPA specified quality assurance and quality control program.

RESULTS AND ANALYSIS

Table 2 summarizes the statistical information of the 31 storm events monitored in this study. According to the rainfall records provided by the U.S. Geological Survey, the average rainfall duration and the average time between storms for all storms occurring in Charlotte within the monitoring period were 6.4 and 108.3 h, respectively. Conductivity and salinity readings for several of the monitored storms were relatively higher, probably due to deicing or roadway maintenance activities. These include storms of October 4, 1995 (Site I); October 13, 1995 (Site II); and January 19, 1996, January 24, 1996, February 20, 1996, and March 6, 1996 (Site III). We were unable to trace the origin of the performed activities nor the type, duration, and amount of salt application during these events.

TABLE 2. Rainfall and Runoff Statistics of Monitored Storms at Sites I, II, and III

Storm Event: Date (1)	Storm Event: Number (2)	Rainfall volume (mm)[b] (3)	Rainfall duration (h) (4)	Antecedent dry day (days) (5)	Runoff coefficient (6)
		(*a*) Site I			
9/22/95	1	2.79	1.30	5.44	0.34
10/4/95	2	14.48	2.97	6.18	0.83
10/13/95	3	5.08	2.20	9.12	0.49
1/24/96	4	7.11	3.83	5.06	0.95
3/15/96	5	6.10	0.63	8.13	0.89
3/19/96	6	15.49	3.03	2.56	0.90
4/20/96	7	8.38	0.85	1.22	0.59
4/26/96	8	13.97	2.60	2.63	0.91
5/28/96	9	8.38	3.90	1.29	0.66
7/1/96	10	6.86	0.20	11.50	0.54
Mean	—	8.86	2.15	5.31	0.71
CV[a]	—	0.46	0.59	0.62	0.29
		(*b*) Site II			
9/16/95	1	26.67	10.60	4.69	0.59
9/23/95	2	20.83	4.05	0.61	0.59
10/4/95	3	14.48	2.97	6.18	0.47
10/13/95	4	5.08	2.20	9.12	0.11
1/24/96	5	7.11	3.83	5.06	0.46
3/7/96	6	18.29	7.83	0.67	0.80
3/19/96	7	15.49	3.03	2.56	0.56
4/13/96	8	9.65	0.42	4.55	0.70
4/20/96	9	8.38	0.85	1.22	0.42
4/26/96	10	13.97	2.60	2.63	0.47
5/11/96	11	8.64	0.48	11.12	0.48
Mean	—	13.51	3.53	4.40	0.51
CV[a]	—	0.46	0.85	0.74	0.33
		(*c*) Site III			
9/23/95	1	27.94	13.60	6.60	0.43
10/4/95	2	60.20	11.60	6.18	0.64
10/20/95	3	15.70	0.58	5.58	0.51
11/2/95	4	35.56	17.90	5.20	0.52
11/7/95	5	39.37	16.00	3.35	0.65
1/19/96	6	13.13	14.75	5.08	0.29
1/24/96	7	7.80	3.83	5.06	0.60
1/27/96	8	44.70	3.92	2.61	0.67
2/20/96	9	7.01	7.92	10.73	0.26
3/6/96	10	31.50	9.75	6.70	0.32
Mean	—	28.29	9.99	5.71	0.49
CV[a]	—	0.58	0.55	0.37	0.31

[a]CV = coefficient of variation.
[b]mm × 0.0394 = in.

Hydrology

The relationship between rainfall (P) and runoff (R) data observed at the monitoring sites can be represented by three linear correlation equations as follows:

Site I:

$$R = -2.032 + 1.007(P); \quad r^2 = 0.95 \tag{1}$$

Site II:

$$R = -1.981 + 0.705(P); \quad r^2 = 0.90 \tag{2}$$

Site III:

$$R = -4.140 + 0.690(P); \quad r^2 = 0.91 \tag{3}$$

where P and R are in millimeters. By setting R equal to zero, the amount of rainfall needed to satisfy initial abstraction and other losses prior to the occurrence of runoff can be estimated from the above expressions. These initial losses accounted for 2.03 mm (0.08 in.), 2.79 mm (0.11 in.), and 6.10 mm (0.24 in.), for Sites I, II, and III, respectively. The site mean runoff coefficients were found to be 0.71 (Site I), 0.51 (Site II), and 0.49 (Site III). Because Site I was highly impervious, hydrologic response to rainfall was typically fast and storms of greater than 2.54 mm (0.1 in.) would provide sufficient runoff volume for sampling. The runoff coefficient of Site I would be higher, e.g., 0.80 or greater, if storms of greater magnitudes were collected and included in the data set.

A normalized peak discharge factor (PDF), defined as the ratio of peak discharge of runoff to total rainfall amount, was calculated for each event. The site mean PDFs for Sites I, II, and III were 2.49, 1.95, and 2.21 m^3/h-mm, respectively. The corresponding coefficients of variation were 0.54 (Site I), 0.58 (Site II), and 0.64 (Site III). In comparison to Site I, Sites II and III exhibited relative reductions of the peak factor by 22 and 11%, respectively. If additional runoff-producing storms of smaller magnitudes had been included in the Site III data, the relative reduction of PDFs at this site could have been greater.

Event Mean Concentration

Tables 3–5 present the event mean concentrations (EMCs) of all water quality constituents analyzed for each storm event and the associated statistics. Comparisons among monitoring sites and with the national data were based on site mean EMCs and site median EMCs.

Site mean EMCs were taken as the arithmetic average of all EMCs observed at a monitoring site. With respect to TSS, the site mean EMCs were 283 mg/L (Site I), 93 mg/L (Site II), and 30 mg/L (Site III). In comparison to Site I, the EMCs of TSS at Sites II and III were, respectively, 67 and 89% lower at these sites. The EMCs of O&G were 40–70% lower at Sites II and III as well. Generally, various levels of EMC reduction for all water quality constituents, except phosphorus, were observed at Sites II and III. Kaighn and Yu (1996) observed that less than satisfactory reduction of TP concentrations by grassed swales was not uncommon. Removal of phosphorus by vegetative filters depends on the partition of phosphorus in solid/dissolved forms and the affinity of phosphorus with different particle sizes. Cadmium in all storm samples and nickel

TABLE 3. EMCs at Monitoring Site I

Storm number (1)	TDS (mg/L) (2)	TSS (mg/L) (3)	COD (mg/L) (4)	NO_{3+2}-N (mg/L) (5)	NH_3-N (mg/L) (6)	TKN (mg/L) (7)	OP (mg/L) (8)	TP (mg/L) (9)	O&G (mg/L) (10)	Cu (ug/L) (11)	Cd (ug/L) (12)	Cr (ug/L) (13)	Pb (ug/L) (14)	Ni (ug/L) (15)
1	173	380	177	6.47	1.26	2.42	0.74	1.54	—	51.5	—	10.0	31.0	14.0
2	577	111	156	13.37	1.01	2.45	0.21	0.77	2.0	14.0	—	6.0	<0.5	10.0
3	181	771	150	0.32	1.74	2.36	<0.01	0.81	2.8	52.0	<0.5	13.0	30.0	17.0
4	119	538	76	0.51	0.67	1.88	0.15	0.40	11.1	47.0	<0.5	20.0	56.0	12.0
5	86	220	4	0.40	0.77	0.78	0.01	0.13	3.7	24.0	<0.5	<0.5	12.0	<0.5
6	61	133	8	0.22	0.59	0.68	0.09	0.13	1.0	12.0	<0.5	5.0	16.0	<0.5
7	95	308	70	0.37	0.64	0.98	0.18	0.26	—	16.0	<0.5	9.0	26.0	9.0
8	62	123	13	0.08	0.50	0.76	0.07	0.13	—	9.0	<0.5	6.0	14.0	<0.5
9	71	32	26	0.36	0.52	0.87	0.05	0.12	—	<0.5	<0.5	<0.5	7.0	<0.5
10	148	210	15	0.38	0.62	1.02	0.04	0.04	6.0	14.0	<0.5	7.0	13.0	9.0
Median	107	215	48	0.38	0.66	1.00	0.08	0.20	3.3	15.0	2.5	6.5	15.0	9.0
Mean	157	283	70	2.25	0.83	1.42	0.15	0.43	4.4	24.2	2.5	8.1	21.0	8.1
CV[a]	0.93	0.76	0.93	1.84	0.45	0.51	1.34	1.04	0.8	0.7	1.0	0.6	0.7	0.6

[a]CV = coefficient of variation.

TABLE 4. EMCs at Monitoring Site II

Storm number (1)	TDS (mg/L) (2)	TSS (mg/L) (3)	COD (mg/L) (4)	NO_{3+2}-N (mg/L) (5)	NH_3-N (mg/L) (6)	TKN (mg/L) (7)	OP (mg/L) (8)	TP (mg/L) (9)	O&G (mg/L) (10)	Cu (ug/L) (11)	Cd (ug/L) (12)	Cr (ug/L) (13)	Pb (ug/L) (14)	Ni (ug/L) (15)
1	48	21	32	0.43	0.92	1.68	0.79	1.27	4.6	—	—	—	—	—
2	53	9	27	0.56	0.55	1.37	0.39	0.85	1.2	<0.5	—	<0.5	<0.5	<0.5
3	38	24	24	0.06	0.65	1.61	0.39	0.72	2.4	<0.5	—	<0.5	<0.5	<0.5
4	100	49	78	0.22	1.11	2.02	0.59	1.27	1.7	5.0	<0.5	4.0	13.0	<0.5
5	211	221	81	0.15	0.77	1.54	0.35	0.39	—	16.0	<0.5	8.0	35.0	<0.5
6	89	57	12	0.12	0.49	0.70	0.05	0.17	—	12.0	<0.5	<0.5	15.0	<0.5
7	67	132	6	0.21	0.58	0.72	0.17	0.20	1.2	15.0	<0.5	<0.5	20.0	<0.5
8	70	136	45	0.18	0.65	0.86	0.07	0.13	2.6	11.0	<0.5	<0.5	10.0	<0.5
9	85	139	61	0.19	0.62	0.95	0.21	0.23	4.9	14.0	<0.5	5.0	16.0	<0.5
10	65	88	48	0.11	0.46	0.90	0.26	0.37	0.2	16.0	<0.5	<0.5	13.0	<0.5
11	138	149	11	0.24	0.53	0.67	0.03	0.07	—	21.0	<0.5	<0.5	11.0	<0.5
Median	70	88	32	0.19	0.62	0.95	0.26	0.37	2.1	12.0	2.5	2.5	13.0	2.5
Mean	88	93	39	0.22	0.76	1.18	0.30	0.52	2.4	11.5	2.5	3.5	13.9	2.5
CV[a]	0.54	0.69	0.65	0.62	0.28	0.38	0.76	0.82	0.7	0.5	1.0	0.5	0.6	1.0

[a]CV = coefficient of variation.

TABLE 5. EMCs at Monitoring Site III

Storm number (1)	TDS (mg/L) (2)	TSS (mg/L) (3)	COD (mg/L) (4)	NO_{3+2}-N (mg/L) (5)	NH_3-N (mg/L) (6)	TKN (mg/L) (7)	OP (mg/L) (8)	TP (mg/L) (9)	O&G (mg/L) (10)	Cu (ug/L) (11)	Cd (ug/L) (12)	Cr (ug/L) (13)	Pb (ug/L) (14)	Ni (ug/L) (15)
1	100	4	45	<0.01	0.38	1.31	0.17	1.31	2.1	<0.5	<0.5	<0.5	<0.5	<0.5
2	51	5	21	<0.01	0.31	1.49	0.30	0.81	2.3	<0.5	<0.5	<0.5	<0.5	<0.5
3	27	10	7	0.03	0.81	0.98	0.34	1.02	1.3	<0.5	<0.5	<0.5	5.0	<0.5
4	52	11	27	0.03	0.31	1.05	0.19	0.26	2.1	<0.5	<0.5	<0.5	6.0	<0.5
5	45	57	26	0.07	0.45	0.94	0.17	0.25	0.9	<0.5	<0.5	<0.5	6.0	<0.5
6	326	113	26	0.41	<0.01	0.98	0.15	0.38	1.4	9.0	<0.5	<0.5	<0.5	<0.5
7	346	39	26	0.12	1.03	1.16	0.11	0.18	0.2	6.0	<0.5	<0.5	12.0	<0.5
8	66	37	7	0.15	1.07	1.13	0.14	0.20	0.5	10.0	<0.5	<0.5	13.0	<0.5
9	965	16	22	0.45	0.51	0.67	0.04	0.14	—	<0.5	<0.5	<0.5	7.0	12.0
10	183	10	11	0.09	0.32	0.26	0.08	0.12	0.9	6.0	<0.5	<0.5	8.0	<0.5
Median	83	14	24	0.08	0.42	1.02	0.16	0.26	1.1	2.5	2.5	2.5	6.0	2.5
Mean	216	30	22	0.14	0.52	1.00	0.17	0.47	1.3	4.6	2.5	2.5	6.5	3.5
CV[a]	1.26	1.07	0.48	1.15	0.63	0.32	0.52	0.86	0.5	0.6	1.0	1.0	0.6	0.8

[a]CV = coefficient of variation.

concentrations at Sites II and III were below their method detection limits (5 ppb). Site mean EMCs for Cu, Cr, Pb, and Ni were in the range of 8–25 ppb for Site I and 5–15 ppb for Sites II and III. Note that the maximum contaminant levels for Cd, Cr, and Pb in drinking water are 10, 50, and 50 ppb, respectively. The secondary maximum contaminant levels for copper in drinking water is 1,000 ppb. Nickel has a criterion level of 10 ppb of the 96-h LC_{50} for freshwater and marine aquatic life. The reduction of pollutant constituent EMCs at Site II appears to be effected by the grassy shoulder that serves as a vegetative filter for pollutant removal. Reduction of EMCs at Site III is likely to be the combined effects of a grassy median and/or lower traffic volumes.

Table 6 compares several key water quality constituents with respect to urban runoff data reported by the Nationwide Urban Runoff Program (NURP) (U.S. EPA 1983) and Wu et al. (1996) for the Charlotte urban watersheds in North Carolina. Site mean TSS EMCs of Site I (bridge deck runoff) were approximately double that of the Charlotte urban runoff and were about 25% higher than the NURP residential runoff data. Site mean COD EMCs of Site I were the same as the NURP data. Sites II and III showed substantially lower site mean TSS (60–90%) and COD (40–70%) with respect to the NURP data. Nitrogen and phosphorus data for all sites were generally between the data range given by NURP and the Charlotte data. It should be noted that the Charlotte runoff data were representative of urban watersheds implementing good management practices and the NURP data were collected in the early 1980s at which time watershed management practices had not been widely implemented.

Table 7 compares the site median EMCs of highway runoff reported by the Nationwide program (Driscoll et al. 1990), the Texas highway runoff study (Irish et al. 1995), and this study. The Charlotte highway data were generally within the range of the Texas highway runoff data. In comparison to the Nationwide data, site median EMCs at all three monitored sites were similar to rural highway runoff but lower than urban highway runoff with the exceptions that (1) the site median TSS EMC at Site I was 50% higher than urban highways; (2) the site median TSS EMC at Site II was 40% lower than that of urban highways but were double that of rural highway runoff; (3) the site median TSS EMC at Site III was much lower than the Nationwide and the Texas data; and (4) the site median EMCs for all metal constituents were substantially lower than the Nationwide and the Texas data.

TABLE 6. Comparison of Urban Runoff and Highway Runoff (Site Mean EMCs)

Water quality parameter (mg/L) (1)	Charlotte urban runoff[a] (2)	NURP Data[b]		Charlotte Highway Runoff		
		Residential (3)	Commercial (4)	Site I (5)	Site II (6)	Site III (7)
TSS	135	228	—	283	93	30
COD	—	—	65	70	39	22
NH_3-N	0.22	—	1.50	0.83	0.67	0.52
TKN	0.88	2.58	0.12	1.42	1.18	1.00
OP	0.10	—	0.33	0.15	0.30	0.17
TP	0.14	0.62	—	0.43	0.52	0.43

[a]Wu et al. (1996).
[b]U.S. EPA (1983).

Pollutant Loadings

The amount of pollutant export from land-based processes is usually reported in terms of mass/unit area/runoff duration. Table 8 compares the long-term average pollutant loading rates (kg/ha-year) of this study with those reported in the literature. In our data set, the long-term average loading rates were obtained by multiplying the site mean loading rates by the ratio of average storm duration (6.4 h) to the average time between storms (108.3 h). The estimated annual loadings are presented in Table 8, together with loading data for different roadway surfaces reported by U.S. and German investigators.

The annual loadings of TSS at Site I were 1.4–5.6 times higher than the U.S. and German data range given in Table 8, whereas COD loadings were comparable to that of a concrete surface with 100% drainage area paved. TSS and COD loadings of Sites II and III approached that of an asphalt highway surface with 40% drainage area paved. The export of nitrogen and phosphorus loadings varied among the three study sites. The total nitrogen loadings (NO_{3+2}-N plus TKN) delivered by Sites I, II, and III were 35.0, 11.3, and 21.4 kg/ha-year, respectively. These nitrogen loading rates when compared with the U.S. highway loading of 14.9 kg/ha-year suggest that the export of total nitrogen at Sites I and III could be 2.3 and 1.4 times, respectively, higher than the U.S. average. The annual TP loadings at Sites I (3.5 kg/ha-year) and II (4.8 kg/ha-year) were similar to the U.S. average but could be 2–8 times higher than the German data. TP loading at Site III (9.1 kg/ha-year) was 3 times higher than the U.S. average. The reported average nitrogen and phosphorus loading rates from agricultural runoff were 44–66 kg/ha-year and 4–9 kg/ha-year, respectively (Novotny and Olem 1994). Loading rates for metal species at all three sites were generally lower than the U.S. and German data. Oil and grease loadings of Sites II and III were about 65% less than that at Site I.

It is not surprising that several of the pollutant loading rates, e.g., TSS and nitrogen, of Site I were higher than those reported for impervious roadways because runoff originating from bridge deck surfaces is impacted to a greater degree and

TABLE 7. Comparison of Highway Runoff Site Median EMCs

Water quality parameter (1)	Texas data[a] (2)	Nationwide Data[b] Urban highway (3)	Nationwide Data[b] Rural highway (4)	Charlotte Highway Runoff Site I (5)	Charlotte Highway Runoff Site II (6)	Charlotte Highway Runoff Site III (7)
ADT (vehicles/day)	16,090–811,060	>30,000	<30,000	25,000	21,500	5,500
TSS (mg/L)	67–291	142	41	215	88	14
COD (mg/L)	24–142	114	49	48	32	24
O&G (mg/L)	0.5–5			3.3	2.1	1.1
NO_{3+2}-N (mg/L)	0.56–1.0	0.76	0.46	0.38	0.19	0.08
TKN (mg/L)		1.83	0.87	1.00	0.95	1.02
OP (mg/L)		0.40	0.16	0.08	0.26	0.16
TP (mg/L)	0.08–0.41			0.20	0.37	0.26
Cd (ug/L)		10–30	10–30	2.5	2.5	2.5
Cu (ug/L)	6–49	54	22	15	12	2.5
Pb (ug/L)	16–123	400	80	15	13	6.0

[a]Irish et al. (1995).
[b]Driscoll et al. (1990).

TABLE 8. Comparison of Long-Term Average Highway Runoff Loading Rates[a]

Water quality parameter (1)	German Highway Study[b] Concrete 100% paved (2)	German Highway Study[b] Asphalt 86% paved (3)	German Highway Study[b] Asphalt 40% paved (4)	U.S. data[c] (average of 10 monitoring sites) (5)	Charlotte Highway Runoff Site I (6)	Charlotte Highway Runoff Site II (7)	Charlotte Highway Runoff Site III (8)
ADT (vehicles/day)	41,000	47,000	11,500–40,600	2,000–57,000	25,000	21,500	5,500
TDS					2,146	546	1,931
TSS	873	848	479	1,966	2,678	528	612
COD	672	557	207	1,143	603	253	309
NO_{3+2}-N				4.1	28.9	2.0	2.0
NH_3-N	4.6	3.2	1.0		9.1	5.1	10.8
TKN				10.8	15.6	9.3	19.4
OP					1.2	2.8	3.8
TP	1.6	1.5	0.6	3.4	3.5	4.8	9.1
O&G					65.4	23.0	22.4
Cu	0.62	0.54	0.13	0.28	0.22	0.07	0.10
Cd	0.04	0.03	0.01		0.03	0.01	0.05
Cr	0.06	0.10	0.01		0.09	0.02	0.05
Pb	1.33	1.15	0.36	3.7	0.20	0.07	0.13
Ni					0.09	0.02	0.05

[a]Units in kg/ha-year (kg/ha-year × 0.892 = lb/acre-year).
[b]Stotz (1987).
[c]Chui et al. (1982).

more frequently by highway management activities such as deicing. Proper control of runoff from bridge deck structures is becoming an area of nationwide concern.

Bulk Precipitation

Atmospheric deposition may contribute a significant amount of certain types of pollutant loads that are later transported in highway runoff. Deposition on roadways, referred to as bulk precipitation, occurs as dustfall during both dry and wet periods. Harrison and Wilson (1985) found that rainfall contributed up to 78% of the major ionic constituents (Na, K, Mg, Ca, Cl, and SO_4) and 48% of suspended solids in highway runoff. The surrounding land use of a highway corridor also may affect the amount and type of dustfall. Highways in or near urban areas have been reported to carry higher levels of pollutant loadings originated from dustfall than those in rural areas (Gupta et al. 1981).

Bulk precipitation data were converted to atmospheric mass loading rates for each storm event. Table 9 presents the site mean mass loadings of bulk precipitation and highway runoff. The bulk precipitation mass loadings of Sites I and II were approximately identical as they were in proximity to each other. Differences in the deposition totals were attributed to differences in the actual precipitation events monitored at each site. Consequently, only the averages of bulk precipitation loadings for Sites I and II are presented in Table 9. The relative

TABLE 9. Comparison of Highway Runoff and Bulk Precipitation (Site Mean Loads)

Water quality parameter (1)	Ratio of bulk precipitation to runoff loads (Site I) (2)	Average bulk precipitation for Sites I and II (mg/m^2-mm) (3)	Bulk precipitation for Site III (mg/m^2-mm) (4)	Ratio of bulk precipitation (Site I and II to Site III) (5)
TDS	0.14	16.3	14.3	1.1
TSS	0.20	39.2	13.2	3.0
COD	0.33	15.4	3.3	4.7
NO_{3+2}-N	0.11	0.23	0.20	1.1
NH_3-N	0.98	0.52	0.56	0.9
TKN	0.88	0.82	0.83	1.0
OP	0.39	0.04	0.03	1.4
TP	0.29	0.07	0.07	1.0
Cu	0.50	0.007	0.006	1.2
Cd	1.50	0.003	0.003	1.0
Cr	0.40	0.003	0.003	0.9
Pb	0.33	0.005	0.004	1.1
Ni	0.50	0.003	0.003	0.9

bulk precipitation loadings between urban and rural highways can be enumerated by comparing the average loadings of Sites I and II, normalized for precipitation difference, with that of Site III. The urban highway Sites I and II were characterized by higher bulk precipitation loadings per unit depth of rainfall for TSS (3.0 times) and COD (4.7 times) when compared to the more rural Site III. Ratios of other chemical constituent loadings the urban and rural sites were in the range of 0.9–

TABLE 10. **Mass Balance Computation of TSS Retention for Sites II and III**

Date (1)	Rainfall (mm) (2)	*VDS* (number of vehicles) (3)	TC_{TSS}[a] (mg/m^2) (4)	BP (mg/m^2) (5)	RO (mg/m^2) (6)	PR[b] (mg/m^2) (7)	TSS retention[c] (%) (8)	Hydrologic retention of TSS[d] (%) (9)
				(*a*) Site II				
10/13/95	5.1	3,013	1,949	41	28	1,962	99	48
1/24/96	7.1	2,193	1,243	408	719	932	56	23
3/7/96	18.3	3,750	2,583	29	834	1,779	68	22
3/19/96	15.5	946	170	170	1,149	−809	−137	—
4/26/96	14.0	1,863	959	409	576	793	56	20
				(*b*) Site III				
10/4/95	60.2	1,993	2,924	30	193	2,762	93	33
11/2/95	35.6	3,055	4,826	71	202	4,696	96	36
1/19/96	13.1	1,988	2,915	289	429	2,775	87	49
1/24/96	7.8	612	451	218	184	485	73	58
2/20/96	7.0	951	1,058	281	29	1,310	98	84
3/6/96	31.5	1,142	1,400	284	101	1,583	94	38

[a]Based on Eq. (6).
[b]Based on Eq. (5).
[c]Calculated as $PR/(TC_{TSS} + BP)$.
[d]Calculated by multiplying the percent TSS retention by the percent reduction in runoff volume estimated from Eqs. (2) and (3).

1.4.

By taking the ratio of bulk precipitation and runoff pollutant loadings at Site I, where retention on pervious surfaces can be ignored, it can be seen from Table 9 that bulk precipitation accounted for 10–30% of runoff pollutant loadings for TDS, TSS, TP, and NO_{3+2}-N; 30–50% for Cu, Cr, Pb, COD, and OP; 70–90% for TKN and NH_3-N; and the majority of Cd loadings. It should be noted that Cd concentrations were always below the method detection limit and any interpretation of the Cd data should be made with great caution.

Pollutant Attenuation by Vegetative Filters

Certain highway contaminants can be effectively removed by vegetated roadside shoulders, medians, and swales. Pollutant removals by vegetative filters are mainly attributed to sorption, precipitation, filtration, coprecipitation, and biological uptake processes. Mass removals of metals, nitrogen, and phosphorus are related directly to infiltration losses and onsite storage (Yousef et al. 1985). Major components needed to account for mass balance of pollutant export from a highway section include bulk precipitation (BP), traffic contribution (TC), runoff (RO), and pollutant retention (PR) by vegetative filters, i.e.,

$$RO = BP + TC - PR \qquad (4)$$

Since the major goal of this project was to characterize highway runoff, no efforts were made to collect runoff samples originating from roadway surface before entering the vegetative filters. Sites II and III data could not be directly used for analysis of bulk precipitation contribution to runoff loadings as both TC and PR cannot be directly enumerated from (4). However, PR can be ignored for Site I because Site I is essentially impervious, making estimation of the traffic contribution using the Site I data possible. It is then possible to estimate TC for Sites II and III by adjusting the traffic contribution at Site I in proportion to traffic volumes at Sites II and III. Pollutant retention for Sites II and III can then be derived using (4) in the following manner:

$$PR = RO - BP - TC_{est} \qquad (5)$$

in which TC_{est} is the estimated pollutant loading in runoff attributed to vehicular traffic.

Of those pollutants such as TDS, TSS, TP, and NO_{3+2}-N that appear to be mostly associated with automobile traffic at Site I, only TSS exhibits a strong positive linear trend with traffic volume

$$TC_{TSS} = -649.9 + 0.86 \times VDS; \quad r^2 = 0.93 \qquad (6)$$

where TC_{TSS} = TSS loading attributed to vehicular traffic for an individual rain event; and *VDS* = total traffic count during a precipitation event. TC_{TSS} must be corrected to account for differences in roadway length between sites. TC_{TSS} values for Sites II and III during individual runoff events were calculated by (6), and the estimated PRs for these two sites were derived from (5). Computational results are presented in Table 10.

In all but one instance the vegetative filters of Sites II and III appeared to function as a sink for TSS removal from roadway runoff. During the precipitation event of March 19, 1996, runoff TSS concentrations actually increased upon moving through the Site II filter strip. We attribute this to the following two reasons: (1) The mobilization of material deposited during the intrastorm period through road maintenance activities not accounted for in our field measurements; or (2) uncertainty in the traffic TSS loading/traffic count relationship inherent at lower vehicle counts. Data from both sites indicated that the simple reduction in runoff volume through infiltration and evaporative losses accounted for 50–84% of the TSS reduction for small rain events. However, as precipitation depth increased the TSS removal attributable to runoff reduction decreased to approximately 20% for Site II and 35% for Site III. Although our data set is limited, substantial differences in TSS

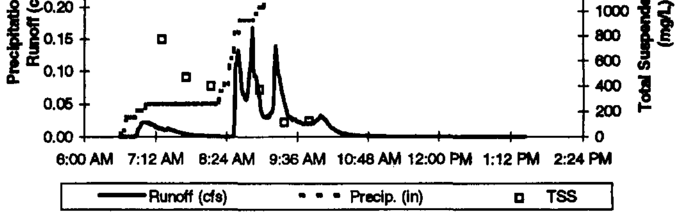

FIG. 3. Rainfall, Runoff, and TSS Data for Storm of January 24, 1996, at Site I

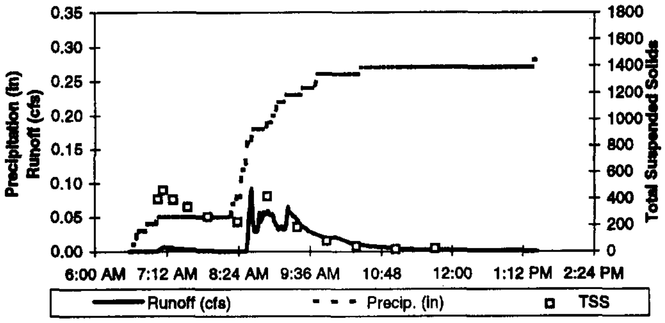

FIG. 4. Rainfall, Runoff, and TSS Data for Storm of January 24, 1996, at Site II

removal efficiency exist between the two sites despite only a 15% increase in the percent of pervious cover for Site III over Site II. For precipitation depths >6.0 mm (0.24 in.), Site II attained an average retention of 60% of TSS inputs, whereas Site III exhibited an average retention of 89% of TSS inputs for precipitation depths greater than 7.0 mm (0.28 in.). It also was observed from the data set that roadside shoulders and medians appeared to help attenuate the first-flush concentrations for most pollutant constituents, particularly TSS as shown in Figs. 3 and 4 for the storm occurring on January 24, 1996, at Sites I and II, respectively.

SUMMARY OF FINDINGS

The quality of highway runoff representative of urban, semiurban, and rural settings in the Piedmont region of North Carolina was characterized by site mean EMCs, site median EMCs, and long-term average pollutant loading rates. It was found that TSS EMCs and loadings at the bridge deck site (Site I) were relatively higher than typical urban highways; therefore, future research should address the management and maintenance issues of bridge deck for proper control of its runoff and water quality. In brief, the following findings can be summarized:

1. Site mean EMCs were employed as a means to compare highway runoff with urban runoff. It was observed that TSS EMCs of runoff from the bridge deck (Site I) were double that of the NURP data, whereas COD EMCs were equal to NURP concentrations. Sites II and III with increasing percentage of roadside shoulder and median exhibited substantially lower TSS EMCs than the NURP data. Nitrogen and phosphorus EMCs for all three highway sites were within the concentration ranges reported by the NURP and Charlotte urban runoff studies.
2. Site median EMCs were used to compare highway runoff constituent concentrations. In comparison to the Nationwide data, the site median EMCs of all three sites can be considered similar to rural highway runoff with the exception that (1) the site median TSS EMCs of Sites I and II approached that of urban and semiurban highways, respectively; (2) the site median TSS EMC of Site III was much lower than the Nationwide data; and (3) site median EMCs for all metals were substantially lower than those reported in the Nationwide data set.
3. With respect to pollutant loadings, TSS loadings of Site I were the highest among the three sites and even higher than the U.S. and German data. COD loadings of Site I were comparable to that of runoff discharged from a concrete surface with 100% drainage area paved. Nitrogen and phosphorus loading rates of Site I were generally within the range of agricultural runoff. TSS and COD loadings of Sites II and III were equivalent to that of an asphalt surface with 40% drainage area paved. O&G loadings of Sites II and III were about 65% of the Site I loading data.
4. Bulk precipitation accounted for approximately 20% of TSS loadings, 70–90% of nitrogen loadings, and 10–50% of the other constituent loadings in urban highway runoff.
5. It was observed that roadside shoulders and medians were the likely factors that provided at least 10–20% hydrologic reduction of peak runoff discharges. Using mass balance estimates, the roadside median (Site III) was likely responsible for an additional 30% reduction of TSS loadings over the roadside shoulder (Site II) despite only a 15% increase in pervious coverage for Site III over Site II. Roadside shoulders and medians appeared to help attenuate the first-flush concentrations for most pollutant constituents, particularly TSS.

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