Chapter 9

Characterization of Stormwater Runoff from Highways

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This chapter provides an overview of ongoing research towards improving the understanding of water quality characteristics of highway stormwater runoff. A review of source contributors, some important water quality constituents, and the requirements of a data collection program is provided. The methodology involved and the comprehensive data base employed in the single-site analyses portion of this work is outlined. Results from an investigation into the presence of the first flush phenomenon, and the identification of surrogate water quality parameters is also included.

9.1 Introduction

The impact of highway stormwater runoff on receiving surface water bodies and ground water aquifers is of increasing concern as a significant nonpoint source. In Ontario, the Ministry of the Environment has recently

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established a set of Best Management Practices for stormwater quality which address the issue of urban runoff control and impact on receiving water bodies. Determining both environmentally-acceptable and cost-effective technologies for the control of highway stormwater quality is a priority concern. Thus the development of a comprehensive understanding of the constituents of highway stormwater runoff, and more importantly, how these constituents vary both temporally and spatially, is an important step in addressing the problem of nonpoint source highway pollution.

9.2 Background

Highway stormwater runoff has the classical attributes of a nonpoint pollutant source. These attributes include the following characteristics: discontinuous in time, not concentrated at one specific location, and responsive to changes in climatic conditions. In the past, highway stormwater runoff was usually considered to be part of urban stormwater runoff; however, this view is changing and highway stormwater runoff is now considered an individual nonpoint source class.

Highway stormwater runoff quality is highly variable in space and time. For example, at a given location the concentration of total suspended solids (TSS) in highway stormwater runoff can vary from 40 to 1200 mg/L within one runoff event, and from an event mean concentration of 8 mg/L to an event mean concentrations of 810 mg/L between events. Moreover, the concentrations of some metals (e.g. copper, iron, zinc, nickel, and cadmium) in highway stormwater runoff exceed maximum concentration guidelines.

The potential impact on receiving water bodies (e.g. streams, lakes, wetlands) and ground water aquifers is of concern. Figures 9.1 and 9.2 indicate two possible highway configurations: a rural and an urban highway. Figure 9.1 is a schematic of a two-lane rural highway circling a lake and cutting through a wetland area. Although a highway of this nature is characterized by a low volume of traffic, there may in fact be an impact to both the lake and wetland. In contrast to this rural highway, Figure 9.2 is a schematic of a four-lane curbed urban highway with a centre median. This highway is characterized by a high volume of traffic and an extensive stormwater drainage system which discharges runoff directly to a nearby stream. Considering the dilution effects of a low-flow stream, this highway system may be significantly impacting the aquatic habitat in this stream. In an urban situation as depicted in Figure 9.2, the runoff from the highway has, in fact, been concentrated at one particular discharge location in contrast to the rural highway.

The source of the constituents found in highway stormwater runoff may be attributed to a number contributors which include: traffic deposition (e.g. tire wear, brake linings, and leakage of oil and lubricants), dustfall from the surrounding environs, pavement wear (the breakdown of asphalt and/or concrete

Figure 9.1
Rural highway

Figure 9.2
Urban highway

surfaces), maintenance operations (e.g. application of deicing compounds, pesticides and herbicides), accidental spills, and littering.

By far, the largest component of highway stormwater runoff is in the form of particulates. Heavy metals represent a significant component of the particulate matter found in highway stormwater runoff, and are regarded as a priority in terms of pollution control. Friction and automobile deterioration as well as the deterioration of highway structures are significant contributors of heavy metals. Within urban settings, heavy metals and other particulates were found to decrease in concentration to a distance of approximately 35 metres from the highway, whereas rural highways displayed declining particulate concentrations to a distance of approximately 15 metres (Harned, 1988; and Smith and Lord, 1990). The presence of roadside vegetation usually helps attenuate heavy metal concentrations in soils. The results from a number of observations of soil and vegetation along rural highways indicate that these materials can act as sinks for heavy metals.

The application of deicing salts (either NaCl or CaCl₂), may contribute to the deterioration of automobiles and highway structures as well as to increase heavy metal concentrations. While this may be predictable at a macro-scale, it is not easily detected at the local-scale. Salts may contain trace heavy metals including both nickel and chromium which can be released through solution. The deicing salts were characterized as impacting up to 40 m from the roadside (McBean and Al-Nassri, 1987). Sodium concentrations can be lowered by the existence of road-side vegetation, although the heavy application of deicing agents can result in disastrous consequences (Pollock, 1988). Chlorides tend to migrate from the upper soil layers and thus pose problems for ground water aquifers (Pollock and Toler, 1973).

Nutrients, such as nitrogen and phosphorus, appear in highway runoff through dry and wet atmospheric deposition, although some carbon compounds can be attributed to hydrocarbon combustion. Highway corridor maintenance of vegetation can also contribute to nutrient loading. Areas of extensive agricultural development show higher rates of nutrient deposition than do urban areas. Highway features can play a major role in nutrient attenuation in the stormwater runoff; for example, grassy swales and ditches can reduce the amount of ammonia, nitrate and phosphorus entering watercourses.

Airborne transport of pesticides from surrounding land uses have also been identified as a source of polluted highway stormwater runoff. In a study of urban runoff in Fresno, California, an increase in the concentration of pesticides including 2-4-D, parathion and diazinon, was noted by Oltmann and Shulters (1989). The heavy application rate of pesticides from the air was a major contributor. While specific highway characteristics were seen to contribute to the removal of some pesticides from highway runoff, many of the detected chemicals were found to remain in solution including chlordane, methoxychlor and diazinon.

Direct highway stormwater runoff has been shown to contain significant amounts of petroleum hydrocarbons (PHC) in solution and as suspended particulate. The incomplete combustion of fossil fuels can contribute to the formation of polycyclic aromatic hydrocarbons (PAHs) and, while these compounds tend to be generally insoluble in water, the presence of other chemicals can increase their solubility. PAHs tend to concentrate in soils and sediments rather than in the aqueous phase directly.

Tailpipe emissions constitute only a small percentage of the total PAHs and PHC in highway runoff. Photospectral analysis of PAHs has identified leaking crank cases (lubricating oils) as a major contributor to runoff contamination. Highway contamination due to leaking oil pans represents a pollution problem not readily controlled by highway construction.

PHC contamination among different land uses appears relatively consistent with residential, commercial and highway uses producing similar concentrations of PAHs in urban runoff, street dust and roadside vegetation samples. Industrial properties, however, tend to show increased levels of PAHs, principally due to the presence of larger vehicles. The presence of increasing numbers of large vehicles on highways, therefore may contribute to greater amounts of PAHs detected in road runoff. A marked difference between urban and rural PAH levels has also been noted (Pope, 1980).

Once the contaminants have been deposited on the highway road surface a complex transport process takes place during removal of these contaminants. It is generally believed that this process can be characterized by the well known build-up/wash-off relationship; however, some studies have shown that the kinetic energy provided by highway traffic during the actual storm event may be responsible for this removal process (Mar 1982). This generally has been observed for lower intensity storms typical of those experienced in the State of Washington.

9.3 Runoff Quality Monitoring

The initial step required for the characterization of highway stormwater runoff quality is the development of a comprehensive data collection program. Generally, for a number of highway catchments the following data are collected for a representative set (i.e., to reflect seasonality and environmental variability) of events: rainfall rate, runoff rate, temperature, dustfall, traffic counts, and a variety of water quality parameters.

Two methods are in general use to collect water quality samples: discrete samples, and composite samples. Discrete samples are grab samples taken from the runoff at discrete points in time, while composite samples represent a flow-weighted sample. The constituent concentrations determined from a composite sample are called event mean concentrations (EMCs). When the EMC is multiplied by the total runoff volume of the associated event the resulting product

represents the total constituent mass discharged for that event. The discrete samples provide information on extreme values as well as the temporal variation of runoff constituents during an event. On the other hand, the composite samples provide a good representation of a given event and therefore are generally used to compare constituent concentrations between events. Due to the nature of PHCs (e.g. oil and grease) only discrete samples are used to sample for these compounds.

From a water quality impact perspective, the total loading to the receiving water body is of concern; however, to allow for the portability of stormwater runoff quality characterization, the focus must be placed on constituent concentrations. This is the approach adopted in this study.

Numerous highway stormwater quality monitoring studies have been conducted, primarily in the U.S. Table 9.1 lists documented highway stormwater quality studies with more than 35 monitored events. Five of the eleven studies listed are from the Washington State area, and only three of the eleven have sufficient data to characterize the water quality of the highway stormwater runoff associated with snow events.

Table 9.1
Existing Highway Stormwater Quality Monitoring Studies

Total Events	Snow Events	Site	Area (ha)	Lanes	ADT	Source
211	47	Minneapolis I-94 ¹	8.5	10	80,000	Moxness (1986)
139	30	Milwaukee I-94 ¹	3.1	8	116,000	Kobriger (1984)
112	41	St. Paul I-94 ¹	6.6	6	65,000	Howard (1981)
97	3	Seattle I-5 ²	0.49	8	106,000	Mar <i>et al.</i> (1982)
93	7	Vancouver I-205 ¹	0.11	6	17,000	Mar <i>et al.</i> (1982)
40	0	Broward County ¹	23.6	6	20,000	Hardee <i>et al.</i> (1978)
39	5	Pasco SR-12 ²	0.51	4	4,000	Mar <i>et al.</i> (1982)
39	2	Pullman SR-270W ²	0.10	2	5,000	Mar <i>et al.</i> (1982)
38	4	Efland I-85 ²	1.01	4	26,000	Kobriger (1984)
37	9	Seattle SR-520 ¹	0.04	4	84,000	Mar <i>et al.</i> (1982)
35	5	Milwaukee I-794 ¹	0.85	8	53,000	Gupta (1981)

¹ Urban. ² Non-Urban.

ADT = average daily traffic

9.4 Methodology

The present investigation involves a revisitation to some of the previous studies in an attempt to determine what information can be used and transferred to highway locations within Ontario. The methodology adopted involves a two-

pronged approach which deals first with a single site analysis, and second with multiple site analyses.

The single-site analysis focuses on an existing comprehensive data base and attempts to investigate some of the following concerns: (1) How much variance in the observed water quality data can be explained by the different types of models (e.g. a build-up/wash-off model, and regression-based model)? (2) How much variance can be expected to be unexplained? (3) How much variance can be explained with various sample sizes (e.g. 5 events, 10 events, 30 events) rather than the entire data set? and (4) What water quality parameters can be used as surrogates for other water quality parameters?

The data base employed in the single-site analyses, and some results pertaining to the first flush phenomenon and the identification of surrogate water quality parameters are discussed in the following sections.

9.5 Minnesota Data Set

The runoff quality data were obtained from the Minnesota Department of Transportation for use in the single-site analyses since these data appear to be the most comprehensive data available (see Table 9.1). The data contain water quality monitoring data from four distinct phases or catchment areas, as detailed in Table 9.2. The data were all hand-entered in ASCII format files by the Minnesota Department of Transportation and require approximately 6.2 mb of

Table 9.2
Characteristics of Minnesota Data Set

Characteristic	Phase 1	Phase 2	Phase 3	Phase 4
Highway	I-94, St. Paul	I-494, Minneapolis	I-694, St. Paul	I-94, Minneapolis
No. of Lanes lanes	6	6	4	10
Area (ha)	6.60	142.4	6.64	8.50
% Impervious	50%	31%	20%	55%
Surface Type	Bituminous	Concrete	Concrete	Concrete
Shoulders	Bituminous	Bituminous	Full Bituminous	Full Bituminous
Median	Concrete	Concrete	Grass	Concrete
Curbs	Curb & Gutter	Curb & Gutter Grass Ditches	Grass Ditches	Curb & Gutter

storage space. Given these data, special computational algorithms were developed in order to detect errors, and to extract pertinent information.

Phase 4 of the Minnesota data set is of particular interest since this phase is the most comprehensive of the four, and is the only phase with monitored traffic levels.

The catchment area associated with Phase 4 is located in north Minneapolis and comprises a 900 m length of depressed 10 lane highway (I-94) situated between two crest curves. The road surface is concrete, the shoulders are full with bituminous, and a concrete barrier separates traffic flow in each direction. The outside curbs are of D4 type with approximately 17 m of grassed bank extending from the curb to the right-of-way. Construction of this portion of I-94 was completed in late 1981. The surrounding land use consists of a mix of single family homes, apartments, commercial and light industrial.

The total area of the catchment is 8.50 ha, with 3.82 ha pervious and 4.68 ha impervious. All of the pervious area is associated with the grass berms which stretch from the curbs to the edge of the highway right-of-way. Based on a rainfall-runoff analysis of data collected as part of this study, the average runoff coefficient for this catchment is 0.3.

A dedicated storm sewer network services the catchment area and consists of a main collection trunk line and twelve lateral collection lines that collect surface drainage from catch basins located along the median and gutters. The runoff quality sampling location was located at a point along the main collection trunk line as it exits the study area.

A total of 211 events were monitored throughout the period from June 1981 through November 1983. Table 9.3 indicates the number of rainfall, snowmelt and mixed (snowmelt and rainfall) events monitored. Figure 9.3 presents a histogram of the runoff flow volumes. For the 196 events that had a

Table 9.3
Details of Events for Phase 4

Event Type	Number of Events	Number of Discretes	Number of Composites
Rainfall	134	1049	73
Snowmelt	47	503	38
Mixed	30	492	31
Total	211	2044	142

Figure 9.3
Runoff histogram for phase 4

recorded runoff volume, the mean and variance were 2.6 mm and 15.5 mm², respectively. The annual precipitation for this region is 630 mm/year.

Table 9.3 also presents the number of discrete and composite samples obtained for each event type. For each discrete or composite sample taken, a number of water quality parameters up to a maximum of 57 were determined. Generally, for each discrete sample the following water quality parameters were determined: solids fractions, total organic carbon, pH, and conductivity. An average of one composite and ten discrete samples were collected for each event. To provide an indication of the variability of EMCs for a given event type and between event types, the frequency histogram for total suspended solids is shown in Figure 9.4. The mean TSS concentration in the runoff for the rainfall events, the snowmelt events, and the mixed events is 100.3 mg/L, 131.6 mg/L, and 137.7 mg/L, respectively. Notice that both the runoff from the snowmelt and the mixed events contain higher levels of TSS than the runoff from just rainfall events. This increased level of TSS is most likely due to de-icing practices.

In addition to flow and water quality data, traffic data (vehicle counts between, and during events) and dustfall data were collected. The average daily traffic (ADT) for this portion of I-94 is 80,000 vehicles/day.

Figure 9.4
Frequency histogram for TSS (mg/L) for (a) rainfall, (b) snowmelt, and (c) mixed.

9.6 First Flush

Concern with the “First Flush” relates to the potential for the first portion of the surface runoff during a storm event to contain high pollutant concentrations. However, attempts to characterize first flush have been varied. Urbonas and Tucker (1980) did not observe a first flush effect, but instead found that loadings tended to follow discharge. These findings may have been attributable to the

pollutant form (i.e. soluble or particulate) since Griffin *et al.* (1980) found that insoluble pollutants are removed primarily by physical processes, whereas soluble components are governed by solubility criteria. As well, Oberts (1977) reported that first flush does not always occur, its absence is affected by such variables as the nature of the storm and antecedent conditions.

Wilber and Hunter (1977) considered the first flush of the storm event to occur in the first hour of the storm. Harned (1977) used dimensionless cumulative analysis to demonstrate the magnitude of the first flush in watersheds. As well, Herrman (1981) used cumulative percentages of loads in comparison with cumulative percentages of flow, to characterize first flush of PAH.

Apparently, no universality of findings or procedures exists to define the first flush phenomenon; however, the existence of the Minnesota database provides an opportunity for first flush characterization. Thus, a working database was developed from the overall database, which included only storm events appropriate for testing. In these analyses of first flush, a sub-set of 25 events from the 211 events monitored during Phase 4 of the Minnesota study were employed. The remaining events were deemed unacceptable for numerous reasons that included: uncertain or no runoff data, low level of runoff, and events with few or poorly-distributed discrete sample measurements. For each of the remaining events, a temporal loading profile for each of the investigated constituents was constructed from the runoff and constitutive concentration measurements. Typical load profiles for TSS and chloride are shown in Figures 9.5 and 9.6 for a rainfall event, a snowmelt event, and a mixed event. For the rainfall and mixed events, rapid die-off from initially high rates (kg/hr) is apparent. For the snow event, a slower attenuation is noted for chlorides. Each loading profile was integrated over the runoff event duration and the percent mass discharged was determined for a range of runoff values. The results of these analyses are presented in Figures 9.7 and 9.8 for TSS and chloride. These figures clearly indicate that the majority of the mass of the constituents are discharged in the initial stages of the runoff. It is to be noted that there is one exception to this initial scavenging phenomena and that is one event responsible for the points located in the lower right portion of Figures 9.7 and 9.8; these points appear to be the result of an application of salt during this snow event.

The results depicted in Figures 9.7 and 9.8 demonstrate that first flush phenomena generally exist. The initial portions of runoff clearly contain the majority of the mass discharged during a runoff event.

9.7 Surrogate Water Quality Parameters

Given the substantial number of constituents that may be present in highway stormwater runoff, a considerable economy in analysis costs could be obtained if a subset of constituents could be employed to predict others. This subset could then be used as surrogates for other water quality parameters from

Figure 9.5
Total suspended solids loading

Figure 9.6
Chloride loading

Figure 9.7
Fraction of total mass of TSS discharged vs runoff

Figure 9.8
Fraction of total mass of chloride discharged vs runoff volume

the perspective of a predictive model, and to reduce the requirements of future highway stormwater quality monitoring programs.

Prior to a statistical and/or regression analysis of a large data set such as the one described in Section 9.5 it is necessary to investigate the distribution and frequency of the measured water quality parameters. Data that are log-normally distributed or highly skewed can result in a misleading “goodness-of-fit” due to highly influential large values. Due to these highly influential observations, the model and conclusions developed depends on the reliability of these few points. Generally, a statistical analysis will identify these highly influential observations and label them as outliers; however, these points could be the most important observations in the data set.

An initial filtering of the data which consisted of a statistical analysis, a preliminary regression analysis, partial visual inspection of the data files, and the creation of numerous scatter plots revealed obvious data input errors. Care was taken so that the outliers of particular interest were not those values which were high, but those values that were most probably an input error. Non-detect values were included in this analysis to ensure that the full distribution of small and large observations were reflected in the generated statistics.

Once the identified input errors were handled, a correlation matrix for both the log and normal constituent concentrations were developed. From the correlation matrices it was determined that the metals (e.g. copper, zinc, iron, and lead) were correlated with the suspended solids, the ionic species (e.g. chloride, sulphate, and sodium) were correlated with the dissolved solids, and the nutrients (e.g. nitrate, nitrite, and phosphorus) were correlated with the organics and the volatile solids. Therefore, the preliminary analyses were to investigate these relationships using a linear, log, and power relationship. The “goodness-of-fit” for these relationships was assessed using the following methods: (a) the coefficient of determination (r^2), (b) scatter plots, (c) residual statistics, (d) Cook’s distance, and (e) leverage. An analysis of residual statistics provides information on i^{th} dependent observation (y_i) and the predicted variable ($\hat{y}_i$). Large differences ($y_i - \hat{y}_i$) indicate that the dependent observation does not follow the trend of the model. Cook’s distance examines the influence of the i^{th} observation on the regression beta variables, and leverage is a measure of the distance between the i^{th} observation of the independent variables and the mean of the independent variables. Using these five methods additional data set input errors were corrected, and those values that were repetitive outliers for all relationships were eliminated.

The water quality parameters investigated as potential surrogates were TSS, TDS, TVS, and TOC. The dependent variable constituents investigated were Cr, Cu, Fe, Pb, Zn, Ni, Cd, Al (as TSS correlated parameters), As, Cl, SO_4 , Na, COD (as TDS correlated parameters), Kjeldahl and total nitrogen (as TOC correlated parameters), and total phosphorus (as a TVS correlated parameter).

Based on these analyses, the models determined from the linear relationship

were superior to those models determined from both log and power relationships. For the TSS-metal relationships, the percent variation explained by the regression models ranged from 41% for cadmium, to 79% for zinc. For the TDS-ionic species relationships, the percent variation explained ranged from 45% for sodium, to 99.6% and 95% for chloride and sulphate respectively. Using the developed linear models as a basis, a multiple regression analyses was performed using TSS, TDS, TVS and TOC as explanatory variables in an attempt to account for the remaining unexplained variation. The results of this analysis produced the following models:

$$\begin{aligned}
 \text{Cadmium} &= 0.233 + 0.00768(\text{TSS}) + 9.08 \times 10^{-5}(\text{TDS}) & [r^2 = 0.726] \\
 \text{Zinc} &= 1.004(\text{TSS}) - 0.00216(\text{TDS}) + 2.066(\text{TOC}) & [r^2 = 0.910] \\
 \text{Iron} &= 36.82(\text{TSS}) - 0.06377(\text{TDS}) & [r^2 = 0.846] \\
 \text{Arsenic} &= 0.00541(\text{TDS}) & [r^2 = 0.808] \\
 \text{Chloride} &= 0.575(\text{TDS}) & [r^2 = 0.996] \\
 \text{Sulphate} &= 0.00819(\text{TDS}) - 0.0555(\text{TSS}) + 0.995(\text{TOC}) & [r^2 = 0.976] \\
 \text{Total P} &= 0.002924(\text{TVS}) + 0.001064(\text{TSS}) & [r^2 = 0.777] \\
 \text{Total N} &= 0.751 + 0.0664(\text{TOC}) + 0.000961(\text{TVS}) & [r^2 = 0.463] \\
 \text{COD} &= 0.0479(\text{TDS}) - 0.344(\text{TSS}) + 4.213(\text{TOC}) & [r^2 = 0.816]
 \end{aligned}$$

To assess the portability of the above relationships, the developed models were used to predict various constituents using the Phase 3 portion of the data set (see Table 9.2). The metal relationships demonstrated poor predictive capabilities; however the ionic species provided a very good comparison for both arsenic and chloride. The sodium and sulphate relationships were good but deviated by an increasing factor (i.e., a change in slope). A difference in slope was also noted for COD, total and Kjeldahl nitrogen. These changes in the slope may possibly be attributed to the physical characteristic differences between each of the drainage areas, and will be the focus of future work within this study.

9.8 Summary

The existence of a first flush phenomena was demonstrated, in which the majority of the constituent mass discharged occurred within the first 5 mm of runoff.

Strong inter-parameter correlations were determined. The results suggest that variations in cadmium, zinc, iron, arsenic, chloride, and sulphate are largely explainable by combinations of TSS, TDS, TVS, and TOC.

The next step in this study will be the statistical investigation of the beta variables at different sites to quantify the effect of physical drainage area variations for the development of a portable predictive model.

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