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POLLUTANT LOADINGS AND IMPACTS FROM HIGHWAY STORMWATER RUNOFF

Volume III: Analytical Investigation And Research Report

Research, Development, and Technology
Turner-Fairbank Highway Research Center
6300 Georgetown Pike
McLean, Virginia 22101-2296

SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

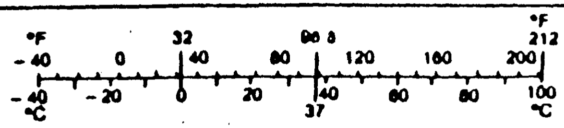
Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimetres	mm
ft	feet	0.305	metres	m
yd	yards	0.914	metres	m
mi	miles	1.61	kilometres	km
		AREA		
in^2	square inches	645.2	millimetres squared	mm^2
ft^2	square feet	0.093	metres squared	m^2
yd^2	square yards	0.836	metres squared	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	kilometres squared	km^2
		VOLUME		
fl oz	fluid ounces	29.57	millilitres	mL
gal	gallons	3.785	litres	L
ft^3	cubic feet	0.028	metres cubed	m^3
yd^3	cubic yards	0.765	metres cubed	m^3

NOTE: Volumes greater than 1000 L shall be shown in m^3.

Symbol	When You Know	Multiply By	To Find	Symbol
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams	Mg
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5(F-32)/9	Celcius temperature	°C

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimetres	0.039	inches	in
m	metres	3.28	feet	ft
m	metres	1.09	yards	yd
km	kilometres	0.621	miles	mi
		AREA		
mm^2	millimetres squared	0.0016	square inches	in^2
m^2	metres squared	10.764	square feet	ft^2
ha	hectares	2.47	acres	ac
km^2	kilometres squared	0.386	square miles	mi^2
		VOLUME		
mL	millilitres	0.034	fluid ounces	fl oz
L	litres	0.264	gallons	gal
m^3	metres cubed	35.315	cubic feet	ft^3
m^3	metres cubed	1.308	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.205	pounds	lb
Mg	megagrams	1.102	short tons (2000 lb)	T
		TEMPERATURE (exact)		
°C	Celcius temperature	1.8C + 32	Fahrenheit temperature	°F



* SI is the symbol for the International System of Measurement

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16. Abstract

This is one of four final documents of an investigation dealing with the characterization of stormwater runoff pollutant loads from highways and the prediction of water quality impacts they cause. Study results are based on monitoring data from 993 individual storm events at 31 highway runoff sites in 11 States. Impact prediction is based on a methodology previously developed and applied to urban runoff and adapted for highway runoff applications. This document describes the procedures used to assemble and analyze the data base and reports the results of these analyses. Included in this document are statistical summaries of the data base, along with a description of procedures to use to predict pollutant discharges from highway sites and the impacts that they will cause to receiving waters.

The publications which collectively represent a final report are:

FHWA-RD-88-006, Volume I: Design Procedure. This document presents a step-by-step procedure for determining and evaluating water quality impacts.

FHWA-RD-88-007, Volume II: Users Guide for Interactive Computer Implementation of Design Procedure. A Users guide for an interactive computer-based, user-friendly version of the design procedure of document FHWA-RD-88-006.

FHWA-RD-88-008, Volume III: Analytical Investigation and Research Report. This document.

FHWA-RD-88-009, Volume IV: Research Report Data Appendix.

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FOREWORD

The highway system is a potential source of a wide variety of possible pollutants to surrounding surface and subsurface waters through the mechanisms of the natural hydrologic cycle. The effects of a highway system on the environment plays an increasingly important role in the planning, design, construction, and operation of a transportation system. The Federal Highway Administration and State highway agencies, charged with the responsibility of protecting the environment from pollution from highway sources, have approached the problem in a multi-phase, multi-million dollar research effort including studies to:

Phase 1 - Identify and quantify the constituents of highway runoff.
Phase 2 - Identify the sources and migration paths of these pollutants from the highways to the receiving waters.
Phase 3 - Analyze the effects of these pollutants in the receiving waters.
Phase 4 - Develop the necessary abatement/treatment methodology for objectionable constituents.

This investigation, primarily a Phase 3 item, is a culminating analytical effort utilizing other research studies and their data, coupled with applied hydraulics and related environmental and highway concerns. A largely statistical based design procedure for estimating highway stormwater pollutant loadings is presented.

This publication will be of interest to hydraulic engineers and environmental scientists involved in planning and designing for highway water quality impacts to lakes and streams.

Sufficient copies of this publication are being distributed by FHWA memorandum to provide three copies to each FHWA Region, one copy to each Division, and two copies to each State highway agency. Direct distribution is being made to the division offices. Additional copies for the public are available from the National Technical Information Service, U.S. Department of Commerce, 5285 Port Royal Road, Springfield, Virginia 22161.

Thomas J. Pasko, Jr., P.E.
Director, Office of Engineering and Highway Operations Research and Development

NOTICE

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LIST OF ABBREVIATIONS AND VARIABLES

ADT	- average daily traffic
APWA	- American Public Works Association
ASDWA	- Association of State Drinking Water Administrators
AWWA	- American Waterworks Association
COD	- chemical oxygen demand
COV	- coefficient of variation
CV	- coefficient of variation (in report)
DAR	- drainage area ratio
EMC	- event mean concentration
EPA	- Environmental Protection Agency
FHWA	- Federal Highway Administration
HSPF	- Hydrological Simulation Program - FORTRAN
M	- mean
MDF	- Master Data File
MIT	- minimum interevent time
NIOSH	- National Institute for Occupational Safety and Health
NPS	- nonpoint source
NURP	- Nationwide Urban Runoff Program
PPCC	- Probability Plot Correlation Coefficient
SS	- suspended solids
STORM	- Storage, Treatment, Overflow, Runoff Model
SWMM	- Storm Water Management Model
SYNOP	- Synoptic Rainfall Data Analysis Program
T	- median
TOC	- total organic carbon
TS	- total solids
TSS	- total suspended solids
U	- log mean
USGS	- United States Geological Survey
VDS	- vehicles during storm
VPD	- vehicles per day
VPH	- vehicles per hour
VSS	- volatile suspended solids
W	- log standard deviation
WDF	- Working Data File

1.0 INTRODUCTION

1.1 PURPOSE

The primary purpose of this study was to develop and present a procedure for predicting the quantity of, and pollutant levels in, highway stormwater runoff discharges. This objective has been attained by the assembly and analysis of monitoring data from 993 separate storm events at 31 highway runoff sites distributed among 11 States, and the consideration of source characteristics and mechanisms involved in the generation of highway runoff pollutant loadings. Secondary objectives of the study were: (1) to describe procedures for using such pollutant discharge estimates and local site conditions to determine whether highway runoff can be expected to be a significant contributor to water quality problems; and (2) for instances where this is likely be the case, to describe procedures for identifying the kind and extent of control procedures (suitable for highways) required to mitigate the problem.

This document (the Research Report) describes the procedures used to assemble and analyze the substantial data base on highway runoff that was assembled from studies completed over the past 10 years that were either directly or indirectly supported by the Federal Highway Administration (FHWA). It evaluates prior approaches for determining highway runoff pollutant loads and considers factors such as climate, surrounding land use, site characteristics and traffic. It presents summaries of pertinent data that characterize highway stormwater, describes the procedure selected for using the information developed to predict pollutant discharges from highway sites, and describes procedures for evaluating the potential for highway runoff to create objectional conditions in receiving waters.

Three companion products were also developed under this study.

- Design Procedures - This document (FHWA-RD-88-006) describes a procedure for the practical application of the data and the analysis methods addressed in this volume. It presents a step-by-step procedure for predicting pollutant discharges from a specific highway site, and the water quality impacts they create in a receiving water. It includes a procedure for evaluating whether the predicted impacts are likely to create a problem condition, and in cases where untreated runoff is indicated to be a potential problem, how to assess the mitigation that will be produced by management practices or controls.

- Data Appendix - This document (FHWA-RD-88-009) provides a tabulated summary of all of the highway runoff data that were assembled and analyzed. The data has also been provided to FHWA on microcomputer floppy disks in spreadsheet format (Lotus 1,2,3 for IBM-PC compatible computers, and in Excel for Apple Macintosh computers).

- Users Guide for Computer Programs - This document presents operational guidance for two microcomputer programs developed under this study. It is accompanied by floppy discs of the programs. One program is an interactive system for the evaluation of pollutant impacts from highway stormwater runoff. This is based on the analysis method presented in the Design Procedures report. The other program provides a microcomputer version of the SYNOP program for analysis of rainfall data. It will process the long-term hourly rainfall data for rain gages throughout the country, that can be obtained on a diskette, from the National Climatic Data Center. This makes it possible for a user to base an analysis on up to date, site specific rainfall data.

This Volume, the Research Report, describes the analysis and interpretation of the data that are tabulated in the Data Appendix, and provides background, discussion and reference for the procedures presented employed in the Design Procedures report and in the interactive computer program.

1.2 SCOPE AND ORGANIZATION OF REPORT

The basic content of each section of this volume is described below. A brief discussion of the basis for the material presented in the section, other sources for reference, and appendixes providing more material, is provided here to give an overview of the organization and content of the full report.

Report Sections 2.0 and 3.0

Section 2.0 describes the methods used to analyze and interpret the highway runoff data, and section 3.0 presents a summary of the characteristics of highway stormwater runoff for the individual sites in the data base. The summaries were developed from the analysis of monitoring data obtained at 31 highway sites, in 11 States. The data base covers a total of 993 separate storm events, and was developed under a number of different studies that were either directly sponsored by FHWA, or conducted by State Transportation Departments with support provided by FHWA. No new runoff monitoring was performed under the study covered by this report. The data collection aspects of this study consisted of assembling the raw data from the referenced sources, reducing and consolidating it for convenient access, and then analyzing and interpreting it.

The consolidated data for each storm event at each of the highway sites has been prepared as hard-copy tabulations that are reproduced in a Data Appendix. Data summaries have also been prepared on microcomputer floppy discs in spreadsheet format, for either IBM compatible PCs (LOTUS 1 2 3), or Apple Macintosh PCs (EXCEL).

Report Section 4.0

This section examines the similarities and differences between the runoff characteristics from separate highway sites, and evaluates the factors or relationships that influence the pollutant load from a specific site. A limited number of site factors, shown in this section to exhibit a demonstrated influence on pollutant runoff levels, were evaluated for use in the predictive model. Both the technical literature and professional judgement suggest a number of additional site factors that might reasonably be expected to influence pollutant levels in highway runoff. A discussion of the more important of such postulated mechanisms and factors is provided at the end of this section, with an indication of the basis on which a factor either was or was not incorporated in the predictive model.

Report Sections 5.0 and 6.0

Sections 5.0 and 6.0 of this volume address the development of a predictive model based on the assembled data. This study effort had the advantage of basing the analysis on a large number of different sites and a very large number of individual events, whereas most of the prior efforts in this area were restricted to an analysis based on one or very few site results. An evaluation of the important features of regression, statistical, and simulation model approaches is presented. The comparative advantages and disadvantages of each technique are discussed. A statistical method was selected as the method of preference for meeting the objective of this study. However, the other predictive methods may be considered either as supplementary or substitute techniques, in appropriate circumstances.

Section 5.0 describes and discusses prior approaches to the development of predictive models and identifies the relative advantages and disadvantages of each. The statistical approach adopted for this study is described in section 6.0, and the rationale and basis for its selection are discussed. The statistical procedure selected is one which describes pollutant levels in probabilistic terms and is considered to be the most useful approach for meeting the specific objectives of this study. This selection was based on the high degree of inherent variability demonstrated by the data, the site data that will be generally available, and its ability to provide the necessary information to support the type of decisions the study is required to address.

Report Section 7.0

Section 7.0 of the report discusses a rationale for determining whether or not the pollutants discharged by stormwater runoff from a highway segment will create, or contribute significantly to, a water quality problem in the water body receiving such discharges. It provides a general description of procedures for computing the impact of highway runoff on a stream or lake.

Procedural details for application of the analysis methods are covered in the Design procedures report. In this section, only the concept and basic approach are described and discussed, and the results of a broad screening analysis (using this procedure and the highway runoff data) are presented. This is to provide an overview that delineates the conditions under which highway runoff is likely or unlikely to create water quality problems.

References

A comprehensive literature search was performed at an early stage of the study program. This was later supplemented with relevant foreign studies which were reported at an international symposium on highway pollution. Those of the screened literature sources that are pertinent to the focus and objectives of this study are identified in the list of references that has been provided, and cited at appropriate places in the body of the report.

2.0
METHOD OF DATA ANALYSIS

2.1 INTRODUCTION

The objective of this section is to describe the procedures used: (1) to consolidate and summarize the pollutant discharge characteristics of stormwater runoff from highway sites; and (2) to evaluate and draw conclusions based on similarities and differences among sites. Sections 3.0 and 4.0 present the results and discussion of the analyses performed using the methodology discussed in this section.

A data base was assembled from stormwater runoff monitoring data obtained at 31 highway sites in 11 States, and covers a total of 993 separate storm events. The data base created for this study is based on information developed under a number of different studies that were either directly sponsored by FHWA [1,2], or conducted by State transportation departments with support provided by FHWA (see references 3 through 9). No new runoff monitoring was performed under the study covered by this report.

The data collection aspects of this study consisted of assembling the raw data from these sources. The data were then reduced and consolidated for convenient access and screened for quality assurance purposes. Questionable data items were referred to FHWA and/or the original data gathering entity for resolution. The data were then analyzed and interpreted. A number of studies other than those identified by the above references were also acquired and reviewed. They are not incorporated in this study because either the focus of the local study, or the nature of the data developed and reported, did not support the specific objectives of this effort.

Figure 1 presents a flow chart of the key steps taken to develop and evaluate the data base created by this study. The remaining sections in this chapter will discuss the methods and analyses used in this study.

2.2 EVENT MEAN CONCENTRATION

In the studies that were examined, pollutant concentrations in highway runoff were reported either as event mean concentrations (EMCs) or as the concentrations in discrete sequential samples collected at intervals during a single storm event. The EMC is defined as the average pollutant concentration present in the total volume of runoff from a storm event. It is equal to the total pollutant mass discharged divided by the total volume of the runoff. In most cases, the data reported by the individual study results were based on a flow-weighted composite sample collected over the entire storm event. This sampling approach provides the EMC directly.

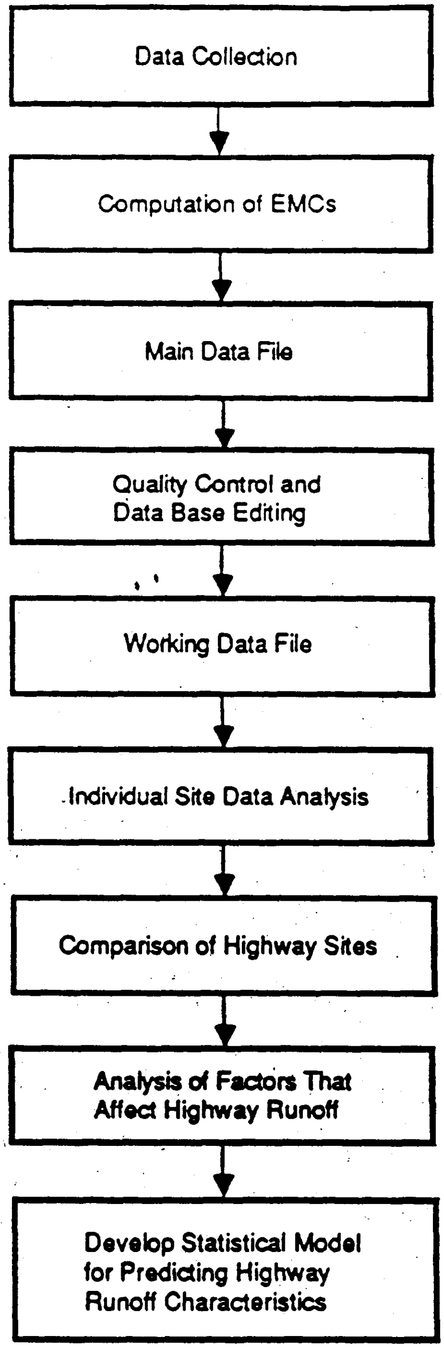


Figure 1. Key steps taken to evaluate highway runoff.

In order to construct this data base and establish a standard unit for characterizing and comparing loadings from highway runoff, the EMC as defined above was used. The EMC was selected for two reasons. First, discrete within-event data were not collected by all of the studies, and we wanted to maximize the number of individual highway sites used in the analysis. Second, and even more important, our prior work in characterizing the water quality of stormwater runoff from other types of nonpoint sources (e.g., agricultural, urban runoff) indicated that knowledge of within-event pollutant concentration fluctuations provided little useful information to the decision maker regarding control measures that might be required. Thus, in this study, individual storm events were characterized by the EMC of each of the pollutants monitored.

For the studies that collected a set of sequential discrete samples during storm events, the reported data were analyzed to estimate the EMC. This was done by integrating the hydrograph (plot of flow rate vs time) and pollutograph (plot of concentration vs time) [10]. Pollutant mass is estimated by applying the trapezoidal rule to a number of corresponding time segments of the hydrograph and the pollutograph, as illustrated in figure 2. The product of the partial flow volume and associated concentration estimates the mass in that segment of the discharge. The sum of all such segment masses estimates the total mass discharged by the event. The estimation of the total area under the hydrograph provides the total volume of runoff. Total mass divided by the total runoff volume provides the desired value for the EMC.

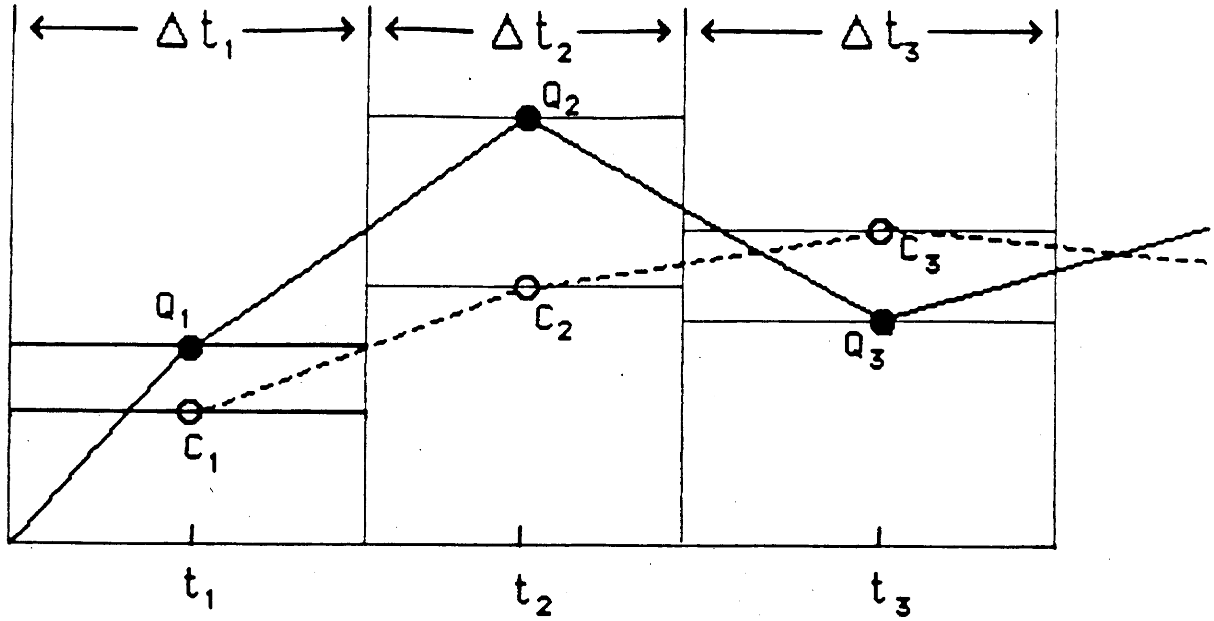
Accordingly, all pollutant concentration data for highway runoff used in the summaries and analyses described in the report volumes for this study are either directly measured EMCs or calculated EMCs.

2.3 DATA BASE COMPILATION AND EDITING

Once all the site data on highway runoff quality characteristics had been converted to similar units (EMC), the data were entered into spreadsheet format for evaluation. The Apple Macintosh spreadsheet program EXCEL was used. The EXCEL spreadsheet also allows one to use LOTUS 123 (IBM PC and Compatibles) on the files created, and the spreadsheets are available in that format as well. The set of records, consisting of a single spreadsheet for each site, is designated the Master Data File (MDF).

A number of editing operations were performed on the Master Data File (MDF). These editing operations were based on a careful quality assurance check and can be classified into one of three categories: (1) rejection of an individual data item at a site, (2) rejection of an entire event at a site, and (3) rejection of an entire site. Each of these will be discussed in turn.

As with any large data base assembled from work performed by many different project entities and at different times, there are invariably questionable data items. The causes may include transcription errors (e.g., use of milligrams per liter instead of micrograms per liter for a single concentration), analytical laboratory errors (e.g., it is very unlikely that Total Suspended Solids (TSS) concentrations for sequential discrete samples could drop from 2,830 mg/l to 53 mg/l in 10 minutes), field instrumentation errors (e.g., flow meter readings are suspect when a runoff coefficient appreciably greater than unity results), and so on. Each of these questionable data items has a common characteristic, namely, it is inconsistent with other data at the site in question and with general levels observed at other sites.



$$\text{Total Runoff Volume} = \text{Volume}(1) + \text{Volume}(2) + \text{------}$$

$$= Q_1 \Delta t_1 + Q_2 \Delta t_2 + \text{------}$$

$$= \Delta_i (Q_i \Delta t_i) \qquad i = 1, \text{number of samples}$$

$$\text{Total Mass Load} = \text{Mass}(1) + \text{Mass}(2) + \text{------}$$

$$= C_1 \text{Volume}(1) + C_2 \text{Volume}(2) + \text{------}$$

$$= C_1 Q_1 \Delta t_1 + C_2 Q_2 \Delta t_2 + \text{------}$$

$$= \Delta_i (C_i Q_i \Delta t_i)$$

Event Mass Concentration (EMC) = Total Mass Load / Total Runoff Volume

$$= \frac{\Sigma_i [C_i (Q_i \Delta t_i)]}{\Sigma_i (Q_i \Delta t_i)}$$

Figure 2. Procedure for computing EMC from sequential discrete sample data.

The entire data base was carefully examined using experienced judgement and qualitative criteria to identify questionable data. For example, a runoff coefficient appreciably greater than unity or an unusually large coefficient of variation for pollutant concentrations at a site were taken to be an indication of bad data. These data were then discussed with FHWA and original project personnel (where possible) to attempt to resolve the discrepancy. This approach was deemed preferable to merely applying standard statistical methods for dealing with outliers as covered, for example, in NIOSH (11). In each case, the data item in question was either successfully resolved in our judgement or was deleted from the data base.

The second category of data editing arose when all values for a storm event seemed questionable. This can result from a number of causes such as equipment malfunction, sample contamination or the occurrence of an unusual phenomenon. For example, the eruption of Mount St. Helens in Washington State had a significant effect on highway runoff quality monitored for some events at certain sites in the State of Washington. While such results may be true data, they are not representative of normal highway runoff. As in the case of the first category, we attempted to resolve such data by referencing original project documentation (final reports, interim reports, field logs, etc.) or contacting the involved personnel. Unless the data for the event could be explained satisfactorily, in our judgement, they were deleted from the data base.

In the third category of data editing, we chose to exclude entire sites from our analysis. Unlike the first two categories, this decision was not based on the occurrence of questionable data, but was made for other reasons, such as the availability of an insufficient amount of data (e.g., the number of events monitored was too small to be statistically meaningful, there was insufficient coverage of pollutants, the monitoring time span was too short to be representative of an entire year, there was a lack of flow measurements) and monitoring objectives that were, in our judgement, inconsistent with our purposes (e.g., monitoring of runoff from grass swales rather than from highway road surfaces). We also chose to delete several Washington State sites (9), as there were 11 of them out of the total 31 sites. We felt that this was necessary to keep our data base from being biased towards Washington State highway runoff data.

An additional form of editing performed involved the segregation of snow washoff events. Inspection of the data indicated these events to be fundamentally different in nature than rainfall/runoff events. We chose to separate snow events from other events in our data base and analyze each set separately. This was accomplished by reviewing the source documents referenced above on the particular sites, to determine which events were snow washoff events. At some sites where the reports did not provide the necessary information, we used the chloride (Cl) and total solids (TS) concentrations to determine, using our best judgement, which events were snow washoff events.

The final data base, which was edited as described above, is identified as the Working Data File (WDF) and was used for all subsequent analyses presented in this report. We wish to emphasize that we had to use our collective best judgement in the data editing process. In recognition of the fact that others might reach different conclusions, we have chosen to present the unedited data base (MDF) in the Data Appendix as well as the WDF. The Data Appendix provides a hard copy listing of both the MDF and the WDF. A set of microcomputer floppy disks containing the data has also been provided to FHWA.

2.4 PROBABILITY DISTRIBUTION OF RUNOFF CONCENTRATIONS

A careful analysis of the pollutant EMCs at each of the sites was performed to determine whether the observed variations conformed to a particular probability distribution. We specifically investigated the hypothesis that distributions of all EMCs could be represented as lognormal. This initial assumption was made because it is consistent with similar findings for a variety of other storm-generated pollutant discharges and because the lognormal distribution has some desirable mathematical features. Other distributions that could have been considered include the normal distribution, the exponential distribution, the uniform distribution, a variety of extreme value distributions, Pearson distributions, and other distributions involving transformations of the data (e.g. power transformations).

The assessment of the lognormality of EMCs in highway runoff was made by examination of probability plots of pollutant EMCs in the storm events monitored at a site. The validity of a lognormal distribution (or its acceptability as a practical approximation) can be determined by examination of the goodness of fit between the plotted points and the straight line that represents the theoretical expected lognormal distribution of the data set, defined by the log mean and log standard deviation.

The procedure employed was to compute the mean and standard deviation of the natural (base e) logarithm transforms of the EMCs. The theoretical distribution is constructed from these values (the log mean [U] and the log standard deviation [W]). This derived distribution indicates the expected value (assuming that the data follow a lognormal distribution) of a pollutant's concentration at any probability of occurrence. This expected probability distribution was compared with the data by plotting the two on the same log probability plot.

The plotting position of the individual data points was determined by assigning an expected probability for each EMC in the ranked series of observed values. This position varies with the number of observations (N) in the sample, and is provided by the following general equation [12].

$$Pr = \frac{m - a}{N + 1 - 2a} \qquad (1)$$

where m is the rank order of the observation.

The term "a" in equation 1 is a functional variable whose value depends upon the form of the probability distribution as well as the number of samples (N). For lognormal distributions, we found the value of a approaches 1/2 asymptotically as the value of N increases. This matches the value suggested originally by Hazen [13], as opposed to the value of a = 3/8 suggested by Blom [12]. We selected the use of a = 1/2 as the most appropriate value.

We examined virtually all site EMC data sets by the above method of superimposing the theoretical distribution and actual data points (i.e. the EMC values) on the same plot. Visual observation of the goodness of fit was the principal method used to assess the lognormality of a data set. Selected samples from the overall data base were tested for the lognormal hypotheses using the "Probability Plot Correlation Coefficient" (PPCC) test [14,15].

The PPCC test examines the degree of linearity of a probability plot. The test statistic is defined as the product moment correlation coefficient between the ordered (ranked) observations (or the logarithm of the observations for lognormal distributions) and the order statistic medians (Z score) for a standard normal distribution [14]. The PPCC value is compared with a known distribution of PPCC values of like sample size, which were sampled from a true normal distribution to see if the hypothesis of normality can be rejected.

Apart from a lack of confidence where N is small, we applied the following interpretation to the evaluation of the lognormality of EMCs. We are not interested, per se, in a single sample of limited size drawn from a much larger population of all storm events. That is, the characteristics of one sample (confidence level that it fits a lognormal distribution) are not particularly important. Sampling or laboratory analysis errors are always possible, as is the fact that the random element in a single sample of size N can distort results.

Our real interest is in the inferences that can be drawn regarding the appropriateness of the lognormal distribution as a satisfactory approximation of the underlying distribution of all highway pollutant discharges. This assessment is influenced by considering the data in total, rather than emphasizing any particular set. For example, consider a data set of TSS concentrations at site A that produces a probability plot that does not conform very well with a lognormal distribution. If TSS concentrations at all other sites are lognormal, and all pollutant concentrations other than TSS at site A are lognormal, we would conclude that lognormality is an appropriate general assumption for TSS concentrations in runoff from highway sites.

2.5 PROPERTIES OF THE LOGNORMAL DISTRIBUTION

Following is a discussion of some properties of the lognormal distribution. If a sample (a data set of N observations) is drawn from an underlying population that has a lognormal distribution, the following apply:

- An estimate of the mean and variance of the population is obtained by computing the mean and standard deviation of the log transforms of the data.

- The arithmetic statistical parameters of the population (mean, median, standard deviation, coefficient of variation) should be determined from the theoretical relationships (see table 1) between these values and the mean and standard deviation of the transformed data.

- The arithmetic mean so computed will not match that produced by a straight average of the data. Both provide an estimate of the population mean, but the approach just described provides a better estimator. As the sample size increases, the two values converge. For the entire population, both approaches would produce the same value.

A few mathematical formulas based on probability theory summarize the pertinent statistical relationships for lognormal probability distributions. These provide the basis for back and forth conversions between arithmetic properties of the untransformed data (in which concentrations, flows, and loads are reported) and properties of the transformed data (in which probability and frequency characteristics are defined and computed).

Since the two-parameter lognormal distribution was investigated in this study, the definition of one single central tendency (e.g., median, mean) and one dispersion (e.g., standard deviation, coefficient of variation) parameter automatically defines the values for all of the other measures of central tendency and dispersion as well as the entire distribution. Table 1 presents the formulas that define these relationships from which other values can be computed.

Table 1. Relationships of lognormal distributions.

T = EXP (U)	S = M * CV
M = EXP (U + 0.5 * W^2)	W = SQRT (LN (1 + CV^2))
M = T * SQRT (1 + CV^2)	U = LN (M / EXP (0.5 * W^2))
CV = SQRT (EXP (W^2) -1)	U = LN (M / SQRT (1 + CV^2))

Parameter designations are defined as:

	ARITHMETIC	LOGARITHMIC
MEAN	M	U
STD DEVIATION	S	W
COEF OF VARIATION	CV	
MEDIAN	T	

LN(x) designates the base e logarithm of the value x
SQRT(x) designates the square root of the value x
EXP(x) designates e to the power x

The statistical parameters of a particular distribution may also be used to compute the magnitude (X_a) of the variable at any specified probability of exceedance (a), or conversely to compute the probability of exceeding any specified value. The equations are:

$$X_a = \text{EXP}(U + Z_a * W) \qquad (2)$$

$$Z_a = \frac{LN(X_a) - U}{W} \tag{3}$$

where Z_a is the standardized normal deviate with a mean of zero and a variance of unity. For normal (or lognormal) distributions, probabilities can be defined in terms of the magnitude of a value normalized by the value of the standard deviation. Cumulative probabilities have a specific relationship to the normalized standard deviate, for which Z is the conventional designation (e.g., Z = 1 is one standard deviation). Tables that summarize this relationship are available in many texts. Table 2 is provided here for convenience.

For a lognormal distribution with a specified median and coefficient of variation, both the mean and any percentile can be readily computed using the formulas presented in table 1 and equations 2 and 3. These equations can be combined and reduced to the following form to determine the value of the variable (X) at any percentile (a), expressed as a multiple of the median (X_a/T).

$$X_a / T = EXP(Z_a * SQRT(A)) \tag{4}$$

where:

$$A = LN(1 + CV^2) \tag{5}$$

For a lognormal distribution, the mean (M) also has a specific relationship with the median (T), which depends also only on the CV. This relationship is:

$$M = T * SQRT(1 + CV^2) \tag{6}$$

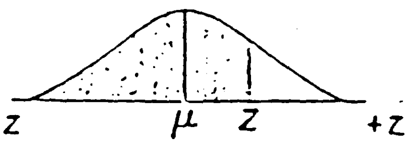
Using the relationships described above, we incorporated into the spreadsheets, assuming a lognormal distribution of the EMC data, an estimate of the mean, median and coefficient of variation of the site EMCs. The same distribution for rainfall/runoff statistics was also used.

2.6 TREATMENT OF DETECTION LIMIT DATA

The treatment of detection limit data is one issue that needs to be discussed separately. It arises due to the analytical methods used in the laboratory to test for a pollutant and the detection limits associated therewith. As defined in 40 CFR Part 136, the detection limit for any analytical method is the lowest concentration of the analyte that can be measured and reported with a 99 percent confidence that the analyte concentration is greater than zero. Since there are a variety of accepted methods that can be used to determine pollutant concentrations, employing fundamentally different techniques (e.g., colorimetric, atomic adsorption, chromatographic), the detection limit for any particular pollutant may vary from laboratory to laboratory. Furthermore, due to advances in analytical methodologies and equipment, detection limits may vary over time at the same laboratory, with the predominant trend being for them to decrease. The selection of a particular analytical method over other acceptable alternatives depends upon a variety of factors, including the amount of

Table 2. Probabilities for the standard normal distribution.

Each entry in the table indicates the proportion of the total area under the normal curve to the left of a perpendicular raised at a distance of Z standard deviation units.



Example: 88.69 percent of the area under a normal curve lies to the left of a point 1.21 standard deviation units to the right of the mean.

Z	0.00	0.01	0.02	0.03	0.04	0.05	0.06	0.07	0.08	0.09
0.0	0.5000	0.5040	0.5080	0.5120	0.5160	0.5199	0.5239	0.5279	0.5319	0.5359
0.1	0.5398	0.5438	0.5478	0.5517	0.5557	0.5596	0.5636	0.5675	0.5714	0.5753
0.2	0.5793	0.5832	0.5871	0.5910	0.5948	0.5987	0.6026	0.6064	0.6103	0.6141
0.3	0.6179	0.6217	0.6255	0.6293	0.6331	0.6368	0.6406	0.6443	0.6480	0.6517
0.4	0.6554	0.6591	0.6628	0.6664	0.6700	0.6736	0.6772	0.6808	0.6844	0.6879
0.5	0.6915	0.6950	0.6985	0.7019	0.7054	0.7088	0.7123	0.7157	0.7190	0.7224
0.6	0.7257	0.7291	0.7324	0.7357	0.7389	0.7422	0.7454	0.7486	0.7518	0.7549
0.7	0.7580	0.7612	0.7642	0.7673	0.7704	0.7734	0.7764	0.7794	0.7823	0.7852
0.8	0.7881	0.7910	0.7939	0.7967	0.7995	0.8023	0.8051	0.8078	0.8106	0.8133
0.9	0.8159	0.8186	0.8212	0.8238	0.8264	0.8289	0.8315	0.8340	0.8365	0.8389
1.0	0.8413	0.8438	0.8461	0.8485	0.8508	0.8531	0.8554	0.8577	0.8599	0.8621
1.1	0.8643	0.8665	0.8686	0.8708	0.8729	0.8749	0.8770	0.8790	0.8810	0.8830
1.2	0.8849	0.8869	0.8888	0.8907	0.8925	0.8944	0.8962	0.8980	0.8997	0.9015
1.3	0.9032	0.9049	0.9066	0.9082	0.9099	0.9115	0.9131	0.9147	0.9162	0.9177
1.4	0.9192	0.9207	0.9222	0.9236	0.9251	0.9265	0.9279	0.9292	0.9306	0.9319
1.5	0.9332	0.9345	0.9357	0.9370	0.9382	0.9394	0.9406	0.9418	0.9429	0.9441
1.6	0.9452	0.9463	0.9474	0.9484	0.9495	0.9505	0.9515	0.9525	0.9535	0.9545
1.7	0.9554	0.9564	0.9573	0.9582	0.9591	0.9599	0.9608	0.9616	0.9625	0.9633
1.8	0.9641	0.9649	0.9656	0.9664	0.9671	0.9678	0.9686	0.9693	0.9699	0.9706
1.9	0.9713	0.9719	0.9726	0.9732	0.9738	0.9744	0.9750	0.9756	0.9761	0.9767
2.0	0.9772	0.9778	0.9783	0.9788	0.9793	0.9798	0.9803	0.9808	0.9812	0.9817
2.1	0.9821	0.9826	0.9830	0.9834	0.9838	0.9842	0.9846	0.9850	0.9854	0.9857
2.2	0.9861	0.9864	0.9868	0.9871	0.9875	0.9878	0.9881	0.9884	0.9887	0.9890
2.3	0.9893	0.9896	0.9898	0.9901	0.9904	0.9906	0.9909	0.9911	0.9913	0.9916
2.4	0.9918	0.9920	0.9922	0.9925	0.9927	0.9929	0.9931	0.9932	0.9934	0.9936
2.5	0.9938	0.9940	0.9941	0.9943	0.9945	0.9946	0.9948	0.9949	0.9951	0.9952
2.6	0.9953	0.9955	0.9956	0.9957	0.9949	0.9960	0.9961	0.9962	0.9963	0.9964
2.7	0.9965	0.9966	0.9967	0.9968	0.9969	0.9970	0.9971	0.9972	0.9973	0.9974
2.8	0.9974	0.9975	0.9976	0.9977	0.9977	0.9978	0.9979	0.9979	0.9980	0.9981
2.9	0.9981	0.9982	0.9982	0.9983	0.9984	0.9984	0.9985	0.9985	0.9986	0.9986
3.0	0.9986	0.9987	0.9987	0.9988	0.9988	0.9989	0.9989	0.9989	0.9990	0.9990
3.1	0.9990	0.9991	0.9991	0.9991	0.9992	0.9992	0.9992	0.9992	0.9993	0.9993
3.2	0.9993	0.9993	0.9994	0.9994	0.9994	0.9994	0.9994	0.9995	0.9995	0.9995
3.3	0.9995	0.9995	0.9995	0.9996	0.9996	0.9996	0.9996	0.9996	0.9996	0.9997
3.4	0.9997	0.9997	0.9997	0.9997	0.9997	0.9997	0.9997	0.9997	0.9998	0.9998
3.5	0.9998	0.9998	0.9998	0.9998	0.9998	0.9998	0.9998	0.9998	0.9998	0.9998
3.6	0.9998	0.9998	0.9999	0.9999	0.9999	0.9999	0.9999	0.9999	0.9999	0.9999
3.7	0.9999	0.9999	0.9999	0.9999	0.9999	0.9999	0.9999	0.9999	0.9999	0.9999
3.8	0.9999	0.9999	0.9999	0.9999	0.9999	0.9939	0.9999	1.0000	1.0000	1.0000
3.9	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000

sample available, the suspected presence of interferences from other constituents in the sample, the resources available for sample analysis, and the perceived need for a particular detection limit.

When detection limit data exist in a data set, they will have an effect on statistical parameters computed from that set. The effect is to cause an overestimation of central tendency measures and an underestimation of dispersion measures as opposed to what would have been obtained had the true values of the detection limit data been known. Figure 3(a) shows an example of the phenomena using a hypothetical lognormal distribution with a detection limit artificially set at 1.0. The magnitude of the error made by failing to properly treat detection limit data will be a function of the size of the data set (i.e., the total number of events for which a concentration was reported [N], the percentage of the total set represented by detection limit data, and the value of the detection limit relative to the median of the data above the detection limit).

The treatment of detection limit data varies among workers in the field and the objectives for which the data are being analyzed. The traditional practice has simply been to take all detection limit data at their face value, the argument being that since the actual values are really lower, the average so calculated will be conservative for prediction of concentrations near the median. However, prediction of values that are exceeded rarely (i.e., pollutant concentrations that are observed less than 5 percent of the time) may very likely be underpredicted (see figure 3(a)). Others have set the values equal to one-half (or some other fraction) of the detection limit. When a significant percentage of a data set is at the detection limit, the treatment method can seriously affect analytical results and their interpretation. In statistical parlance, data sets with "less-than" observations are termed "censored data." Gilliom and Helsel (16) provide a recent discussion of the estimation of distributional parameters for censored water quality data.

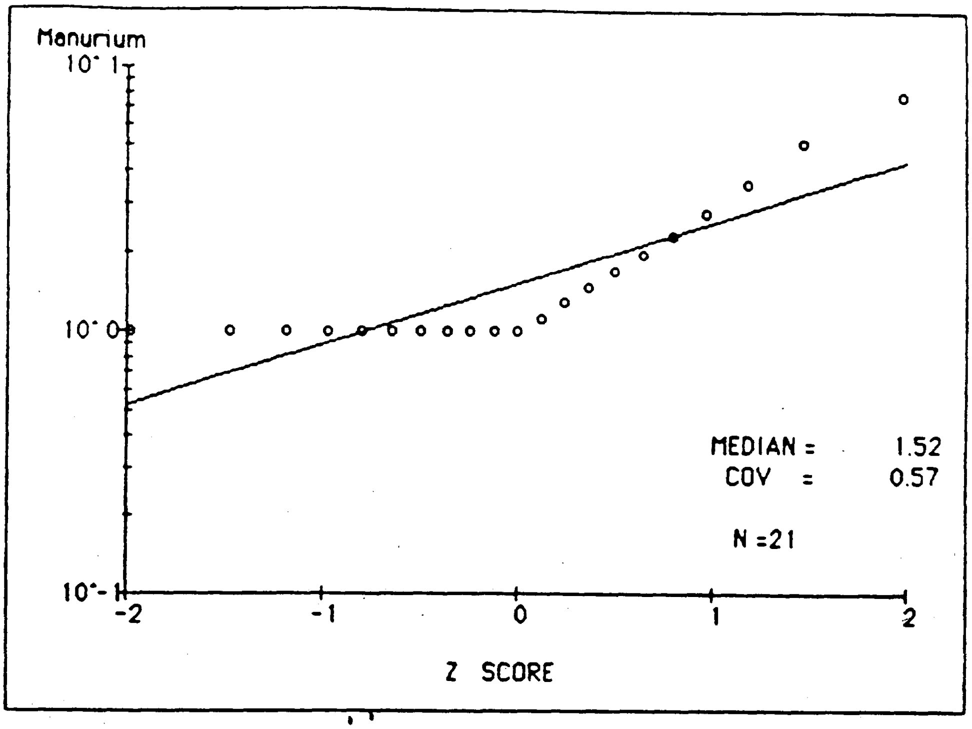
The data in the Master Data File (MDF) represent the work of a number of different analytical laboratories over an extended period of time. Furthermore, some projects changed laboratories over the course of the project. Thus, it was virtually impossible to unequivocally determine the actual detection limit associated with each pollutant concentration reported. As a practical matter, however, the existence of a number of repeated values at the lower end of a rank-ordered data set indicates the presence of detection limit data and their magnitude. For the present study, we carefully reviewed the MDF data sets and, using best professional judgement, selected those data sets for which treatment of the detection limit data was deemed necessary to avoid errors in data analysis and interpretation.

Simply stated, the method that we used to treat detection limit data was to ignore their magnitude, but use their probability (or plotting position) in determining the lognormal distribution that best fit the data set in question. That is, using regression, we fit all of the data above the detection limit to a lognormal curve and assumed the detection limit data followed the same lognormal frequency distribution. The way in which this was accomplished is as follows:

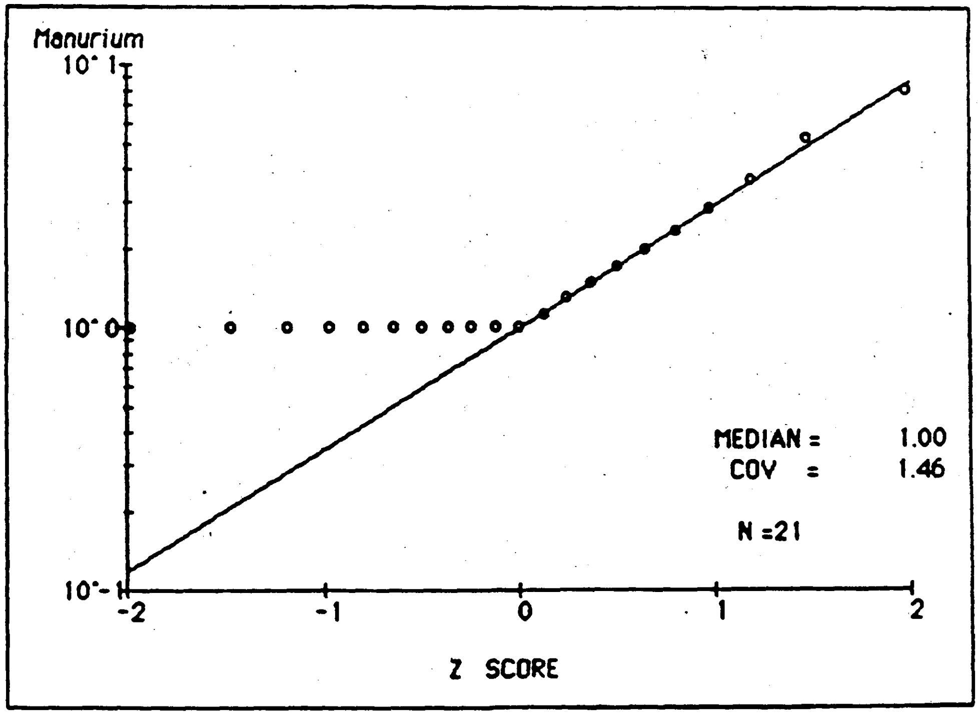
1. Transform the data to a normal distribution (in this case using a log transformation).

2. Rank order the data set in question (m = 1, 2,..., N).

3. Compute the probability (i.e., plotting position) associated with the rank



(a)



(b)

Figure 3. Comparison of approach to analysis of detection limit data.

order (m) as discussed earlier.

4. Compute the corresponding Z score for each probability value.

5. Determine the regression line that best fits the data subset above the detection limit.

6. Determine the log mean and log standard deviation from the regression line (i.e., the mean is the intercept of a Z score value of zero, while the standard deviation is the slope of the line).

7. Compute the arithmetic statistical parameters from these values as discussed earlier.

The actual execution of the correction is much simpler than its description. This approach for treating detection limit data was used and its results are reflected in the Working Data File summary given in section 3.0. However, the statistics given in the MDF and the WDF in the Data Appendix have not been corrected for detection limit problems. A graphic illustration of the results of the procedure is presented by figure 3(b), which also indicates how the pertinent statistics are affected.

2.7 COMPARISON OF HIGHWAY SITES

This section describes the procedures used to develop an overview of the characteristics of stormwater runoff from highway sites in general, and to evaluate the factors or relationships, evident from the available data, that influence the pollutant discharges from a specific site. The statistics of the lognormal distribution of individual storm event EMCs, determined for each study site, are summarized in section 3.0 as "site characteristics." Specifically, the site median and coefficient of variation of event EMCs for each of the pollutants are presented. These two values are considered to completely describe the magnitude and variability of pollutant discharges characteristic of that site.

Comparisons between different sites and evaluations of the significance of site factors that might influence the pollutant discharge characteristics were made by using site median concentrations as the primary measure of a site's pollutant discharge characteristics. The initial step was to pool the site median EMC values (the median EMC of all of the storms monitored at each of the sites) and examine the probability distribution of "site medians" for each pollutant. We again investigated the hypotheses that these pooled data could also be represented as being lognormally distributed. A similar analysis was completed for the site coefficients of variation. We created separate spreadsheets for both rainfall/runoff events and for snow washoff events. The results of these analyses are presented and discussed in section 3.0.

Additional comparisons between sites were made using their site median EMCs in correlation plots with site factors of interest, and are presented in section 4.0. The obvious factor that is the first choice for investigation at a highway site is the amount of traffic carried. Previous studies have suggested some measure of average traffic density as the parameter form of major importance. We investigated the total average daily traffic (ADT) at sites versus the runoff concentrations found. We also looked at the ADT per lane to see if the pollutant concentrations were affected more by traffic density that total number of vehicles. Other factors investigated included correlations of single event EMCs with runoff quantity and total suspended solids, and correlations between site median EMCs and certain physical site factors (pavement type, percent impervious area, annual rainfall, presence of curbs).

3.0
CHARACTERISTCS OF HIGHWAY RUNOFF

3.1 INTRODUCTION

This section presents the results of the evaluation of the individual site EMCs and the distribution of site median EMCs. An example of how each site was evaluated is presented in section 3.2 using the Milwaukee I-794 site. Then, evaluations of the acceptability of the lognormal distribution for characterization of highway runoff EMCs at individual sites is presented in section 3.3. Section 3.4 summarizes the physical characteristics of the study sites. Sections 3.5 and 3.6 discuss the observed site median concentrations and their variability. Pollutants for which insufficient data were available to adequately characterize highway sites, or those that were deemed not to have a significant potential for water quality problems are discussed in section 3.6. Section 3.7 discusses the snow washoff events that were treated separately, but evaluated using the same analysis methods as rainfall/runoff events.

3.2 EXAMINING DATA FOR AN INDIVIDUAL SITE

The procedures used to summarize the variable EMCs at a particular highway runoff site are illustrated below using part of the data from one of the study sites.

Table 3 provides a summary of several of the pollutants monitored at the Milwaukee I-794 site. A complete listing of all pollutants, at all 31 study sites, is presented (as the WDF) in the Data Appendix using a format similar to that presented here. These tabulations serve several purposes. First, they provide a convenient record of all the data. Second, visual inspection provides a qualitative appreciation of the magnitude, range and variability of EMCs of pollutants in the runoff. Finally, they organize the data so that the desired analyses can be conveniently performed.

At this site, like others in the northern States, a few of the runoff events are associated with snowmelt. A snowpack traps pollutants by preventing normal dissipation by natural or traffic-induced winds, and concentrates them due to evaporation and melting. Thus, significantly elevated concentrations for many of the pollutants are observed during rainfall events that melt and wash off snow accumulations from the sides of the highway. As shown by table 3, such events are segregated and dealt with separately.

Many locations have little or negligible snow accumulations. Even for those that do, there will normally be only a handful of snow washoff events each year, usually amounting to less than 10 percent of all storm events producing runoff. Accordingly, for purposes of generalizing highway runoff characteristics, general site characteristics have been defined using the EMC data that exclude snowmelt-washoff events. For example, the I-794 site used in this illustration is assigned a median EMC of 140 mg/l and coefficient of variation of 0.70 for TSS, for comparisons with other highway sites. The statistical parameters presented in the table are based on the

Table 3. Storm runoff EMCs at MILWAUKEE I-794 site.

EVENT	DATE (MDY)	RUNOFF (in.)	Rv	SS (mg/l)	COD (mg/l)	TKN (mg/l)	Pb (mg/l)	CL (mg/l)
1	61876	0.72	0.80	176	52	2.10		
2	72876	0.28	0.83	111	133	1.96	1.10	59
3	73076	1.39	0.88					
4	80576	0.04	0.72	92	226	4.01	1.10	110
5	81376	0.58	0.90	146	148	1.99	3.10	20
6	82576	0.12	0.87	179	190	4.90	1.70	45
7	82876	1.17	1.12	173	57	2.00	1.80	13
8	90976	0.85	1.00	87	48	1.85	0.90	10
9	91976	0.28	0.93	61	87	2.13	0.80	21
10	103076	0.15	1.03	193	5	1.60	2.60	422
16	32777	0.20	0.69	201	158	2.20	1.80	220
17	32877	0.85	0.76	416	178	2.50	2.50	62
18	53177	0.18	0.89	86	78	2.50	0.80	24
19	60577	0.66	0.95	119	52	2.40	1.10	16
20	60577	0.46	0.85	475		1.90		
21	60877	0.24	0.95	185	163	1.00	1.70	45
22	61077	0.04	0.74	170	191	1.60	1.50	118
23	61177	1.15	0.94	127	66	0.60	1.20	13
24	61777	0.61	1.00	169	94	1.50	2.10	30
25	63077	0.76	0.96	109	85	0.70	1.10	16
26	70377	0.33	0.95	63				
27	71777	1.66	0.79	26				
28	80477	0.17	1.00					
29	80577	0.14	0.93					
30	80577	0.15	0.60					
31	81377	0.93	0.73					
32	82877	0.79	0.72	128				
33	92377	0.01	0.16	433				
34	92377	0.11	0.86	228				
35	92477	0.77	0.95	90				
	Mean	0.68	0.87	172	130	2.11	1.59	69
	Median	0.32	0.82	140	88	1.86	1.46	39
	COV	1.88	0.35	0.70	1.08	0.54	0.44	1.47
	N	30	30	25	18	19	17	17

SNOWMELT / SNOW WASHOFF EVENTS

EVENT	DATE (MDY)	RUNOFF (in.)	Rv	SS (mg/l)	COD (mg/l)	TKN (mg/l)	Pb (mg/l)	CL (mg/l)
11	22377	0.10	0.70	1576	1058	8.60	13.10	1030
12	30377	0.11	0.72	632	534	6.30	5.00	13300
13	30377	0.43	0.69	496	494	6.50	5.00	425
14	31277	0.21	0.70	886	638	10.70	7.40	299
15	31777	0.18	0.84	387	234	6.60	3.90	1063
	Mean	0.21	0.73	814	614	7.77	6.98	3404
	Median	0.18	0.73	701	530	7.57	6.24	1131
	COV	0.64	0.08	0.59	0.59	0.23	0.50	2.84
	N	5	5	5	5	5	5	5

assumption that the parameters are lognormally distributed as discussed in section 2.5. The validity of this assumption will be discussed below and in section 3.4.

TSS concentrations in snowmelt events at this site have a median EMC of 701 mg/l, five times greater than under the conditions that prevail most of the time. Concentrations are 4 to 6 times larger for the pollutants illustrated, other than chloride. At this site, road salting operations result in a thirtyfold increase in the median EMC of chloride ions. The significant differences in pollutant levels during snowmelt events versus non-snowmelt events, together with the low frequency of occurrence of such events, was the basis for the decision to segregate them and treat them independently.

The statistics listed at the bottom of each column (mean, median and coefficient of variation) are computed from the EMCs using the procedure described in section 2.4 that assumes they follow a lognormal probability distribution. The validity of this assumption is illustrated by figure 4 which shows probability plots of the EMC data for TSS and Lead. The match between the plotted points and the line that represents a lognormal distribution of the data set are typical of the vast bulk of the data sets in the full data base, as is indicated by an inspection of the probability plots provided in the Data Appendix and the discussion in section 3.3. The variability of pollutant EMCs in stormwater runoff is quantified by the value for coefficient of variation listed in the table for each pollutant, and the slope of the probability plot.

Other than the segregation of snow washoff events discussed above, the pollutant EMCs at a site were considered to fluctuate randomly, but to conform to a lognormal distribution. This allows one to define the central tendency of the EMCs (the median value), and the spread in the values which is characterized by the coefficient of variation (designated as CV in this written text for brevity, and as COV in the figures and tables). Further, quite good estimates of other items of information useful in an assessment can also be made. For example, for the illustrated site data, one can determine that for TSS (median = 140 mg/l, CV = 0.70), 95 percent of all storm events will have EMCs equal to or less than 396 mg/l. How well such an estimate (using the lognormal distribution assumption) compares with actual observations can be assessed by inspection of the probability plot. For example, looking at the TSS plot, one can compare the prediction of the 95th percentile value (Z score of 1.645) with the actual observed value closest to the 95th percentile.

The statistical parameters of the lognormal distribution of individual storm event EMCs are designated as "site characteristics." Of particular interest is the site median EMC concentration and the site coefficient of variation (CV). These two values provide a concise summary of the stormwater pollutant discharges at that site. The following sections present results of our investigation of each of the sites in the Working Data File.

3.3 STUDY SITES

The highway sites that provide data on pollutant runoff for this study are identified by table 4, which also tabulates certain of their physical characteristics. Locations are shown on the map in figure 5. More complete descriptions of the sites are provided in the Data Appendix.

Numbers on the map that are not circled represent sites that were examined and are in the MDF, but which were excluded from the WDF and subsequent analyses. They were excluded after

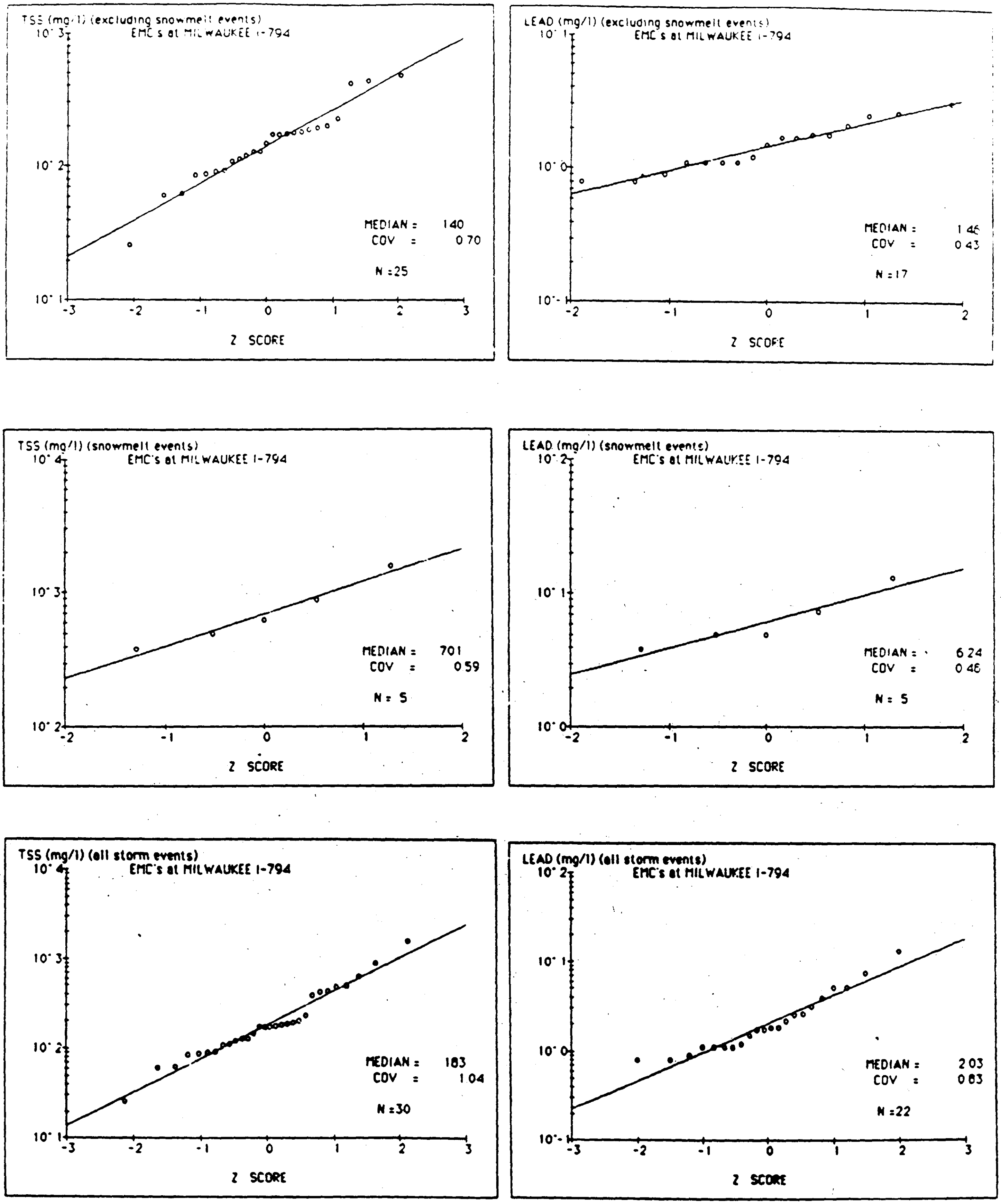


Figure 4. Probability distribution of pollutant EMCs.

Table 4. Physical characteristics of highway study sites.

SITE NO.	STATE CODE		AVG DAILY TRAFFIC 1000 VPD total	monitor lanes	NUMBER of TRAFFIC LANES total	monitored	SECT TYPE (B)	SURF TYPE (C)	CURB	LAND USE (A)	AREA (ACRES)	% IMP	Annual RAIN in/YR
1	AR-1	LITTLE ROCK I-30	42	42	4	4	BF	ASP	NO	U-3	1.5	90	48.7
2	CA-1	LOS ANGELES I-405	200	200	8	8	F	CON	YES	U-2	3.2	100	12.6
3	CA-2	SACRAMENTO HWY 50	86	43	8	4	G	CON	YES	U-4	2.45	82	16.3
4	CA-3	WALNUT CREEK I-680	70	70	6	6	H	CON	YES	U-3	2.1	100	20.3
5	CO-1	DENVER I-25	149	149	10	10	G	ASP	YES	U-4	35.3	37	14.8
6	FL-1	BROWARD CO HWY 834	20	20	6	6	G	ASP	BOTH	U-2	58.3	36	62.0
8	FL-2	MIAMI I-95	140	70	6	3	B	ASP	YES	U-1	1.43	100	59.8
11	MN-1	MINNEAPOLIS I-94	80	80	10	10	C	CON	YES	U-2	21	55	24.8
12	MN-2	ST PAUL I-94	65	65	6	6	CF	CON	YES	U-2	16.3	49	24.8
13	NC-1	EFLAND I-85	26	26	4	3	G	ASP	NO	N-1	2.49	51	43.6
14	PA-1	HARRISBURG I-81 (Ph. 1)	24	24	6	6	G	CON	NO	U-4	18.5	27	37.7
15	PA-2	HARRISBURG I-81 (Ph. 2)	56	28	4	2	G	CON	NO	U-4	2.81	45	37.7
17	TN-1	NASHVILLE I-40	88	88	6	6	CG	CON	YES	U-1	55.6	37	45.0
18	WA-5	MONTESANO SR-12 (5)	7.3	7.3	2	2	G	ASP	YES	N-4	0.28	100	84.0
19	WA-6	PASCO SR-12 (6)	4.0	2.0	4	2	C	CON	YES	N-5	1.25	100	7.5
21	WA-9	PULLMAN SR-270E (9)	5.0	2.5	2	1	G	ASP	YES	N-4	0.25	100	18.0
23	WA-1	SEATTLE I-5 (1)	106	53	8	4	G	CON	YES	U-3	1.22	100	34.1
25	WA-2	SEATTLE SR-520 (2)	84	42	4	2	B	CON	YES	U-1	0.099	100	35.0
26	WA-4	SNOQ. PASS I-90 (4)	15	7.7	6	3	G	CON	YES	N-2	0.18	100	97.0
27	WA-7	SPOKANE I-90 (7)	35	17	6	3	B	CON	YES	U-1	0.22	100	17.2
28	WA-3	VANCOUVER I-205 (3)	17	8.6	6	3	G	CON	YES	U-4	0.28	100	39.0
29	WI-1	MILWAUKEE HWY 45	85	85	6	6	CG	CON	YES	U-3	106	31	27.6
30	WI-2	MILWAUKEE I-794	53	53	8	8	B	CON	YES	U-1	2.1	100	27.6
31	WI-3	MILWAUKEE I-94	116	116	8	8	H	ASP	YES	U-3	7.6	64	27.6

NOTES :

(A) land use surrounding area - U = URBAN 1= undefined , 2= commercial/residential , 3= residential , 4= suburban
N = NON-URBAN 1= undefined rural , 2= forest , 3= undeveloped , 4= agricultural , 5= desert

(B) section type - C = cut , F = fill , G = at grade , B = bridge

(C) road surface type - CON = concrete , ASP = asphalt

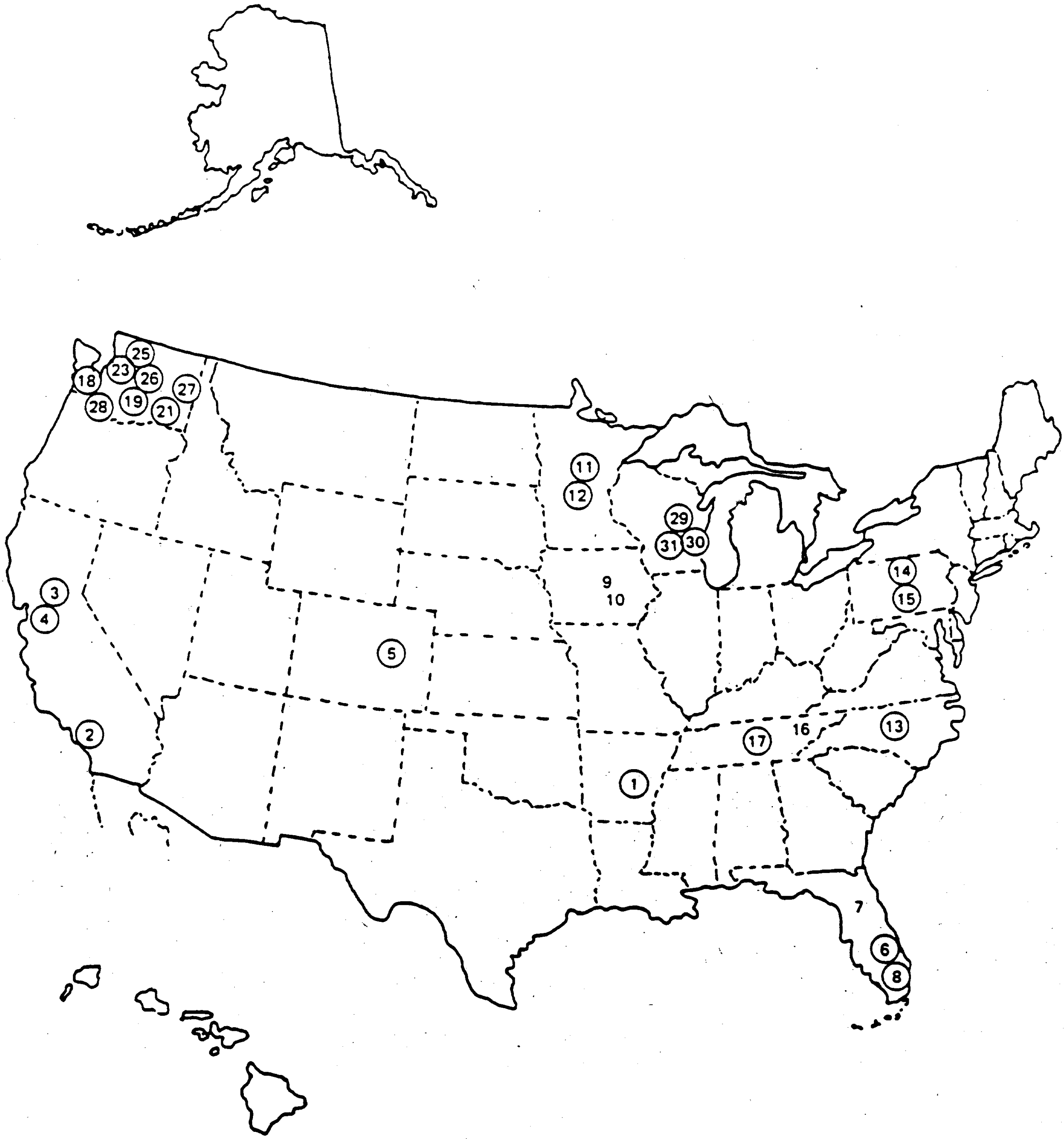


Figure 5. Location of highway runoff study sites.

careful review for the reasons discussed earlier in section 2.4.

The physical characteristics listed are limited to those which were reported by all of the sources. A number of additional site properties may have an important bearing on pollutant levels, but were not reported at enough of the sites to provide a sufficient basis for comparisons among all sites. A general discussion of factors that may influence pollutants in highway stormwater runoff is presented in section 4.7.

3.4 LOGNORMALITY OF EMCs AT HIGHWAY SITES

A careful analysis of the distribution of the variable EMCs at each of the highway sites supports the conclusion that the distribution of average pollutant concentrations in highway stormwater runoff events either are lognormal or can be approximated as lognormally distributed. This analysis is consistent with similar findings for a variety of other storm generated pollutant discharges, and in fact for many water quality situations. The EPA NURP study [17] reached a similar conclusion regarding pollutant concentrations in stormwater runoff from urban areas, based on a significantly larger data base than is available here. Other studies, using somewhat smaller data bases, reached similar conclusions for pollutants in combined sewer overflows [18]. In fact, there is an ever increasing body of evidence indicating that, in a wide variety of water quality situations, pollutant concentrations can be adequately represented by a lognormal distribution [19,20,21].

The probability distributions in figure 6 show the expected probability of each observed EMC as a plotted point, for comparison with the theoretical lognormal cumulative distribution shown by the line. Lognormality is judged by how well the plotted points correspond with the theoretical straight line. Also tabulated on each plot is the Plotting Position Correlation Coefficient (PPCC) [14,15], which provides a statistical measure of the goodness of fit (see section 2.4). Critical values for PPCC which establish the appropriateness of a lognormal assignment vary with the number of values in the data set, and with the confidence level. For the range in the number of observations in the highway runoff data base, and confidence levels in the range of 1 to 5 percent, the critical values of PPCC usually fall between about 0.91 and 0.98.

The particular data sets used in this illustration were selected to present samples that are typical of the observed range of conformance to a lognormal distributional hypothesis as indicated by visual inspection of the comprehensive set of probability plots included in the Data Appendix. A substantial majority of the pollutant concentration data provide direct visual support for the acceptance of the lognormal distribution. Three samples showing high degrees of conformance (PPCC about 0.99) are shown, together with two data sets that show lesser, but still quite strong, patterns (PPCC about 0.95). One sample is provided to illustrate the very few cases in which the lognormality of the data set is clearly questionable. In such cases, the value of PPCC is usually in the range of about 0.87 to 0.91.

In evaluating these results, particularly the fact that some data sets do not provide strong PPCC values, we based our conclusions on the following primary consideration. We are not interested, per se, in a single sample of limited size drawn from a much larger population of all storm events. The particular characteristics of that sample are not particularly important. Sampling or laboratory analysis errors are always possible, as is the fact that the random element in a single

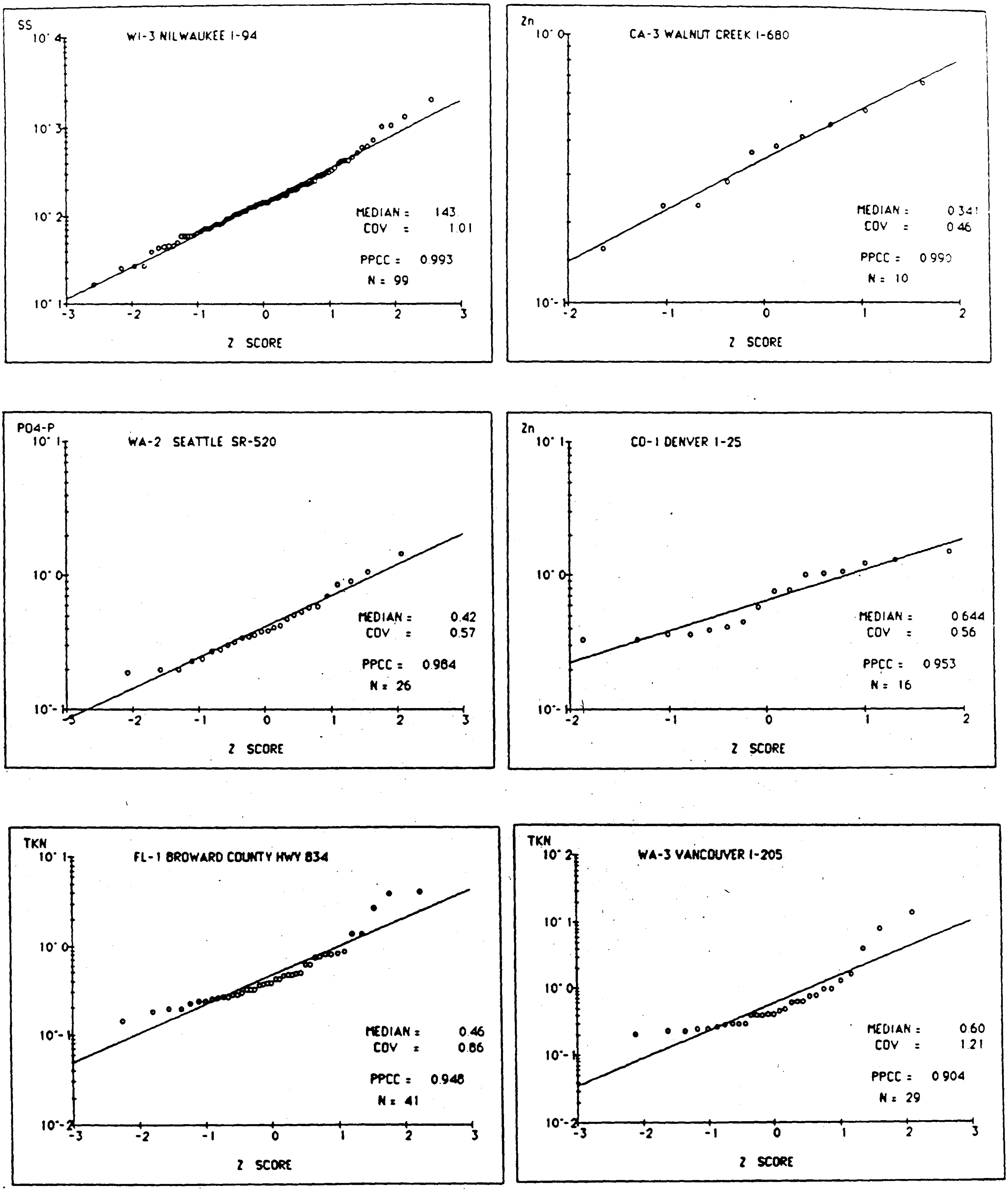


Figure 6. Probability distribution of EMCs.

sample of size N can distort results. The overall pattern shown by all pollutants at all study sites was considered in reaching the conclusion that pollutant concentrations in highway runoff can be treated as lognormally distributed random variables.

On the basis of evaluations described above, we conclude that the assumption of a lognormal distribution for runoff pollutants is a satisfactory practical approximation. The fact that EMCs can be assigned a lognormal distribution allows us to deal with this natural variability in a straightforward and effective way. Site runoff characteristics can be described concisely, and matched up with other site properties (ADT, physical site properties) to evaluate the potential importance of site-to site differences.

3.5 HIGHWAY RUNOFF QUALITY - SITE MEDIAN CONCENTRATIONS

The individual event data at each site were analyzed as described in section 2.7 to compute the statistical parameters of the EMCs for each pollutant. The median EMC concentration (designated the site median) is listed in table 5 for 10 of the pollutants that were monitored at nearly all of the sites. The pollutants listed in this table, with concentrations reported in milligrams per liter, include:

• PARTICULATES	TSS	total suspended solids
	VSS	volatile suspended solids
• OXYGEN DEMAND	TOC	total organic carbon
	COD	chemical oxygen demand
• NUTRIENTS	NO2+3	nitrate + nitrite nitrogen
	TKN	total kjeldahl nitrogen
	PO4-P	phosphorus
• HEAVY METALS	Cu	copper
	Pb	lead
	Zn	zinc

A number of additional pollutants received varying monitoring coverage, but are summarized and discussed separately in section 3.7. An independent discussion of these pollutants was determined to be appropriate because either the number of sites that measured them was considered to be too small for use of the procedures discussed here, or because the contaminant does not have direct environmental consequences. It is further noted that the data summaries represented by this table are based on data that exclude snowmelt/washoff events, and reflect runoff conditions common to all areas of the country. Snow related events were analyzed separately and results are discussed in section 3.8.

The statistics listed at the bottom of each pollutant column provide a basis for evaluating the site median concentrations in the tabulation. The possible influence of physical site factors on the site medians is discussed in section 4.0. The statistics listed provide an overall characterization of highway sites in general, without regard for site-specific factors such as traffic density, etc., which might permit finer distinctions of pollutant levels to be made on a site specific basis. It provides a

Table 5. Site median concentrations for monitored storm events.

SITE NO.	STATE CODE	SS (mg/l)	VSS (mg/l)	TOC (mg/l)	COD (mg/l)	NO2+3 (mg/l)	TKN (mg/l)	PO4-P (mg/l)	Cu (mg/l)	Pb (mg/l)	Zn (mg/l)
1	AR-1	112	20		94	0.71			0.019	0.108	0.167
2	CA-1	172			196		3.35	0.453		0.987	0.666
3	CA-2	90	20	22	51	0.21	1.67	0.099	0.068	0.278	0.269
4	CA-3	218			125		2.01	0.408		0.900	0.341
5	CO-1	406	77	88	291		3.51	0.821	0.104	0.705	0.644
6	FL-1	9		12	41	0.23	0.46	0.036	0.005	0.236	0.071
8	FL-2	67	70	46	169	1.02	1.25	0.140	0.043	0.623	0.303
11	MN-1	51		15			1.04	0.227	0.020	0.116	
12	MN-2	85		20			1.56	0.429	0.030	0.407	
13	NC-1	20	6	24	67	0.19	1.68	0.124	0.038	0.011	0.050
14	PA-1	25	8	11	31	0.61	1.14	0.267	0.029	0.091	0.051
15	PA-2	184	18	16	34	3.32	2.16	1.075	0.087	0.026	0.167
17	TN-1	190	49	29	113		1.86	1.687	0.056	0.411	0.259
18	WA-5	126	21	3	46	0.73	0.64	0.168	0.036	0.175	0.100
19	WA-6	101	25	10	114	0.81	3.32	0.476	0.025	0.101	0.325
21	WA-9	104	21	17	60	0.57	0.75	0.428	0.026	0.130	0.099
23	WA-1	93	26	13	106	0.83	0.90	0.217	0.037	0.451	0.382
25	WA-2	244	59	33	145	0.79	1.09	0.415	0.072	1.065	0.280
26	WA-4	43	9	2	41	0.53	0.38	0.123	0.025	0.065	0.071
27	WA-7	119	29	10	156	1.11	1.69	0.865	0.041	0.173	2.892
28	WA-3	34	9	7	32	0.45	0.60	0.098	0.017	0.046	0.040
29	WI-2	334	72	32	111	0.77	2.77	0.417	0.075	0.738	0.371
30	WI-3	140	47	27	88	1.27	1.86	0.287	0.088	1.457	0.336
31	WI-1	143	47	30	122	0.79	3.09	0.315	0.155	0.817	0.465
	MEAN	143	36	24	103	0.84	1.79	0.435	0.052	0.525	0.368
	MEDIAN	93	26	16	84	0.66	1.48	0.293	0.039	0.234	0.217
	COV	1.16	0.97	1.06	0.71	0.77	0.67	1.10	0.87	2.01	1.37
	N	24	19	21	22	18	23	23	22	24	22

useful overview of highway pollutant levels, and can be used as a basis for a first-cut estimate, and where specific site conditions have not been defined.

The statistical parameters of highway pollutant discharges (the median and coefficient of variation of all highway site median EMCs) listed at the bottom of the table, are computed on the basis that the listed site medians are lognormally distributed. Since these values are based on estimates from a lognormal fit of site EMCs, it follows that the site summary statistics (site EMCs and COVs) when analyzed together would also be lognormally distributed. The probability plots presented in figures 7 through 16 indicate the appropriateness of this assumption. Each figure covers a different pollutant. In each figure, the upper left hand plot shows the probability distribution of the site median EMCs for all of the monitored highway sites in the WDF.

Previous studies have reported that highways in urban areas have significantly greater pollutant levels than highways in rural settings. The nature of the surrounding area also has a direct effect on traffic levels. The data from table 5 were sorted into two groups. Those with an average traffic density (ADT) in excess of 30,000 vehicles per day (VPD) were assigned to the "Urban Highway" classification. Otherwise the site was assigned to the "Nonurban Highway" (or Rural) group. The eight sites in the latter grouping include all five of the "rural" sites in the land use descriptions, and three sites classified as suburban.

The upper and lower plots on the right side of each figure present separate probability distribution plots for each of these two groupings. A careful inspection of the information presented in these plots indicates:

- The lognormal pattern holds and is, in general, improved.
- The degree of variance (measured by the coefficient of variation) is reduced.
- The median concentration for each group of sites appears to be appreciably different from each other for all of the pollutants.

The latter observation is tested by computing the 90 percent confidence intervals on the true value of the median, given the number of observations and the variance of the data. Results are summarized by the box plots presented in the lower left quadrant of each figure. In the box plot, the upper and lower tics represent the 90th and 10th percentiles of the site median concentrations. The upper and lower bounds of the rectangle conform to the 75th and 25th percentiles. The pinched-in section indicates the median and the 90 percent confidence range for its true value.

These results shown in figures 7 to 16 clearly demonstrate that "nonurban" highway settings with lower traffic densities have significantly different pollutant discharge levels than highways in urban settings with traffic densities in excess of 30,000 vehicles per day. The "median" urban site is about 2 to 4 times higher in runoff concentration than the median rural site. For example, the 90 percent confidence interval for the median of the "urban" highway site median EMCs for TSS is between 111 and 182 mg/l with an expected value of 142 mg/l. In contrast, the median "non-urban" highway has a 90 percent confidence interval between 22 to 76 mg/l, and an expected value of 41 mg/l. The lack of overlap in the confidence bands indicates that there is a statistically

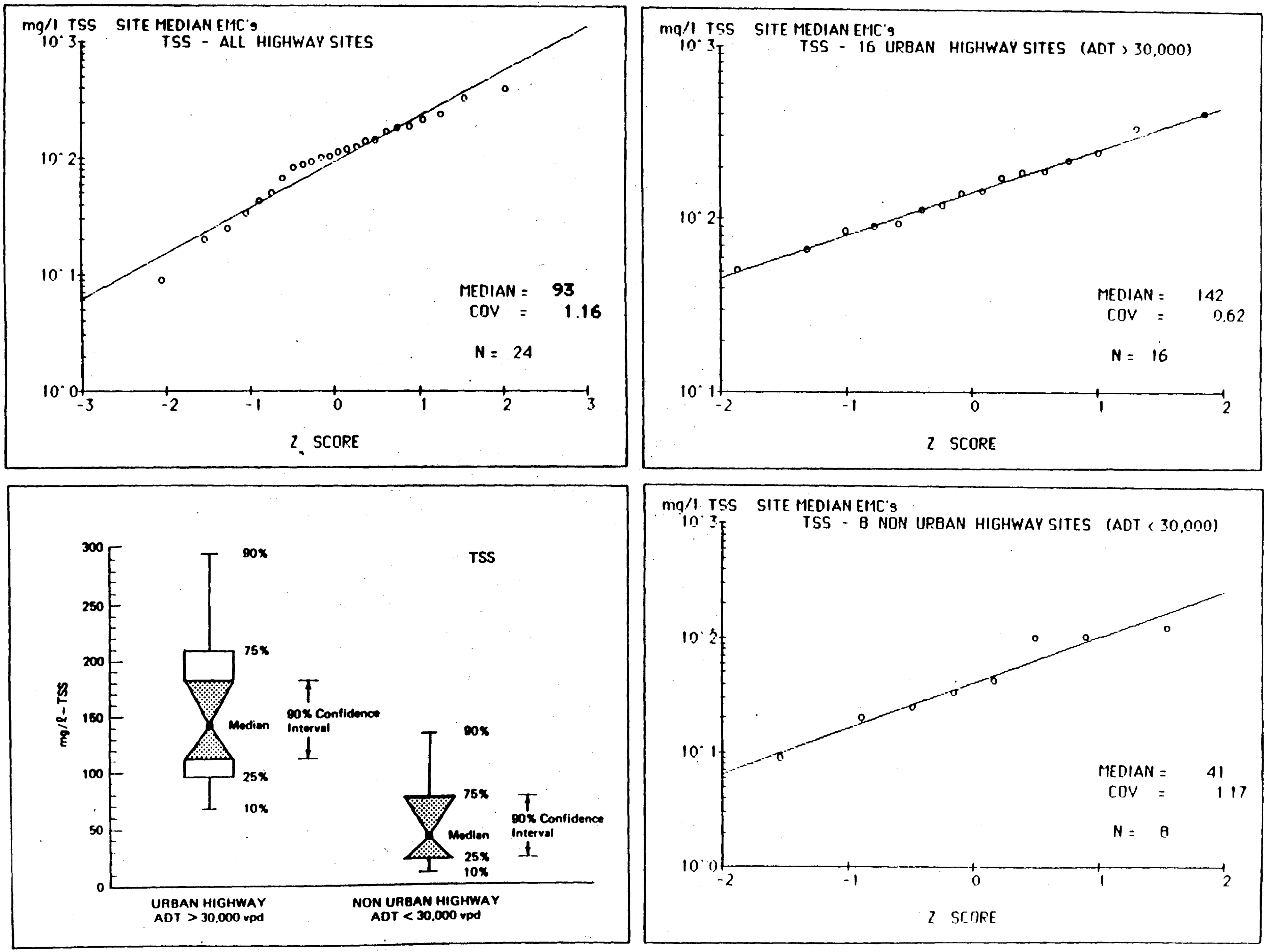


Figure 7. Highway site medians - Total Suspended Solids.

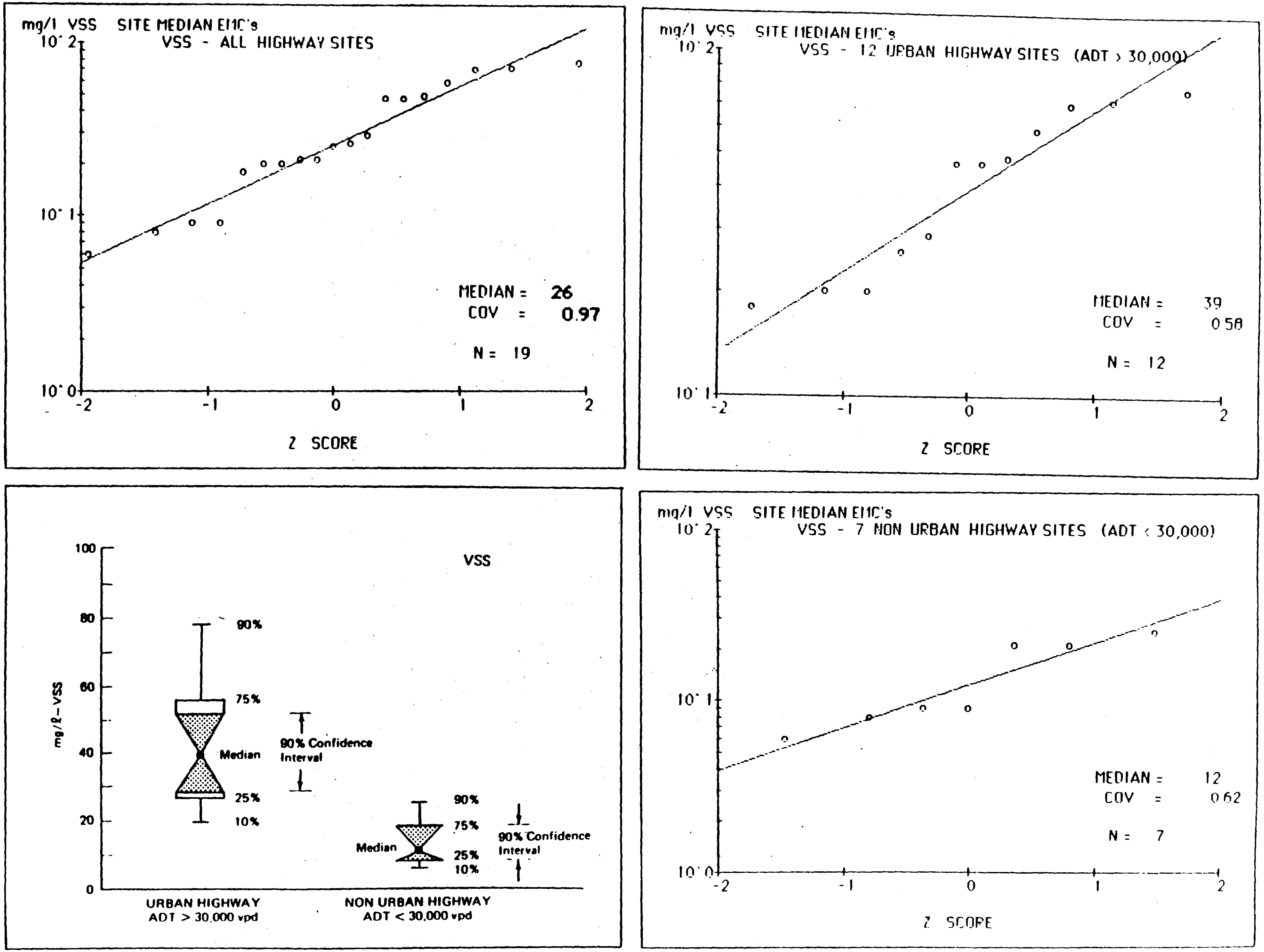


Figure 8. Highway site medians - Volatile Suspended Solids

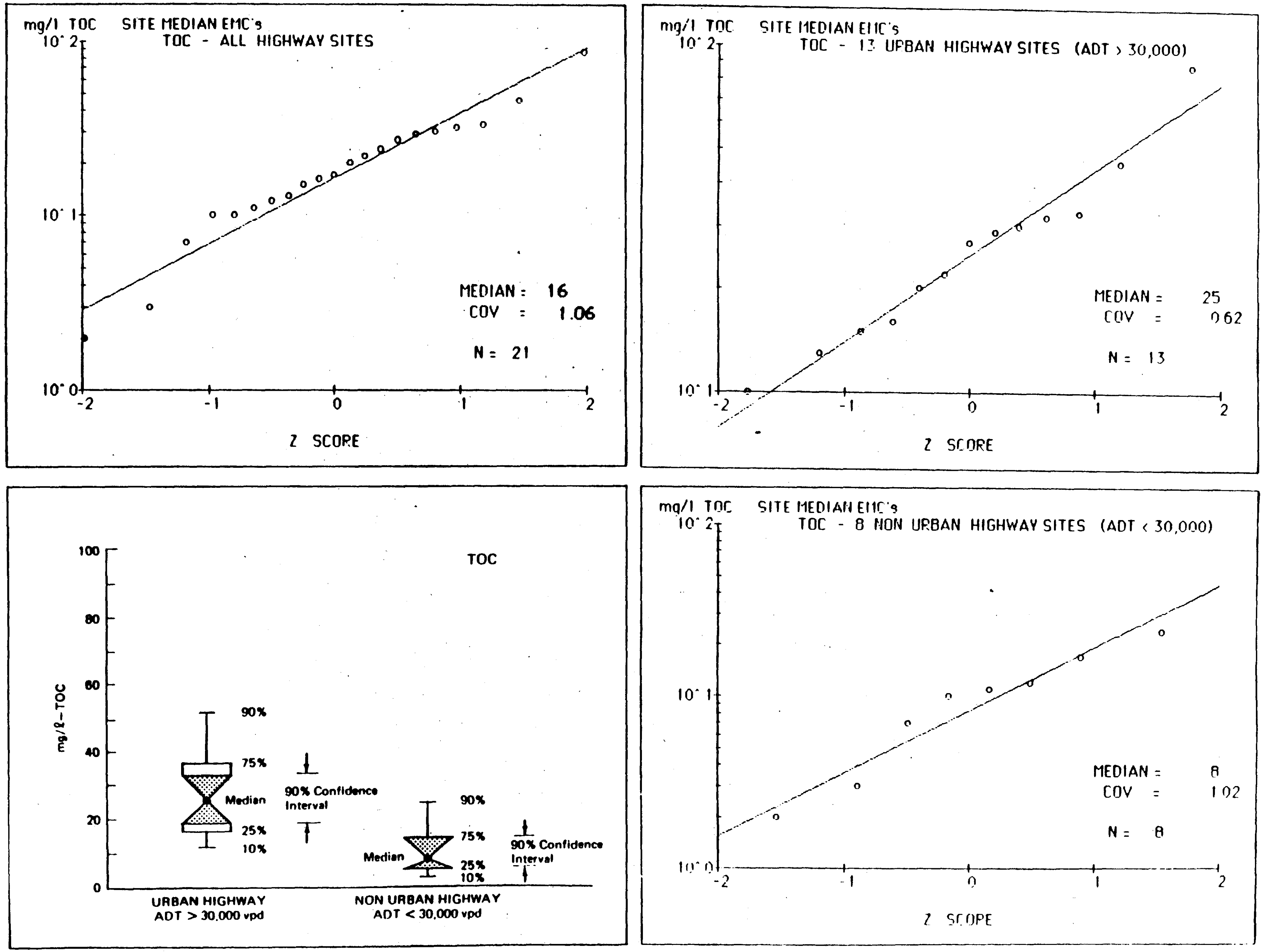


Figure 9. Highway site medians - Total Organic Carbon.

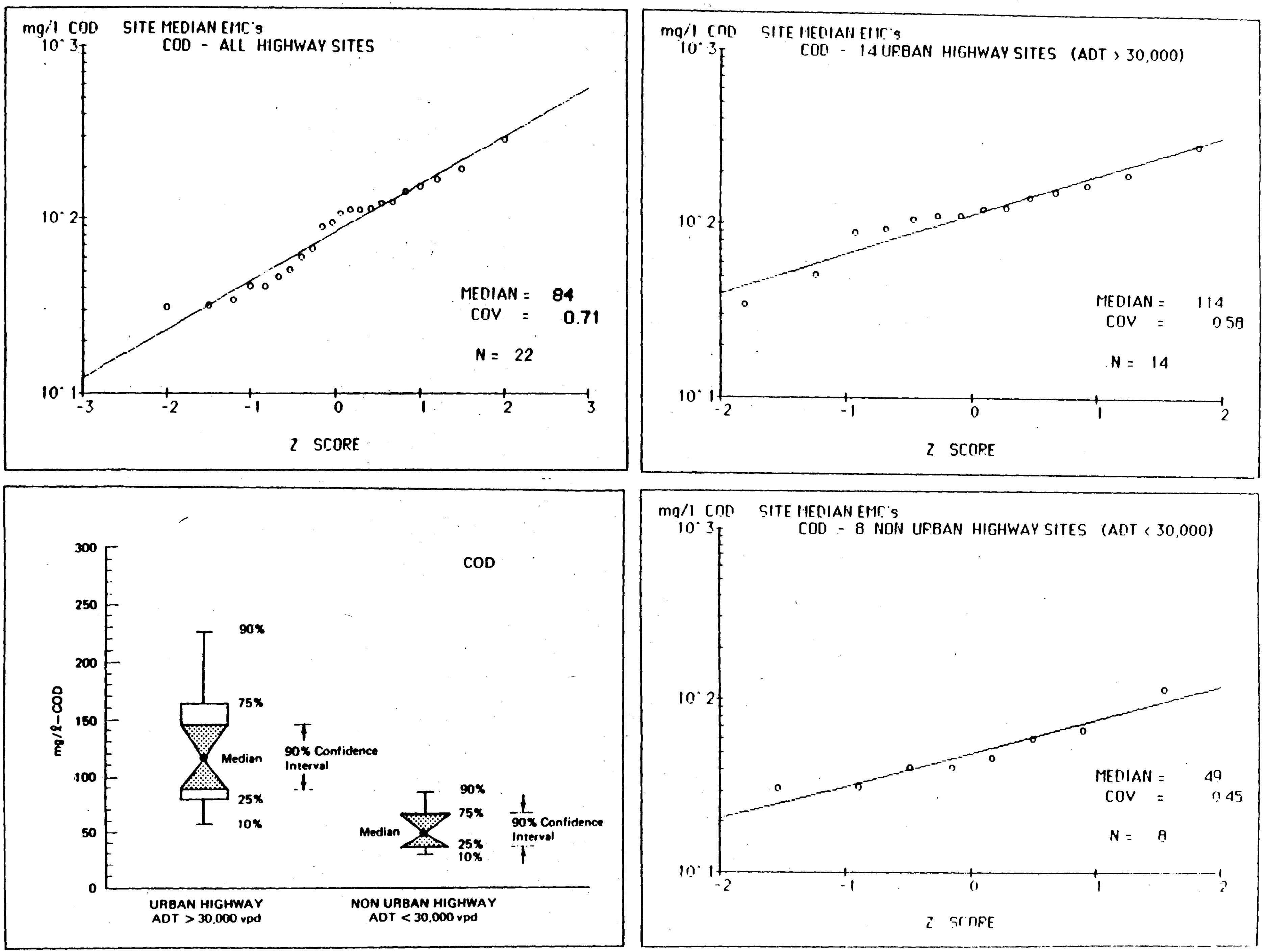


Figure 10 Highway site medians - Chemical Oxygen Demand

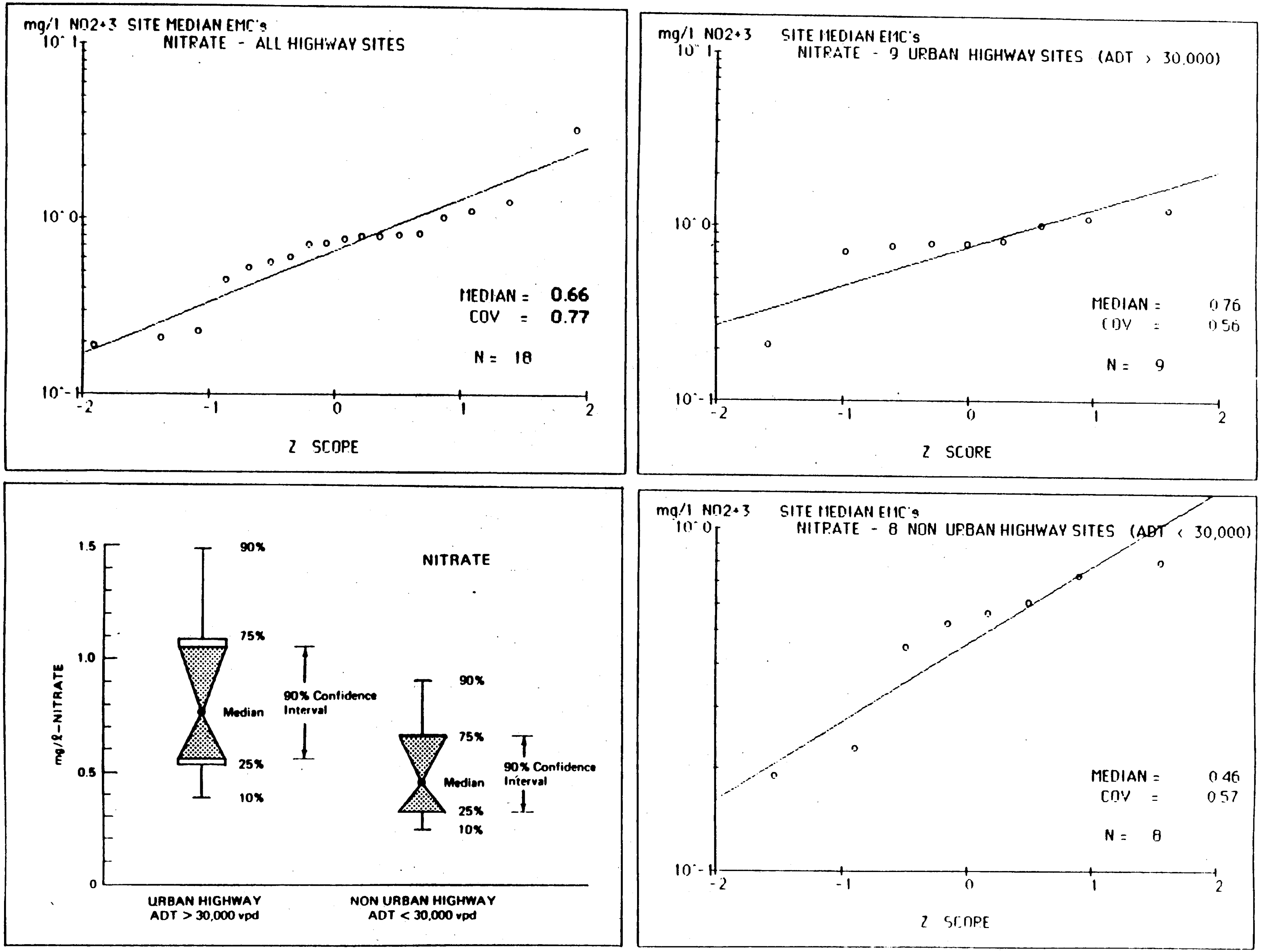


Figure 11. Highway site medians - Nitrate and Nitrite.

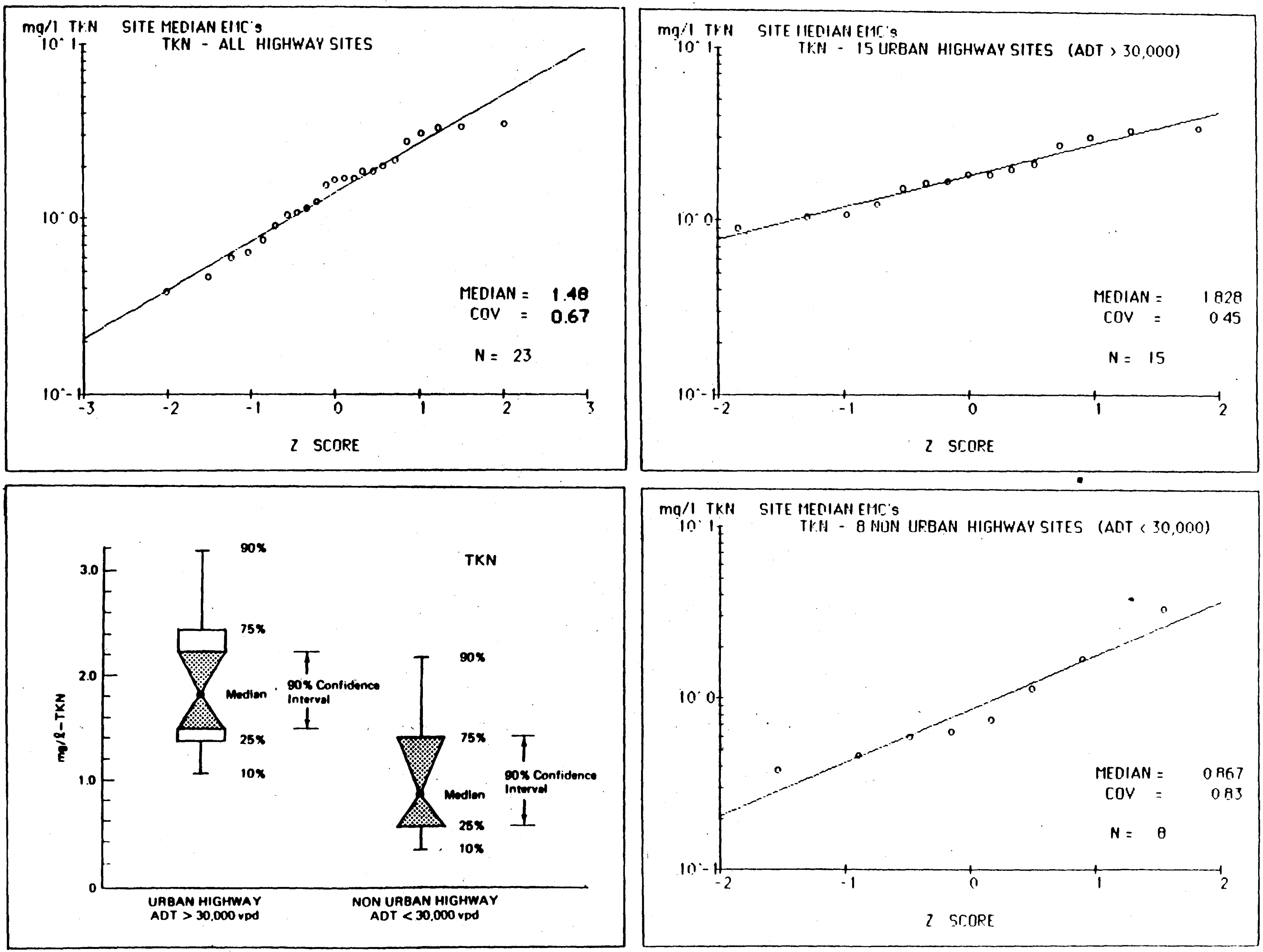


Figure 12. Highway site medians - Total Kjeldahl Nitrogen.

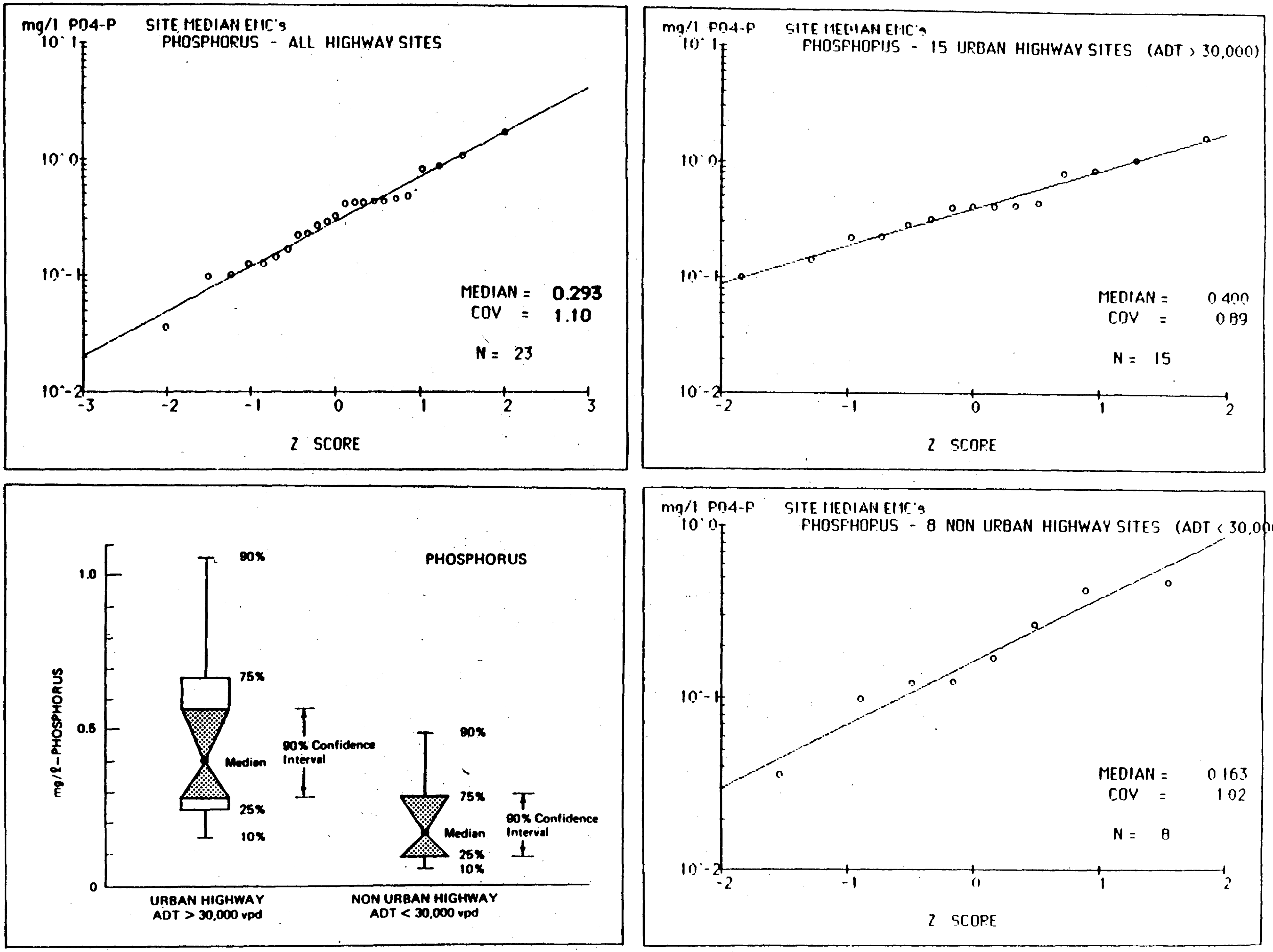
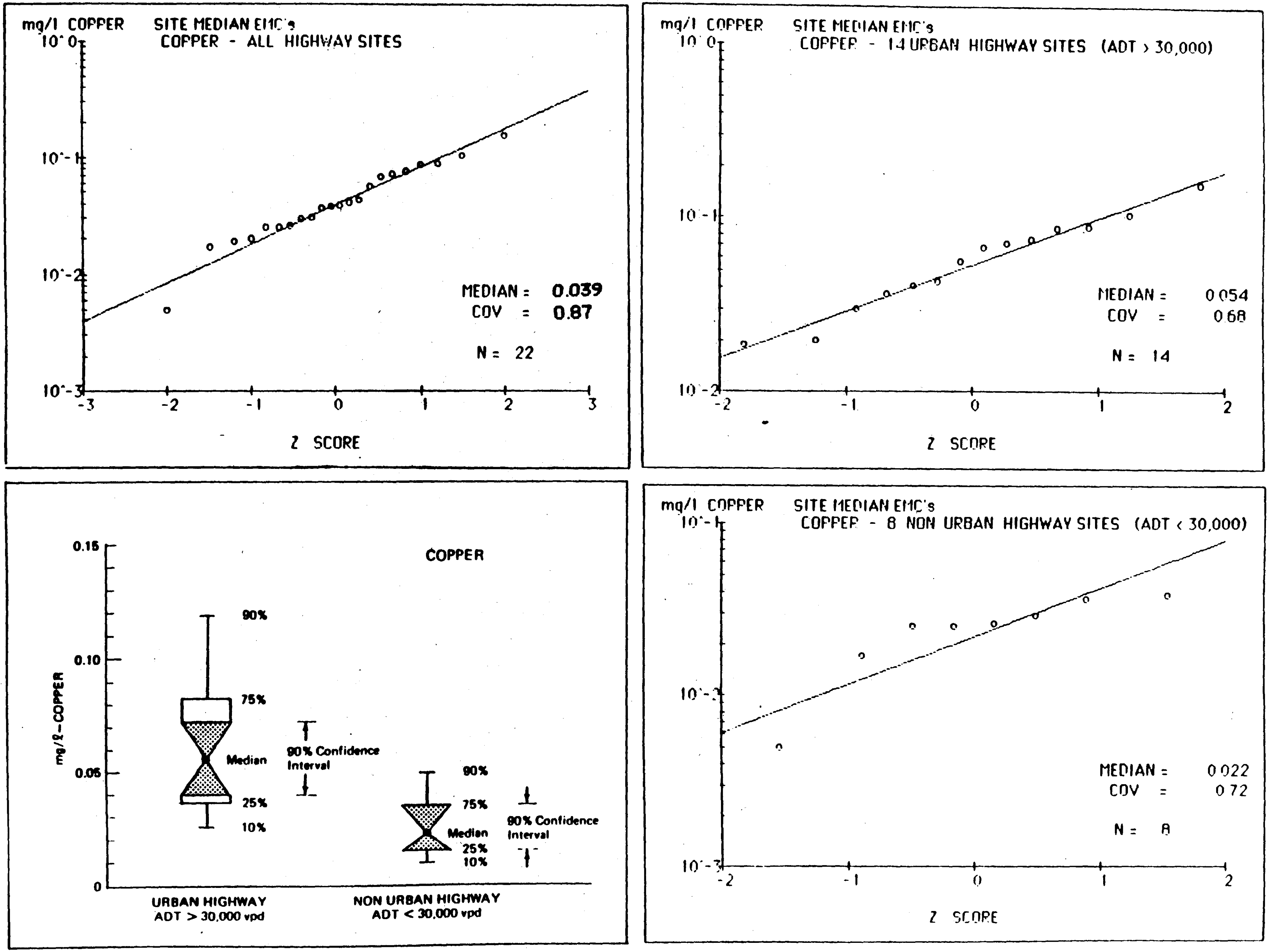


Figure 13. Highway site medians - Phosphorus.


mg/l COPPER
SITE MEDIAN EMC's
COPPER - ALL HIGHWAY SITES
MEDIAN = 0.039
COV = 0.87
N = 22
Z SCORE
mg/l COPPER
SITE MEDIAN EMC's
COPPER - 14 URBAN HIGHWAY SITES (ADT > 30,000)
MEDIAN = 0.054
COV = 0.68
N = 14
Z SCORE
COPPER
mg/ℓ-COPPER
90%
75%
Median
25%
10%
90% Confidence Interval
URBAN HIGHWAY
ADT > 30,000 vpd
NON URBAN HIGHWAY
ADT < 30,000 vpd
mg/l COPPER
SITE MEDIAN EMC's
COPPER - 8 NON URBAN HIGHWAY SITES (ADT < 30,000)
MEDIAN = 0.022
COV = 0.72
N = 8
Z SCORE

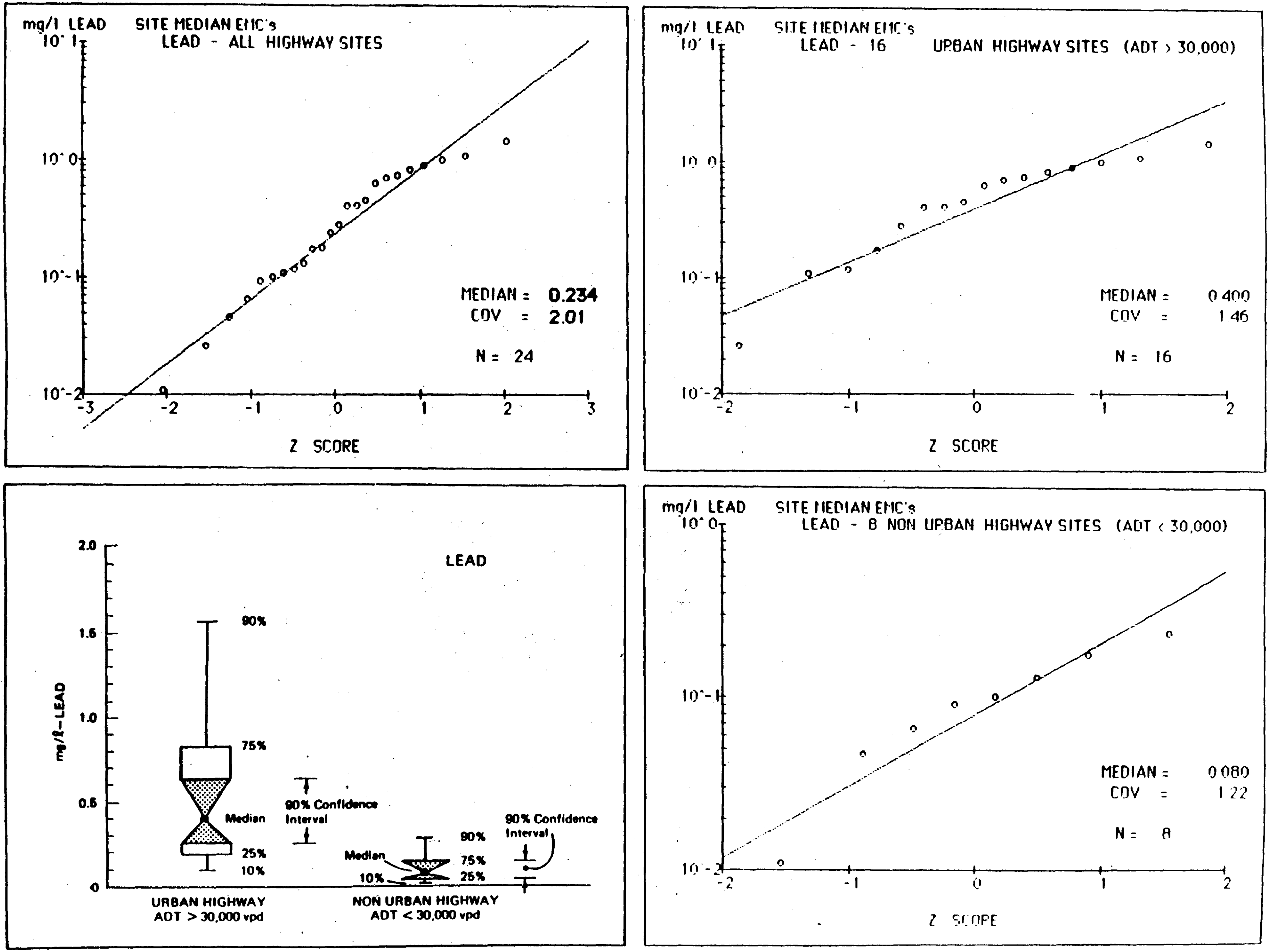


Figure 15. Highway site medians - Lead.

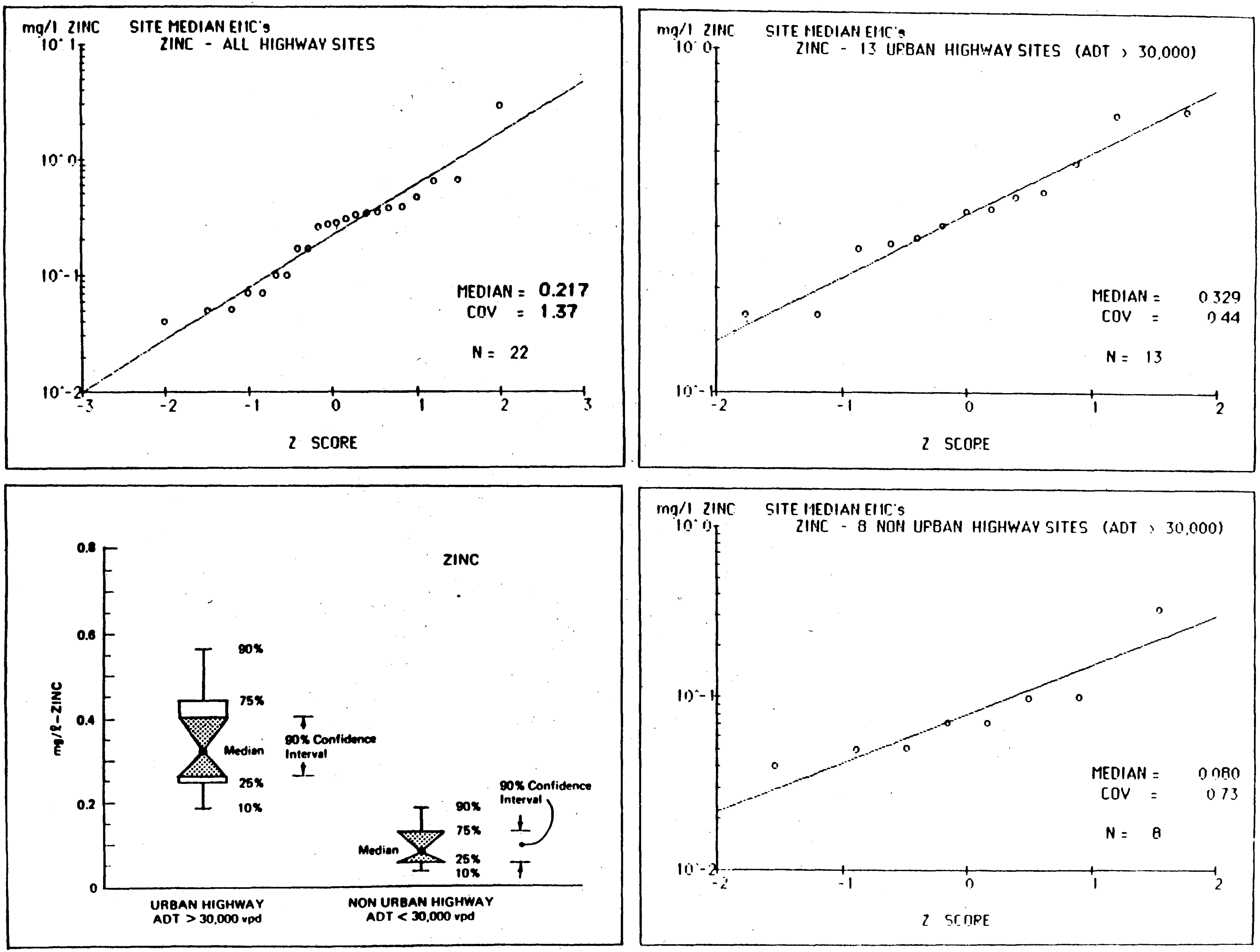


Figure 16. Highway site medians - Zinc.

significant difference in the data sets.

Based on the foregoing characterization, a generalized summary description of highway sites can be developed and compared with similar generalizations for other runoff sources. Table 6 provides a concise tabulated summary of pollutant levels in highway runoff. For each of the pollutants addressed in this section, the site median concentration is tabulated for the median (50th percentile) site, and for the 10th and 90th percentiles of all sites. Use of these values for prediction at a site assumes that within each of the two groups, pollutant levels in runoff, as defined by the site median EMC, are random and defined only by the lognormal probability distribution. The median of all sites in the group provides the most probable estimate for a new-site prediction. A conservative estimate might use the 90th percentile site value, or some other high percentile value. Note that any percentile of interest can be determined, using the procedures described earlier in section 2.5.

3.6 HIGHWAY RUNOFF QUALITY - SITE EMC VARIABILITY

The event-to-event variability for each of the pollutants at each of the listed sites can be quantified using the coefficient of variation of the EMCs. The coefficient of variation (CV) of EMC concentrations is listed in table 7 for the 10 pollutants that were monitored at most of the study sites.

The summary at the bottom describes the statistical parameters of the listed site values. The event-to-event EMC variations reflected by these CVs are seen to vary from site to site for a particular pollutant, and vary to a smaller degree with the particular pollutant measured. Small sample sizes tend to provide a less reliable estimate of variability than for comparable estimates of the median EMC discussed in the preceding section. Nevertheless, the median CV of the listed site CVs proves to be quite comparable for all of the pollutants in this summary. Values fall in the relatively narrow range between 0.62 and 0.92 for the different pollutants.

A review of the tabulated CVs indicates that with two exceptions, there is no consistent pattern of generally higher or lower CVs for all sites with a particular pollutant, or for all pollutants at a particular site. The Miami urban highway site shows consistently higher CVs for pollutants monitored than from all other sites. At the Efland, NC rural highway site a consistent pattern of unusually low values is exhibited. Since both of these sites monitored only three to five events for most of the pollutants, the abnormal levels of variability indicated were considered to be questionable, and the CV data from these sites were excluded from the analysis discussed below. In addition, two individual event values were also excluded from the analysis. TKN at the Spokane WA site (CV + 5.61), and Lead at the Phase 2 Harrisburg PA site (CV + 3.84), were excessively high and judged to be outliers.

The excluded data are probably poor estimates of typical EMC variability, but even if they are good estimates for the particular site, they reflect rarely encountered conditions. Since the objective of this analysis was to develop an estimate of the event-to-event variability of the EMCs of any pollutant, at any highway site, the above deletions were made and all of the remaining CVs for all pollutants were pooled together for analysis.

An overall estimate of the event-to-event variability of EMCs for any pollutant at any highway site was developed by evaluating the probability distribution of this large sample of CV

Table 6. Pollutant concentrations in highway runoff.
site median concentration in mg/l

(A) URBAN HIGHWAYS
AVERAGE DAILY TRAFFIC MORE THAN 30,000 VEHICLES PER DAY

POLLUTANT	COV of SITE MEDIANS	10% of Sites LESS THAN	MEDIAN SITE	10% of Sites MORE THAN
TSS	0.62	68	142	295
VSS	0.58	20	39	78
TOC	1.02	12	25	52
COD	0.58	57	114	227
NO2+3	0.56	0.39	0.76	1.48
TKN	0.45	1.05	1.83	3.17
PO4-P	0.89	0.15	0.40	1.07
COPPER	0.68	0.025	0.054	0.119
LEAD	1.45	0.102	0.400	1.564
ZINC	0.44	0.192	0.329	0.564

(B) RURAL HIGHWAYS
AVERAGE DAILY TRAFFIC LESS THAN 30,000 VEHICLES PER DAY

POLLUTANT	COV of SITE MEDIANS	10% of Sites LESS THAN	MEDIAN SITE	10% of Sites MORE THAN
TSS	1.17	12	41	135
VSS	0.62	6	12	25
TOC	0.62	3	8	24
COD	0.45	28	49	85
NO2+3	0.57	0.23	0.46	0.91
TKN	0.83	0.34	0.87	2.19
PO4-P	1.02	0.06	0.16	0.48
COPPER	0.72	0.010	0.022	0.050
LEAD	1.22	0.024	0.080	0.272
ZINC	0.73	0.035	0.080	0.185

Table 7. Coefficient of variation of site EMC s.

SITE NO.	STATE CODE		SS	VSS	TOC	COD	NO2+3	TKN	PO4-P	Cu	Pb	Zn
1	AR-1	LITTLE ROCK I-30	0.56	0.95		0.83	1.28			0.50	0.52	0.67
2	CA-1	LOS ANGELES I-405	1.74			1.10		0.95	0.98		0.75	0.99
3	CA-2	SACRAMENTO HWY 50	0.76	0.47	0.56	0.56	0.91	0.86	0.69	0.74	0.97	0.49
4	CA-3	WALNUT CREEK I-680	0.70			0.77		0.43	0.42		1.03	0.46
5	CO-1	DENVER I-25	0.58	1.01	0.65	0.68		0.77	0.51	0.97	0.57	0.59
6	FL-1	BROWARD CO HWY 834	1.16		1.00	0.91	0.85	0.92	0.68	1.01	0.60	0.83
8	FL-2	MIAMI I-95	1.70	2.57	2.16	1.15	1.22	2.26	0.67	1.34	1.10	1.10
11	MN-1	MINNEAPOLIS I-94	1.38		0.78			0.74	0.78	1.15	1.24	
12	MN-2	ST PAUL I-94	0.92		0.81			0.75	0.90	0.72	0.81	
13	NC-1	EFLAND I-85	0.67	0.22	0.12	0.43	1.86	0.31	0.24	0.39	0.82	0.27
14	PA-1	HARRISBURG I-81	1.65	1.46	0.34	0.42		1.24	0.82	0.94	0.24	0.82
15	PA-2	HARRISBURG I-81	1.21	0.94	0.28	0.40	0.71	0.58	0.68	0.77	3.84	0.50
17	TN-1	NASHVILLE I-40	0.57	1.10	0.58	0.60		1.02	0.56	0.88	0.90	0.46
18	WA-5	MONTESANO SR-12	0.86	0.70	1.59	0.99	1.28	0.60	0.73	1.87	1.10	1.50
19	WA-6	PASCO SR-12	1.49	0.90	1.54	0.62	0.66	0.56	0.49	0.59	1.02	0.84
21	WA-9	PULLMAN SR-270E	1.41	1.07	1.57	1.23	0.72	0.56	0.91	0.45	1.28	0.93
23	WA-1	SEATTLE I-5	0.80	0.80	1.10	0.68	0.71	0.65	0.65	0.74	0.76	0.79
25	WA-2	SEATTLE SR-520	0.75	0.87	0.35	0.91	0.98	0.61	0.57	0.34	0.81	0.88
26	WA-4	SNOQ. PASS I-90	0.74	0.98	1.22	0.79	0.67	0.72	0.72	0.33	0.87	1.18
27	WA-7	SPOKANE I-90	0.95	0.69	0.63	0.40	1.23	5.61	0.61	0.43	1.12	1.68
28	WA-3	VANCOUVER I-205	0.82	0.64	1.12	0.97	1.01	1.40	0.66	0.51	0.93	0.67
29	WI-1	MILWAUKEE HWY 45	0.57	0.74	0.37	0.35	0.43	0.64	0.57	0.69	0.37	0.34
30	WI-2	MILWAUKEE I-794	0.71	0.62	0.79	1.08		0.54	0.44	0.78	0.44	0.56
31	WI-3	MILWAUKEE I-94	1.02	0.86	1.14	0.74	0.57	0.50	0.60	0.57	1.19	0.73
		Mean	0.99	0.94	0.93	0.76	0.95	0.95	0.65	0.76	0.96	0.79
		Median	0.92	0.83	0.73	0.71	0.88	0.79	0.62	0.69	0.84	0.71
		COV	0.38	0.51	0.80	0.40	0.39	0.65	0.31	0.47	0.56	0.47
		Number of Sites	24	19	21	22	16	23	23	22	24	22

data. This is shown in the upper left-hand plot in figure 17, which uses the entire set of pooled data. The two plots on the right examine potential differences when sites are grouped into urban highways (ADT > 30,000) and nonurban highways (ADT < 30,000). The box plots in the lower left quadrant show the grouped data in this format, and the 90 percent confidence intervals for the median.

The event-to-event CV for any pollutant was treated as a lognormally distributed random variable. The range into which most values fell was relatively small (the CV of the individual CV values is only about 0.4). There was a small but statistically significant difference between urban highways with an ADT of more than 30,000 vehicles per day, and rural highways with an ADT of less than 30,000 vehicles per day. The urban highways exhibited lower event-to-event EMC variability, with a median CV of 0.71. For the rural highways, the median CV was 0.84. Both of these results compare quite well with the typical value of 0.75 estimated by the NURP study (17) for pollutants in urban runoff.

3.7 OTHER POLLUTANTS

Certain water quality parameters addressed in monitoring programs of the sources that were accessed were not incorporated in the general summary presented earlier in sections 3.5 and 3.6, and used for overall site comparisons. The two reasons for separate treatment were (1) not enough sites monitored the parameter to provide an acceptable basis for inclusion in the general analysis, or (2) the water quality parameter, per se, does not have significant potential for negatively impacting water quality.

Table 8 tabulates the site median EMCs and table 9 lists the CVs of these additional pollutants along with statistical summaries. The following discussion addresses the available data on these "other" pollutants.

Total Solids (TS) - measures the total of all particulate and dissolved contaminants in a sample. TS has no environmental significance, of itself, unless concentration levels are excessive, and high enough to alter the salinity regime of a receiving water. Less than half the study sites monitored TS, and for the non-snowmelt periods reflected by the basic data set, the concentration levels reported do not suggest cause for concern.

Chloride ion (Cl) - is analogous to TS in terms of environmental significance. With about two-thirds of the study sites monitoring chloride in the stormwater runoff, confidence in estimates of typical concentration levels is improved. Levels in runoff are low and of no environmental significance.

pH - was recorded for runoff at 75 percent of the study sites. It averages 6.5, with a range of 5.5 to 7.5 at different sites. Levels in this range have no significant potential for causing water quality problems.

Iron - was monitored at only about half the study sites. Results indicate runoff concentrations in a range of about 3 to 12 mg/l. This level is relatively high compared with typical concentrations at which iron is present in virtually all natural waters. However, it is essentially all in the particulate form, and even the dissolved forms of iron compounds are not known to be harmful.

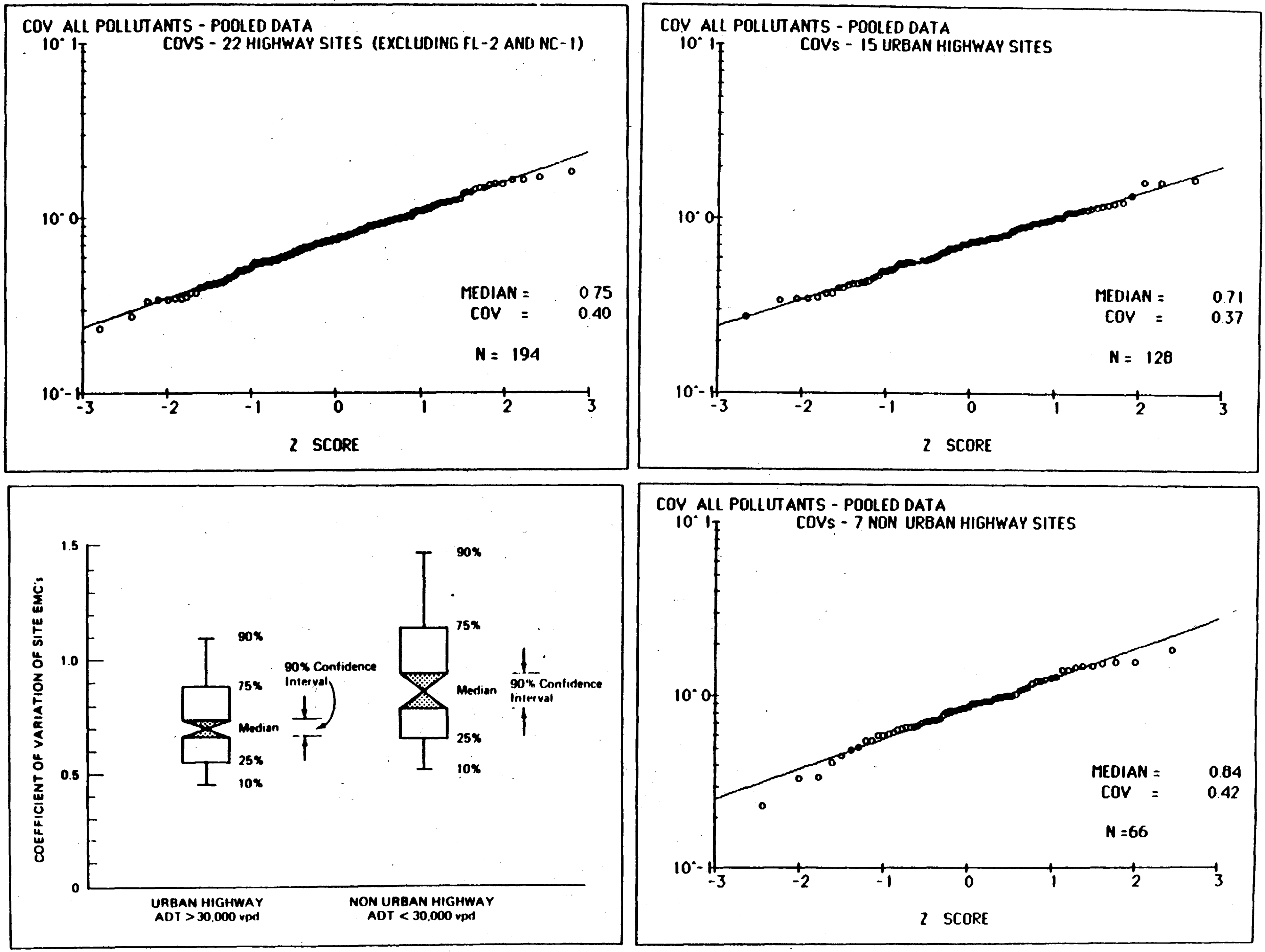


Figure 17. Pooled coefficients of variation of pollutant runoff concentrations summary.

Table 8. Other pollutants site median concentrations.

SITE NO.	STATE CODE		TS (mg/l)	CL (mg/l)	O&G (mg/l)	BOD (mg/l)	pH	Cd (mg/l)	Cr (mg/l)	Fe (mg/l)	Hg (ug/l)
1	AR-1	LITTLE ROCK I-30		6			6.6			2.90	
2	CA-1	LOS ANGELES I-405			8			0.006			
3	CA-2	SACRAMENTO HWY 50	184	7	9		6.9	0.012	0.012	3.23	0.001
4	CA-3	WALNUT CREEK I-680			11			0.001			
5	CO-1	DENVER I-25	655	29		55	6.9	0.019	0.024	14.32	0.886
6	FL-1	BROWARD CO HWY 834				6		0.001		0	
8	FL-2	MIAMI I-95	287					0.002	0.014		
11	MN-1	MINNEAPOLIS I-94		10							
12	MN-2	ST PAUL I-94		13							
13	NC-1	EFLAND I-85	187	28	4		6.4	0.001	0.002	2.42	
14	PA-1	HARRISBURG I-81 (Ph. 1)	384	60		3	7.5	0.022	0.016	0.99	0.831
15	PA-2	HARRISBURG I-81 (Ph. 2)	485	32			6.8	0.007	0.019	7.58	0.281
17	TN-1	NASHVILLE I-40	429	17		22	7.6	0.024	0.019	4.89	1.330
18	WA-5	MONTESANO SR-12 (5)					5.6				
19	WA-6	PASCO SR-12 (6)					6.0				
21	WA-9	PULLMAN SR-270E (9)		9			5.4				
23	WA-1	SEATTLE I-5 (1)		2	53		6.1				
25	WA-2	SEATTLE SR-520 (2)		4			5.6				
26	WA-4	SNOQ. PASS I-90 (4)		1			6.5				
27	WA-7	SPOKANE I-90 (7)					6.0				
28	WA-3	VANCOUVER I-205 (3)		2			6.2				
29	WI-2	MILWAUKEE HWY 45	905	168		15	7.6	0.029	0.036	11.72	1.551
30	WI-3	MILWAUKEE I-794	359	39		19	7.2	0.032	0.032	6.22	1.368
31	WI-1	MILWAUKEE I-94	393	51	7		6.8	0.011	0.018	6.03	0.002
		MEAN of all sites	432	33	15	23	6.5	0.017	0.022	7.63	15.429
		MEDIAN of all sites	382	13	10	14	6.5	0.007	0.016	3.47	0.189
		COEF of VAR of site medians	0.53	2.33	1.08	1.32	0.11	2.10	1.02	1.96	81.55
		NUMBER of SITES	10	17	6	6	18	13	10	11	8

Table 9. Other pollutants coefficient of variation of site EMC s.

SITE NO.	STATE CODE		TS	CL	O & G	BOD	Cd	Cr	Fe	Hg
1	AR-1	LITTLE ROCK I-30		0.89		1.08			0.84	
2	CA-1	LOS ANGELES I-405			0.19		1.11			
3	CA-2	SACRAMENTO HWY 50	0.49	0.84	0.63		0.98	1.09	0.87	1.06
4	CA-3	WALNUT CREEK I-680			0.39					
5	CO-1	DENVER I-25	0.52	0.82		1.11	0.82	0.84	0.57	1.60
6	FL-1	BROWARD CO HWY 834				0.75	0.31		0.71	
8	FL-2	MIAMI I-95	1.86				0.59	0.24		
11	MN-1	MINNEAPOLIS I-94		2.74						
12	MN-2	ST PAUL I-94		1.36						
13	NC-1	EFLAND I-85	0.72	1.55	1.30		0.58	1.17	0.70	
14	PA-1	HARRISBURG I-81 (Ph. 1)	0.47	0.96		0.59	0.78	0.95	1.61	3.55
15	PA-2	HARRISBURG I-81 (Ph. 2)	0.72	0.94			0.64	2.21	0.75	12.4
17	TN-1	NASHVILLE I-40	0.43	0.78		0.78	0.71	0.65	0.58	0.80
18	WA-5	MONTESANO SR-12 (5)								
19	WA-6	PASCO SR-12 (6)								
21	WA-9	PULLMAN SR-270E (9)		0.33						
23	WA-1	SEATTLE I-5 (1)		0.70	3.85					
25	WA-2	SEATTLE SR-520 (2)		1.70						
26	WA-4	SNOQ. PASS I-90 (4)								
27	WA-7	SPOKANE I-90 (7)								
28	WA-3	VANCOUVER I-205 (3)		0.84						
29	WI-1	MILWAUKEE HWY 45	0.51	1.04		0.64	0.96	1.37	0.52	4.93
30	WI-2	MILWAUKEE I-794	0.61	1.47		0.81	0.65	1.30	0.70	3.17
31	WI-3	MILWAUKEE I-94	0.89	2.53	1.01		1.02	1.72	0.95	7.49
		Mean	0.72	1.23	1.35	0.78	0.77	1.22	0.80	4.76
		Median	0.65	1.07	0.79	0.76	0.73	1.01	0.76	3.03
		COV	0.46	0.56	1.39	0.22	0.36	0.68	0.32	1.22
		Number of Sites	10	16	6	7	12	10	11	8

Oil and Grease (O & G) - was monitored at only a few of the sites, and at these for relatively few of the total events. Typical concentration levels are in the order of 5 to 10 mg/l. Much of this is expected to be in particulate form, and/or adsorbed on suspended solids. While the concentration levels deserve consideration, there is no evidence that either the quantity or the form in which these substances are present in highway runoff has created any visual or water quality problems.

BOD - was monitored at only six of the study sites. The Denver site may be an outlier, with the quite high site median of 55 mg/l. The other sites range between about 5 and 25 mg/l.

Cadmium - was monitored at 13 sites. The CVs are all in the range typical of other pollutants in highway runoff, which lends credibility to the reported data, even though concentrations are quite low. Site median concentrations range from 1 to about 30 micrograms per liter. For comparison, the average concentrations observed at three highways in the FRG, Federal Republic of Germany, (22) were between 3 and 6 micrograms per liter.

Chrome - was monitored at 10 sites. Site median concentrations are generally in the range of about 15 to 35 micrograms per liter, and event-to-event EMC variability is for the most part comparable to the CV values recorded for the bulk of the data. The concentration levels shown are probably good estimates. The three FRG sites (22) had averages between 5 and 20, and a highway site in Maitland, Florida (23) produced values between 6 and 9 micrograms per liter. The form of the chrome present in the runoff is almost certainly not the highly toxic reduced form (Cr+6) found in plating wastes, but rather the oxidized chromate ion which is significantly less toxic.

Mercury - was monitored at eight of the study sites. Site median concentrations ranged between 0.001 and 1.5 micrograms per liter. The excessively high CVs for the EMCs at most of the sites raise doubts about the analytical precision of the very low concentration levels reported.

3.8 SNOW WASHOFF EVENTS

As previously indicated, some of the monitored events at sites in States where snowfall occurs represent the results of rainfall on snowpack or snowpack melt. These events were identified and segregated based upon an inspection of event chloride and total solids concentrations and were confirmed by notations in original field records, project reports, or the data sets themselves. It must be emphasized at the outset that these are not snowmelt events in the strict sense of the word, i.e., they did not result solely from melting snow. In many instances the snow pack had been on the ground for some time, and some of the original snowfall moisture had been lost due to evaporation and melting, thereby tending to concentrate any pollutants present, especially those in particulate form. The rainfall that gave rise to a monitored snowmelt runoff event undoubtedly caused some additional melting and carried much of the accumulated pollutant load with it.

A summary of the site median concentrations for snow events is given in table 10. This summary is analogous to that presented earlier in table 5 for the bulk of the data where snow events were excluded. Since these are rarely occurring events, the sample sizes are much smaller than those that were used in computing the rain event results. The data for nearly half of the sites in table 10 were computed from five or fewer monitored events and, as a result, have much wider

Table 10. Site median concentrations for snow events.

SITE NO.	STATE CODE	SS (mg/l)	VSS (mg/l)	TOC (mg/l)	COD (mg/l)	NO2+3 (mg/l)	TKN (mg/l)	PO4-P (mg/l)	Cu (mg/l)	Pb (mg/l)	Zn (mg/l)
1	AR-1	61	12		170	1.69			0.036	0.202	0.303
11	MN-1	175		28			1.61	0.44	0.078	0.416	
12	MN-2	200		48			2.73	0.93	0.122	1.579	
13	NC-1	11	5	16	26	0.24	8.00	0.14	0.023	0.020	0.127
14	PA-1	102	20	22	42	1.09	1.32	0.46	0.062	0.165	0.165
18	WA-5	1202			250			2.33			
19	WA-6	155	48	28	173	0.84	1.39	0.67	1.000	0.300	0.259
21	WA-9	465	46		171			1.45	0.040	0.378	0.310
23	WA-1	150	49		110	1.06	0.61	0.48	0.063	0.524	0.402
25	WA-2	435	103	43	250	0.48	1.71	0.71	0.094	2.004	0.577
26	WA-4	124	23	8	56	0.37	0.42	0.27	0.023	0.168	0.113
27	WA-7	752	139	14	509	1.15	6.77	1.81	0.136	1.213	6.786
28	WA-3	114	25		45	0.36	0.28	0.26	0.050		0.086
29	WI-1	375	94	63	265	0.56	2.82	0.57	0.196	1.510	0.750
30	WI-2	701	139	85	530		7.57	1.06	0.285	6.239	1.415
31	WI-3	240	178			0.82	4.64	0.16	0.233	2.285	1.537
	Mean	388	78	37	220	0.81	3.49	0.81	0.154	1.606	0.901
	Median	204	44	28	138	0.68	1.94	0.57	0.091	0.549	0.420
	COV	1.61	1.46	0.85	1.23	0.66	1.50	1.01	1.37	2.75	1.90
	N	16	13	10	13	11	13	15	15	14	13

confidence intervals associated with them (i.e., we are much less certain about the true value of the site median). To remedy this situation and facilitate a comparison of pollutant discharges during snow and rain events, table 11 was constructed. In this table, urban and non-urban highway sites have been segregated. The entries in table 11 represent the ratio of the site median concentration from snow events to the site median concentration produced by rainfall events. Thus, the entries in the table represent multipliers that convert median rain event data to median snow event data for each site. As an example, for the Minneapolis site (MN-1), the median EMC of suspended solids for snow events is 3.43 times the median EMC of suspended solids for rain events.

Since the EMCs at a site could be considered to be lognormally distributed, it follows that their ratios could also be represented as lognormally distributed. Therefore, the mean, median, and coefficient of variation values across all of the sites in table 11, which are given at the bottom of each portion of the table, were calculated based on a lognormal distribution. In the following discussion, attention will primarily be focused on the results for the urban sites. There are two main reasons for doing so. First, the sample sizes in the nonurban data set tend to be much smaller, and hence, the data are less reliable. Second, if water quality impacts are to be found from this class of events, it is believed that they will primarily occur in an urban setting.

An examination of the quantity data indicates that the median rainfall amount for the snow events is less than that for the rain events (i.e., it is a little over 80 percent of that for rainfall events). However, the median duration is almost twice as long. This means that the rainfall for the monitored snow events was much less intense than that for the rain events. The median total runoff is a little less (88 percent) for snow events, but the median runoff coefficient is about 25 percent higher. This latter observation is reasonable in light of the fact that the ground will tend to be either frozen or saturated during snowmelt/washoff events, thus increasing the effective runoff.

For the pollutant concentrations, the median concentration of suspended solids during snow events averages about twice that in rain events (snow/rain = 2.09 for SS, and 2.02 for VSS). The same is true for the oxygen demand indicators (snow/rain = 1.93 for COD, and 2.31 for TOC). With respect to nutrients, there is little difference in nitrate plus nitrite concentrations between snow and rain events. This is probably because these constituents largely occur in the dissolved form. However, for TKN and phosphorus, the median concentration in snow events averages about 75 percent more than that in rain events (snow/rain = 1.71 for TKN, and 1.74 for P04-P). The multiplier for median metals concentrations is closer to 2.5 (2.42 for copper, 2.78 for lead, and 2.21 for zinc). As can be noted, the data for the nonurban sites tend to follow these generalizations, although with somewhat more variability.

Site median concentrations for the "other" pollutants are tabulated in table 12 but the values listed are based on very few observations. For this reason the corresponding ratio data for the other pollutants is not presented. With the exception of total solids and chlorides (understandable in view of the use of chloride containing de-icing chemicals), the multipliers are on the same order as those found for the pollutants in table 11.

An analysis of the variability of EMCs during snow events indicates that it is essentially the same as during rain events. For example, the ratios of the median CVs across all snow sites to those across all rain sites are 1.05 for SS, 1.01 for VSS, 1.14 for COD and P04-P, 1.06 for copper, and 1.08 for lead. For all practical purposes, we can assign the same coefficient of

Table 11. Site median EMC ratio snow events / rain events.

URBAN SITES

SITE	CODE	RAIN	DUR.	RUNOFF	Rv	SS	VSS	TOC	COD	NO2+3	TKN	PO4-P	Cu	Pb	Zn
1	AR-1	0.92	3.69	2.12	0.69	0.54	0.59		1.82	2.37			1.96	1.87	1.82
11	MN-1	1.02		1.03	3.93	3.43		1.89			1.54	1.93	3.82	3.59	
12	MN-2	0.29		0.08	0.74	2.36		2.44			1.75	2.17	4.02	3.88	
23	WA-1	0.69	0.65	0.91	1.27	1.62	1.87		1.04	1.28	0.68	2.19	1.70	1.16	1.05
25	WA-2	2.22	2.33	2.22		1.79	1.75	1.32	1.72	0.61	1.56	1.70	1.30	1.88	2.06
27	WA-7	2.72	1.67	3.33		6.34	4.72	1.34	3.27	1.04	4.01	2.09	3.35	7.02	2.35
29	WI-1	0.57	2.03	1.13	1.96	1.12	1.32	1.97	2.39	0.73	1.02	1.37	2.62	2.05	2.02
30	WI-2	0.62	2.60	0.55	0.89	5.00	2.97	3.18	6.03		4.08	3.70	3.22	4.28	4.22
31	WI-3	0.44		0.41	0.93	1.67	3.77			1.03	1.50	0.51	1.50	2.79	3.30
	Mean	1.07	2.28	1.63	1.49	2.78	2.58	2.04	2.77	1.19	2.06	2.05	2.65	3.22	2.44
	Median	0.82	1.91	0.88	1.22	2.09	2.02	1.93	2.31	1.06	1.71	1.74	2.42	2.78	2.21
	COV	0.83	0.65	1.57	0.69	0.88	0.80	0.35	0.66	0.50	0.68	0.62	0.44	0.59	0.47

NONURBAN SITES

SITE	CODE	RAIN	DUR.	RUNOFF	Rv	SS	VSS	TOC	COD	NO2+3	TKN	PO4-P	Cu	Pb	Zn
13	NC-1	0.59		0.61	1.63	0.70	0.83	0.67	0.39	1.26	4.76	1.13	0.61	1.82	2.54
14	PA-1	0.87	0.45	0.45	1.20	4.08	2.50	2.00	1.35	1.79	1.16	1.71	2.14	1.81	3.23
19	WA-6	1.00	0.49	0.84	0.90	1.53	1.92	2.60	1.52	1.04	0.42	1.40		2.97	0.80
21	WA-9	0.56	1.47	0.43	1.41	4.47	2.19		2.85			3.37	1.54	2.91	3.13
26	WA-4	1.61	0.77	1.91	1.18	2.88	2.56	4.00	1.37	0.70	1.11	2.16	0.92	2.58	1.59
28	WA-3	0.81	0.60	0.83	1.05	3.35	2.78		1.41	0.80	0.47	2.65	2.94		2.15
	Mean	0.91	0.77	0.85	1.23	3.08	2.20	2.58	1.58	1.13	1.67	2.10	1.72	2.43	2.33
	Median	0.85	0.68	0.73	1.21	2.39	1.99	1.93	1.28	1.06	1.04	1.93	1.40	2.36	2.03
	COV	0.40	0.50	0.59	0.21	0.81	0.47	0.89	0.72	0.39	1.25	0.42	0.70	0.25	0.56

Table 12. Site median concentrations for snow events - other pollutants.

SITE NO.	STATE CODE	TS (mg/l)	CL (mg/l)	O & G	BOD (mg/l)	pH	Cd (mg/l)	Cr (mg/l)	Fe (mg/l)	Hg (ug/l)
1	AR-1		421			7.1			4.29	
11	MN-1		443							
12	MN-2		605							
13	NC-1	1560	928			6.5	0.007	0.003	0.43	
14	PA-1	1447	552		5	7.3	0.016	0.020	3.83	7.541
18	WA-5					5.9				
19	WA-6		39			5.8				
21	WA-9					4.3				
23	WA-1		2			5.5				
25	WA-2		2			5.6				
26	WA-4		3			6.6				
27	WA-7		145			6.1				
28	WA-3		4			5.6				
29	WI-1	3594	1672		34	7.5	0.053	0.044	12.62	0.824
30	WI-2	3238	1131		64	7.5	0.088	0.071	20.50	0.758
31	WI-3	9432	5575			7.2	0.021	0.018	9.81	
	Mean	4020	5621		56	6.3	0.042	0.042	13.087	3.917
	Median	3012	122		22	6.3	0.025	0.020	5.120	1.676
	COV	0.88	46.24		2.38	0.15	1.31	1.82	2.35	2.11
	N	5	14	0	3	14	5	5	6	3

variation for both snow and rain events. The few exceptions are all less than unity (e.g., 0.71 for TOC, 0.62 for NO2+3 and TKN, 0.68 for zinc), so taking the ratio to be unity will result in a conservative assessment.

To summarize, if one wishes to estimate median values for snow events and has no monitoring data for a site, a reasonable first approximation can be obtained from the data for rain events by using the same quantity data, and adjusting the quality data as indicated above. For a conservative first estimate, double the median EMC values for all constituents except metals, which should be tripled. In assessing receiving water impacts, these data should be used in the same way that a seasonal analysis would be conducted. For example, the population of stream flows considered should be only those that occur during snow events, etc. Because snow events certainly will be much fewer in number than rain events, and receiving water conditions when they occur will be relatively favorable (e.g., high stream flows, low temperatures), we believe that signnificant receiving water impacts due to snow events will not be a commonplace occurrence.

4.0 FACTORS THAT INFLUENCE HIGHWAY RUNOFF CHARACTERISTICS

4.1 INTRODUCTION

This section presents the evaluation of factors that influence the characteristics of the reported highway runoff quality and quantity. Section 4.2 discusses the determination of runoff coefficients. The effects and magnitudes of measurement errors is presented in section 4.3. Section 4.4 discusses the effect of storm size on runoff characteristics. The relationship between average daily traffic and runoff characteristics is presented in section 4.5. The relationships between observed suspended solids other water quality parameters is presented in section 4.6. Section 4.7 presents a summary listing and discussion of the range of mechanisms and factors that have been postulated to influence highway runoff pollutant loading.

4.2 HIGHWAY RUNOFF VOLUME AND RUNOFF COEFFICIENT

A determination of the relationship between rainfall and the amount of runoff from a highway site is required because:

- Runoff volumes must be estimated in order to determine mass loads.
- Monitoring programs are usually restricted to a small sample of sites, and at such sites, to a small sample of storm events.
- Long-term predictions of runoff volumes and pollutant loads must be based on rainfall records (which are available), rather than runoff records (which are not).

Since runoff is caused by rainfall (except possibly snowmelt events), one would expect a very strong correlation between rainfall and runoff data at a site. As an example, the results of a regression of runoff on rainfall for the Sacramento site (CA-2) are given in figure 18. Recognizing the difficulties encountered in measuring runoff flows, the data correlate extremely well (R squared = 0.979). Considering the form of the regression equation (y = ax + b), the value of b is expected to be a very small number since it represents dependence of runoff on rainfall. In other words, when there is no rainfall, we would not expect there to be any runoff; the regression line should have a zero intercept and b should be zero. In this example, an F test showed the value of b (-0.018) to be indistinguishable from zero at the 99.9 percent confidence level. Thus, the relationship at this site can be written as

$$\text{Runoff} = 0.88 \times \text{Rainfall} \tag{7}$$

The value obtained by dividing runoff by rainfall is the runoff coefficient, Rv. It represents the fraction of rainfall that would be expected to run off at a site, on average. The strength of the

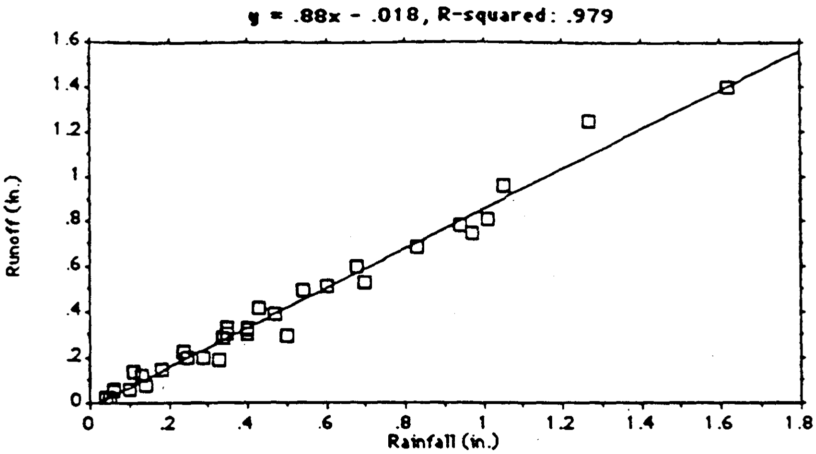


Figure 18. Runoff vs rainfall for CA-2 Sacramento Hwy 50.

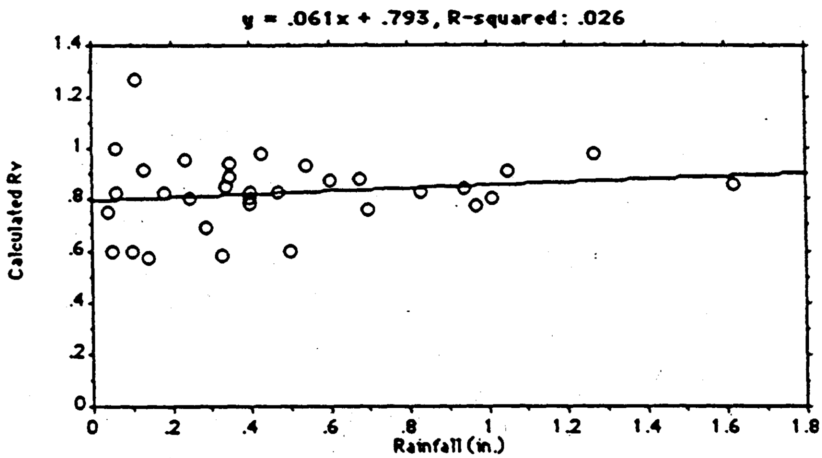


Figure 19. Runoff coefficient vs rainfall for CA-2 Sacramento Hwy 50.

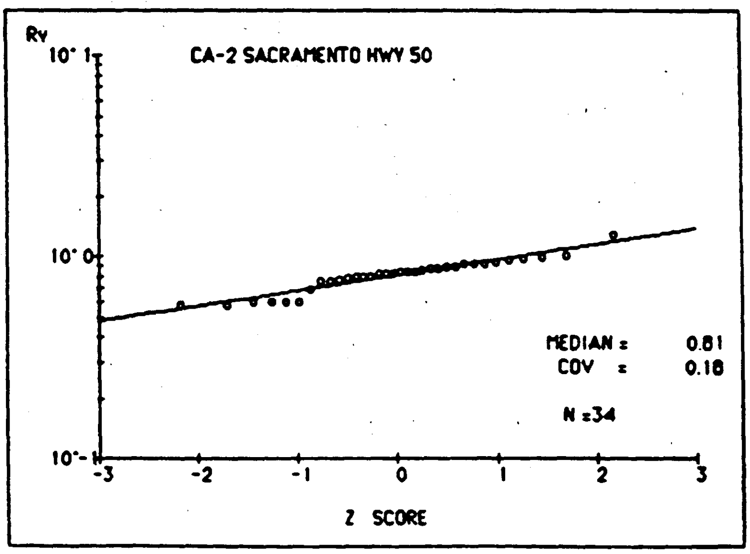


Figure 20. Probability distribution of R_v values at site CA-2.

linear relationship implies that the runoff fraction is independent of storm size or other factors, and can be treated as a constant. In this case, Rv = 0.88.

There are a number of reasons why the value of the runoff coefficient might vary in a predictable way with rainfall characteristics, and some models account for such factors. For example, larger more intense storms would be expected to produce a higher fraction of runoff. However, other factors tend to modify or dilute such effects on an event basis. In these models, antecedent conditions are usually accounted for to reflect the expectation of more runoff from a storm that occurs shortly after a heavy rain, than from a storm of the same magnitude that occurs following an extended dry period.

However, the regression data at the Sacramento site suggest that the runoff fraction may be properly treated as a constant ratio. This can be tested further by calculating the values of the runoff coefficient for each event at a site and then regressing the Rv's on rainfall. For the same Sacramento site, this analysis is shown in figure 19. The slope of the regression line is nearly zero, which supports the previous indication that the runoff coefficient is independent of rainfall amount. In fact, for this site the probability that the slope is nonzero is less than 0.0001. Therefore, the runoff coefficient at this site can be estimated to be 0.88, though there is some variability in the value as shown in figure 19.

Note in figure 19 that the spread in runoff coefficient values decreases as rainfall increases. This is a typical characteristic of such plots and is largely a result of the runoff measurement process. Rainfall is usually measured with a recording rain gage (e.g., a tipping bucket), and measurement accuracy tends to be independent of rainfall amount. However, the point measurement of rainfall at a gage is assumed to reflect the average over the catchment that contributes the runoff. The accuracy of this assumption is likely to be higher for large storms than for small ones. In addition, stormwater flow measurement is difficult, and especially so for small runoff quantities. Some of the errors in flow measurement tend to be independent of flow (or are expressed as a percent of full scale) and, hence, have a larger effect on accuracies at low flow rates. These factors are probably responsible for the scatter pattern observed in figure 19.

If the variability in Rv values is not strongly related to storm size, and can be considered to be random variations due to measurement errors and compensating physical factors, an estimate of the true value can be obtained from an examination of the probability distribution of the observed values. Figure 20 indicates that the variable Rv values at this site (with an impervious area of 82 percent) can be represented as lognormally distributed, that the most probable value for Rv is 0.81, and that the variability from storm to storm is relatively small, having a CV of only 0.18.

The foregoing analyses were repeated for each of the highway sites for which there were sufficient data, and the results are summarized in table 13. The foregoing observations are, with a few exceptions, generally true for all of the sites. The worst case was the Harrisburg site (PA-1), and its regression results are depicted in figure 21. In the upper portion, the results of regressing runoff on rainfall suggest that there is no runoff at this site for rainfall values less than about one-third of an inch. Although some initial abstraction might be expected, this value seems excessively large. A problem with flow measurement at this site is a distinct possibility. The regression of Rv on rainfall given in the lower portion of figure 21 indicates that the runoff coefficient varies directly with rainfall, the b term being only 0.008. The R-squared value, although

Table 13. Site runoff coefficient analysis summary.

		RO on Rainfall y = ax + b			Rv on Rainfall y = ax + b			Computed Rv Statistics			%
		a	b	R^2	a	b	R^2	Mean	Median	COV	Imp.
AR-1	Little Rock	0.776	-0.121	0.907	0.182	0.416	0.124	0.76	0.35	1.92	90%
CA-2	Sacramento	0.880	-0.018	0.979	0.061	0.793	0.026	0.82	0.81	0.18	82%
CO-1	Denver	0.598	-0.063	0.869	0.371	0.211	0.424	0.36	0.31	0.54	37%
FL-1	Broward Co.	0.194	-0.006	0.901	0.011	0.172	0.013	0.18	0.17	0.46	36%
MN-1	Minneapolis	0.277	-0.006	0.656	0.106	0.167	0.061	0.22	0.14	1.24	55%
MN-2	St. Paul	0.577	-0.061	0.943	0.139	0.303	0.266	0.39	0.34	0.58	49%
NC-1	Efland	0.947	-0.213	0.939	0.217	0.386	0.283	0.66	0.46	1.04	51%
PA-1	H'burg. Ph-I	0.906	-0.312	0.798	0.489	0.008	0.560	0.44	0.30	1.65	27%
TN-1	Nashville	0.334	0.035	0.616	-0.024	0.414	0.006	0.41	0.35	0.58	37%
WA-5	Montesano	0.735	0.020	0.836	0.068	0.617	0.065	0.94	0.70	0.91	100%
WA-6	Pasco	0.714	0.013	0.889	-0.086	0.800	0.014	0.82	0.78	0.33	100%
WA-9	Pullman	0.408	0.020	0.608	-0.035	0.472	0.005	0.53	0.45	0.61	100%
WA-4	Snoq. Pass	0.694	-0.072	0.866	-0.019	0.726	0.042	0.68	0.65	0.32	100%
WA-1	Seattle I-5	0.810	-0.046	0.877	0.114	0.611	0.043	0.67	0.60	0.50	100%
WA-3	Vancouver	0.364	0.044	0.691	-0.035	0.462	0.010	0.46	0.38	0.69	100%
WI-2	Milw. 45	0.473	-0.061	0.782	0.138	0.254	0.094	0.33	0.29	1.64	31%
WI-3	Milw. 794	0.835	0.021	0.961	0.047	0.822	0.019	0.87	0.82	0.35	100%
WI-1	Milw. 94	0.870	-0.004	0.982	0.065	0.805	0.020	0.83	0.81	0.21	64%

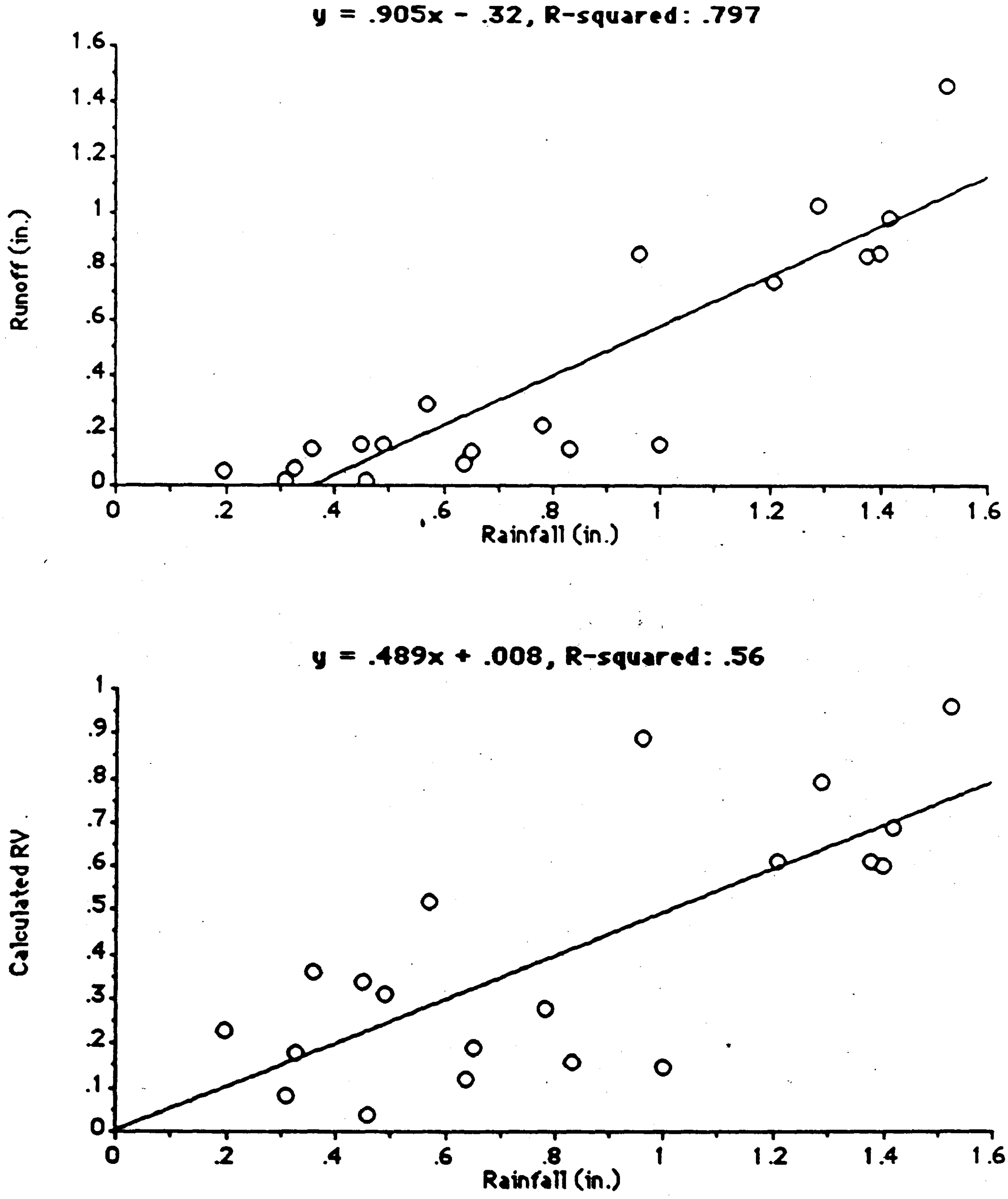


Figure 21. Runoff vs. rainfall and runoff coefficient vs. rainfall observed at the PA-1 Harrisburg site.

unusually large for this type of regression in general, suggests that the relationship can only explain a little over half of the observed variability.

In summary, the analyses suggest that, for the highway sites in the WDF, the runoff coefficient at a given site is independent of the rainfall amount and that its statistical parameters can be reasonably estimated from the monitoring data. This finding is consistent with that observed in the much larger urban runoff data base developed as a part of NURP (17).

The analyses support the assignment of a single runoff coefficient to a highway site. For a predictive model, we must estimate its value for any given site where we have no rainfall-runoff data. As indicated earlier, there are many possible influences on the runoff coefficient at a site, but based on previous studies on urban runoff, the most likely is the percent imperviousness of the site. To examine this possibility, the mean runoff coefficient values for each site in table 13 were regressed on each site's percent imperviousness. The results are depicted in figure 22. In view of possible flow measurement errors discussed earlier, sites with an area of about a quarter of an acre or less (actually those with median event runoffs less than about 400 cubic feet) were excluded from the regression. This led to dropping three sites (WA-9, WA-4, and WA-3). In figure 22, the 95 percent confidence bounds on the mean are also depicted. We note that, although there is certainly some scatter, the results (R = 0.83) indicate that percent imperviousness can be a reasonable predictor of runoff coefficient. This finding was also borne out by the NURP data (17).

The methodology adopted for us in the Design Procedures document uses the relationship shown by figure 22 to estimate runoff coefficient (Rv) from the impervious fraction of a highway site.

$$Rv = 0.007 * IMP + 0.10 \qquad (8)$$

where

Rv = Runoff coefficient
IMP = Impervious fraction of the highway drainage area (percent)

4.3 MEASUREMENT ERROR

Possible errors in the measurement of concentration data and their influence are the subject of this subsection. Possible errors in flow measurement and their influence were discussed earlier, in the analysis of rainfall and runoff data. Errors in reported concentration values fall into two separate categories, those associated with sample collection and handling and those associated with laboratory analytical technique. Both of these are examined in turn.

Gathering representative water quality samples from stormwater flows is not an easy task. Runoff flow and concentration characteristics can change rapidly over time and over wide ranges, much more than for sanitary sewage or treatment plant discharges. It is difficult to predict event occurrence, and when events do occur, the conditions for sampling are not ideal. Equipment has often been in a standby condition for some time and, unless proper maintenance procedures have been faithfully followed, malfunction can be commonplace. The collection of a flow weighted

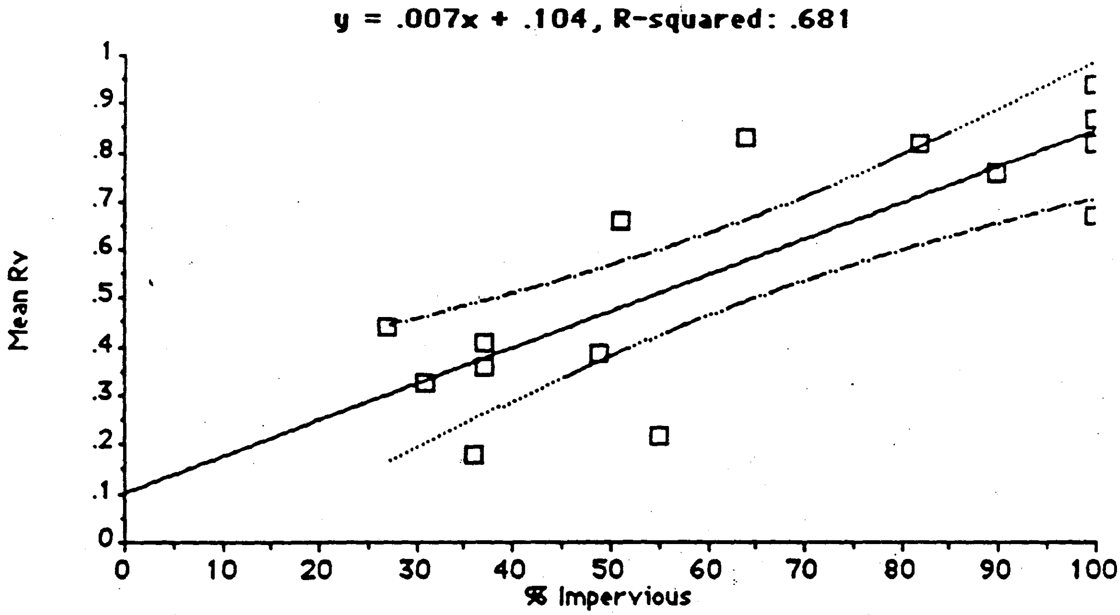


Figure 22. Regression plot of median and mean runoff vs. percent impervious.

sample depends upon the accuracy of the flow measurement device that is pacing the sampler (or the flow record that is being used for manual compositing of sequential discrete samples). Therefore, there can be considerable variability associated with field aspects of the measurement process. Field sample collection problems are compounded by the uncertainties associated with analytical determination in the laboratory.

Assuming that the sampling equipment functions properly (e.g., a sample is taken when it is supposed to be, the sample volume does not change with flow, the sample is not contaminated, the sample is held at an appropriate temperature until it is evaluated, etc.), there are still possibilities for error associated with the position of the sampling intake in the highway runoff flow and the sampling intake velocity. It is typical for stormwater runoff to contain relatively high concentrations of suspended solids compared, for example, to more conventional sanitary flows. Furthermore, the nature of the solids is different. In sanitary flows, a large fraction of the suspended solids is organic, and their specific gravities are fairly low, being on the order of 1.05 to 1.2. In stormwater runoff, by contrast, most of the suspended solids tend to be inorganic and much denser, with specific gravities frequently in the 2.0 to 2.6 range. This means that there will be considerable differences in particle momentum characteristics, vertical concentration gradients, fall velocities, and the like, all of which affect the ability to collect a representative sample. For example, with the heavier particles found in stormwater runoff it will be much more important to have nearly isokinetic sampling conditions in order to collect a representative sample. Sample intake velocities appreciably lower than the flow velocity will result in over-representation of suspended solids (and any other pollutants associated with them), while a sample intake velocity that is appreciably greater than the flow velocity will result in under-representation of the suspended solids. Since runoff flow velocities often vary from one to three orders of magnitude at a site, and most samplers have a constant intake velocity, some errors of this type are inevitable.

With regard to the placement of the sample intake in the flow stream, it is nearly impossible to find a location where the fluid will be well mixed over the entire range of flows so that a fixed sampling depth will yield representative samples. Concentration gradients will vary with flow rate, as will the depth of flow. Thus the most appropriate sampling depth will be changing nearly constantly. However, virtually all sampling installations have a fixed intake location. The potential errors mentioned above might tend to be offsetting to some extent so that, on average, they may tend to cancel out. Nevertheless, one can easily see that high variabilities are to be expected and that the direct comparison of two runoff samples will be difficult at best. For a more in-depth discussion of field sampling errors see Shelley [24].

A brief discussion of analytical problems in the laboratory follows. Once the sample is received by the laboratory, there is a similar problem to that encountered in the field in extracting representative aliquots (sub-samples) for analytical determination. Flow splitters have been developed recently that help to resolve this problem, but they generally were not available at the time the highway runoff data analyzed in this study were being gathered.

With any laboratory analytical determination for a pollutant, there are usually several acceptable methods. The final choice depends upon the expected pollutant concentration in the sample, possible interferences due to the presence of other compounds in the sample, the desired precision and accuracy of the results, the funding available for laboratory analysis, and the equipment available to the analyst. Each method has associated with it typical expected values for its precision and accuracy. These usually are a function of analyte concentration. The precision can vary considerably, especially at lower concentrations, and contribute to the overall variation found in concentration results. Refer to the current edition of Standard Methods [25] or the EPA Methods for Chemical Analysis of Water and Wastes [26] for a more in-depth discussion and typical precision and accuracy values for different constituents.

There are a number of sources of variation in EMCs apart from variations in the runoff stream itself, and these should be recognized in any data analysis methodology. In the Master Data File there were data from a site where an attempt was made to assess the validity of the field and laboratory procedures being employed. The sampling sites were immediately adjacent to one another and sampled from the same runoff flow. Therefore, differences in results cannot be attributable to differences in flow characteristics. These sites were established to monitor the runoff from Interstate 5 in Seattle and are designated as I-5 (the primary site) and I-5* (the check site). Taking only matched event data, i.e., events that were successfully monitored simultaneously at both sites, table 14 was constructed.

Consider first the pairs of phosphorus values. For some events they are virtually the same, while for others they are quite different. Where differences occur, the PO4-P values at the I-5* site seem to be greater as often as they are less when compared to those at the I-5 site. This observation is confirmed by the summary statistics given at the bottom of the columns. We tested the hypothesis that each sample set was drawn from the same underlying population (which was actually the case in the field). This was accomplished by conducting a paired t-test (two-tailed) to see if the difference between the means of the two samples was significantly different from zero. Since this test has the underlying assumption that the data are normally distributed, it was applied using the logarithms of the data. The result was that at the 90 percent confidence level the null hypothesis could not be rejected, i.e., we conclude that the means of the two samples were not significantly different.. This can be seen visually from the percentile comparison line chart and the cumulative frequency distribution chart for log of PO4-P and log of PO4-P* (*refers to I-5* file) given in figure 23.

Next a pairwise correlation of the event phosphorus concentrations was examined. This was done by regressing PO4-P* on PO4-P. Note that this regression was done in arithmetic space. (Had it been done in log space, we would in reality be fitting a power relationship.) The resulting scattergram is given in figure 24. Several things are evident. First, the correlation is virtually nonexistent (e.g., R-squared is only 0.00019). Second, the slope of the regression line is virtually zero (-0.012), not unity as would be expected for an exact match. Finally, the regression curve does not pass through the origin, which again would be expected for an exact match. What is evident is the effect of individual laboratory and field errors on the regression. It is important to note that when it was demonstrated statistically that the samples could not be proved to be drawn from the different populations, all of the data in each set were used to test the hypothesis. On the other hand, the regressions considered the sample concentrations pair-wise at a time, and the effects of the measurement errors became much more pronounced. For this reason, regression results for stormwater runoff data have varied much among investigators. This suggests that considerable caution is warranted in interpreting the results of such regressions (and correlations).

The foregoing analysis was next repeated for lead. Table 14 indicates that, unlike phosphorus, when the Pb* concentration was different from the Pb concentration for an event, it

Table 14. Comparison of concentrations at I-5 and I-5*.

DATE (MDY)	RAIN (in.)	DUR. (hr.)	Rv	Rv*	SS (mg/l)	SS* (mg/l)	COD (mg/l)	COD* (mg/l)	PO4-P (mg/l)	PO4-P* (mg/l)	Cu (mg/l)	Cu* (mg/l)	Pb (mg/l)	Pb* (mg/l)	Zn (mg/l)	Zn* (mg/l)	VSS (mg/l)	VSS* (mg/l)
90380	0.52	16.00	0.30	0.12	167	97	211	140	0.450	0.170		0.060		0.700		0.670	42	29
90780	0.15	9.00	0.03	0.45	29	30	139	128	0.670	0.140	0.050	0.050	0.310	0.360	1.020	0.980	11	16
91580	0.17	9.00	0.02	0.41	41	41	130	134	0.170	0.110	0.050	0.040	0.320	0.500	2.580	2.550	11	25
92380	0.25	6.00	0.24	0.69	120	76	244	136	0.260	0.240	0.050	0.040	0.860	0.580	0.910	1.040	50	42
93080	0.36	7.00	0.31	0.49	169	168	253	187		0.160	0.060	0.060	0.880	0.960	0.880	0.980	65	69
100980	0.14	7.00	0.24	0.29	104	112	169	177	0.350		0.050	0.060	0.720	0.890	1.200	1.610	44	45
101380	0.22	7.00	0.42	0.50	62	62	134	79	0.170	0.160	0.030	0.040	0.500	0.470	1.540	0.590	22	21
102180	0.25	6.00	0.40	0.32	215	324	205	272									56	86
102680	0.33	6.00	0.50	0.54	100	99	120	136	0.310	0.280		0.040		0.730		0.690	48	36
110480	1.64	35.00	0.75	0.89	67	60	79	68	0.190	0.200	0.030	0.030	0.430	0.480	0.250	0.270	25	16
110580	0.43	4.00	1.14	1.16		178	141	96	0.300	0.260	0.050		0.830		0.360		43	40
110780	1.09	16.00	0.84	0.80	68	237	38	111	0.160	0.590	0.030	0.060	0.410	1.040	0.210	0.390	27	48
111080	0.41	10.00	0.75	0.85	28	63	36	47	0.110	0.180	0.020	0.020	0.210	0.420	0.110	0.450	13	22
111880	0.20	2.00	0.22	0.21	48	36	80	76	0.110	0.080	0.030	0.020	0.300	0.300	0.640	1.040	26	19
112080	0.16	3.00	0.81	0.73	94	174	107	155	0.130	0.220	0.030	0.050	0.560	1.010	0.360	0.610	35	52
112280	1.51	16.00	0.80	0.80	102	110	79	68	0.140	0.120	0.030	0.020	0.470	0.480	0.230	0.230	28	24
112480	0.07	3.00	0.90	0.21	41	110	91	117	0.060	0.100	0.010	0.020	0.220	0.450	0.370	0.870	16	27
120180	1.75	34.00	1.07	0.95	46	62	52	60		0.050	0.020	0.030	0.250	0.310	0.130	0.200	16	21
120380	1.50	28.00	0.96	1.06	68	108	70	47	0.090	0.160	0.040	0.040	0.350	0.530	0.190	0.230	24	36
120680	0.27	13.00	0.46	0.07	115	267	82	180	0.150	0.440	0.020		0.510		0.310		42	62
122380	1.62	35.00	0.80	0.81	93	80	85	110	0.170	0.230							29	25
122880	0.29	7.00	0.93	1.42	66	65	37	73	0.140	0.110	0.010		0.260		0.170		17	13
123180	1.18	34.00	0.62	0.66	95	172	64	137	0.220	0.290	0.030		0.440		0.270		21	48
Mean			0.74	0.67	89	120	117	120	0.217	0.206	0.034	0.040	0.467	0.603	0.617	0.805	31	36
Median			0.43	0.51	77	98	99	108	0.185	0.176	0.030	0.037	0.421	0.557	0.415	0.622	27	32
COV			1.40	0.87	0.60	0.70	0.63	0.49	0.62	0.61	0.55	0.43	0.48	0.41	1.10	0.82	0.56	0.54
N	23	23	23	23	22	23	23	23	20	21	19	17	19	17	19	17	23	23

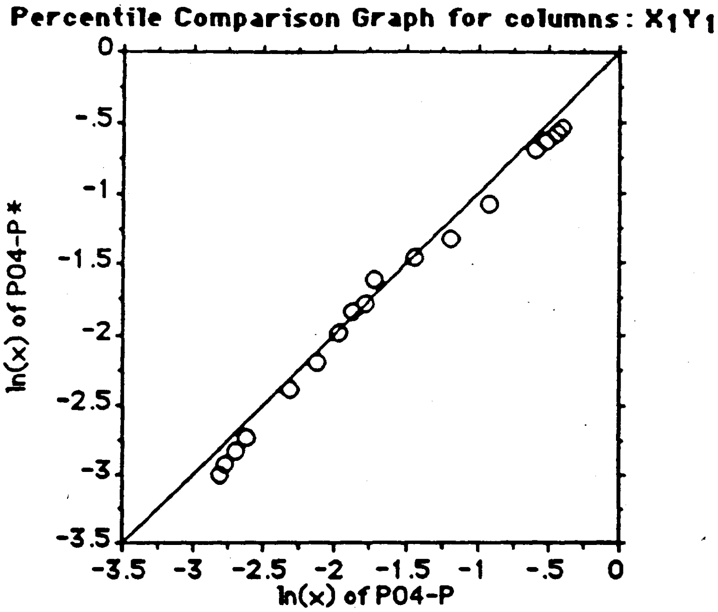


Figure 23. Percentile comparison line chart for PO4-P and PO4-P* at the Seattle I-5 site.

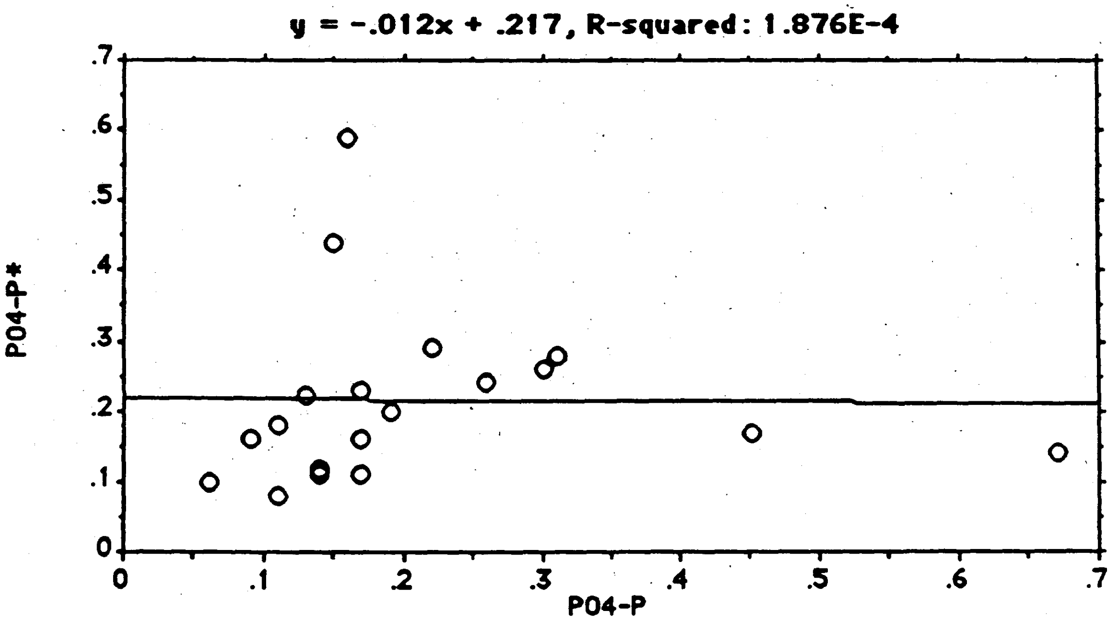


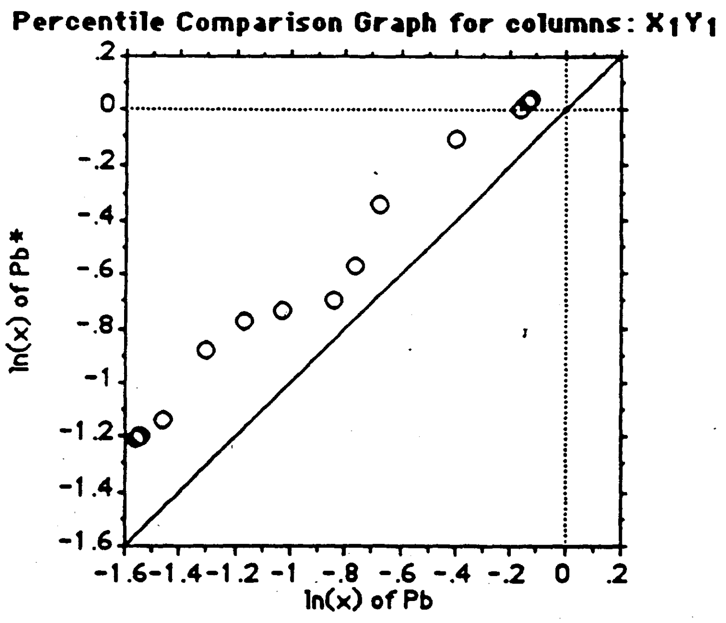
Figure 24. PO4-P and PO4-P* scatter plot for the Seattle I-5 site.

was most often higher, an observation that is substantiated by inspecting the statistical summary at the bottom of the columns. This was confirmed by the t-test, the results of which indicated that the samples means were significantly different. Strictly speaking, we were unable to disprove that they came from two different populations—we had to reject the null hypothesis. The comparable frequency charts are given in figure 25. In the percentile comparison line chart in the upper portion of the figure, the line falls well above the 45° line on which it would be expected to fall if, in fact, the samples had been drawn from the same population. Comparison of the corresponding plots for phosphorus and lead is especially informative. That there appear to be two different distributions is more strongly suggested by the cumulative frequency distributions given in the lower portion of the figure.

Given the foregoing, the results of a regression of Pb* on Pb become especially interesting. The regression of PB* on PB is shown in figure 26. While the regression results are not strong (R-squared = 0.38), at least there is a slope (0.73), and it is in the expected direction. Furthermore, although not zero, the intercept is small (0.257). The 95 percent confidence limits (i.e., the interval within which there is a given level of confidence that the true value lies) are shown, for the mean in the upper scatter diagram, and for the slope in the lower scatter diagram. With respect to the latter, at the 95 percent confidence level, it is possible that the regression line actually passes through the origin (which is what would be expected).

The above analyses were conducted for the other constituent concentrations given in table 14, and the results fall between the extremes just presented. The following summary observations are made:

- Measurement errors can and do occur in even the most carefully conducted runoff investigations.
- Measurement errors may or may not exhibit a bias.
- Measurement errors can hinder attempts to make event comparisons (or predictions) for individual events.
- Measurement errors do not unduly affect data analysis methods that have been designed to be robust in the face of them.
- Although the differences between the summary statistics for a constituent at the two sites given in table 14 may be statistically significant in certain instances, as a practical matter there is little difference between the two.
- One can use EMC data to estimate population statistical parameters reliably, even in the face of measurement errors. However, the ability to use sequential discrete samples to reliably construct pollutographs for individual events is questionable.



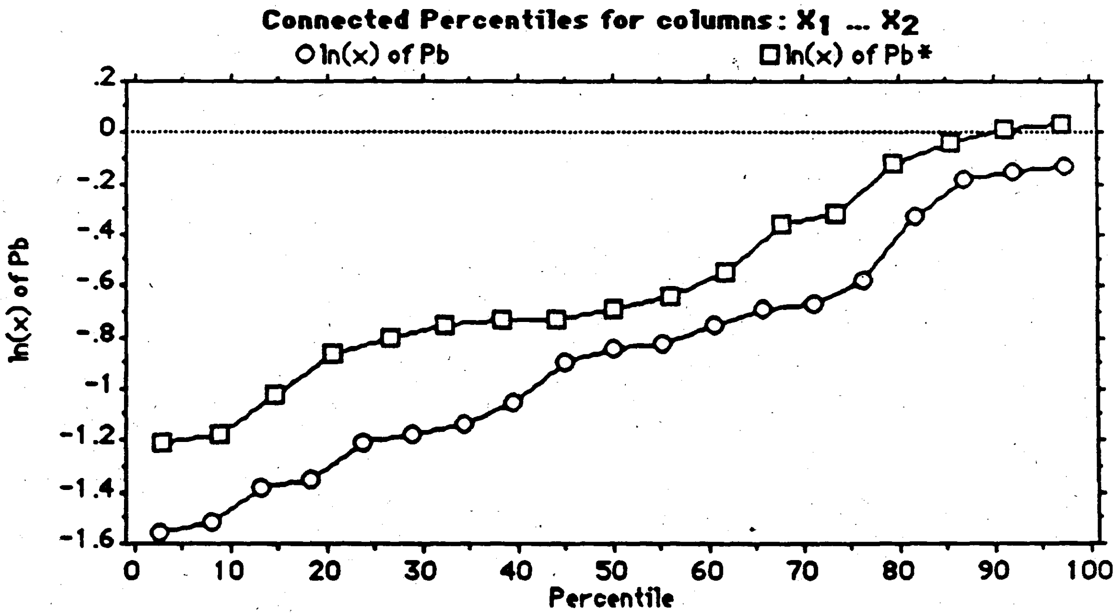
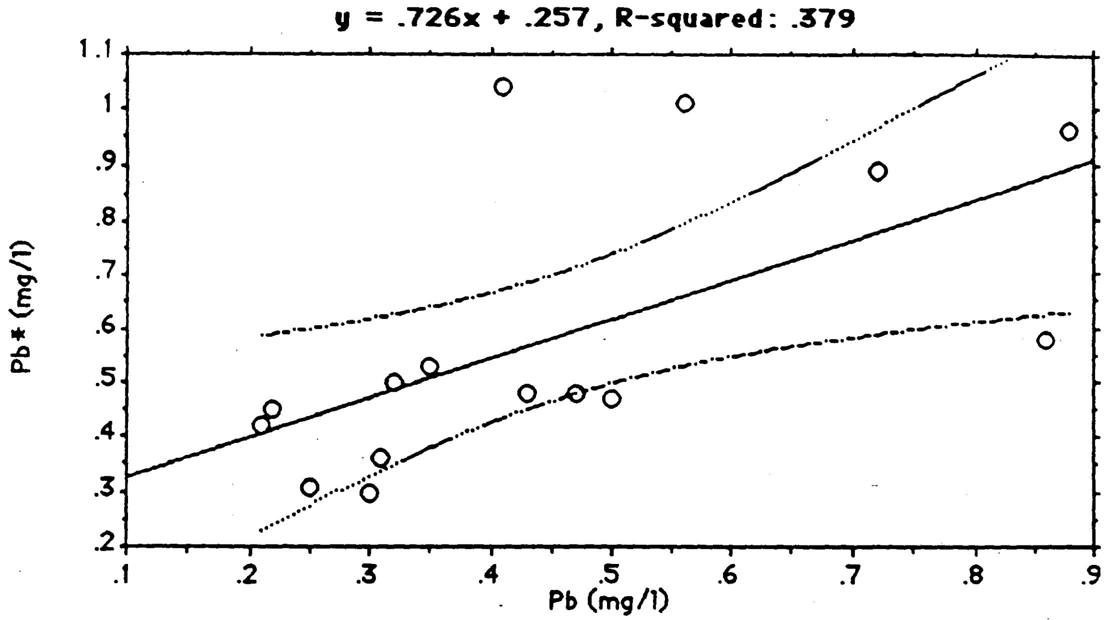


Figure 25. Comparison of lead EMCs at I-5 and I-5*.



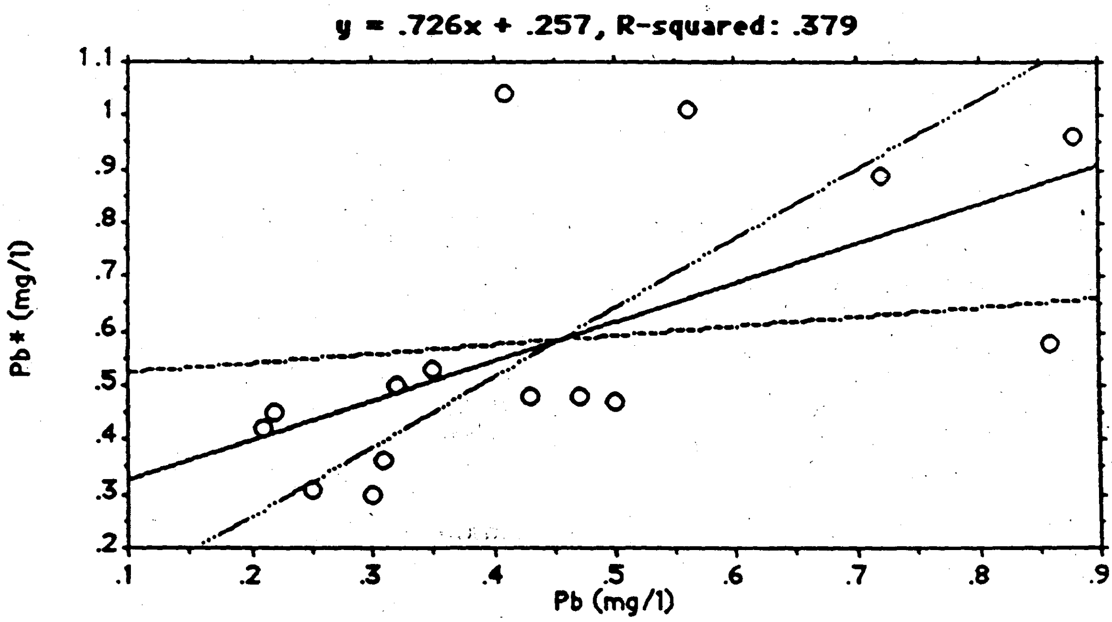


Figure 26. Regression of PB* on PB showing both the 95% confidence lines for the mean and the slope.

4.4 EFFECT OF STORM SIZE ON RUNOFF QUALITY

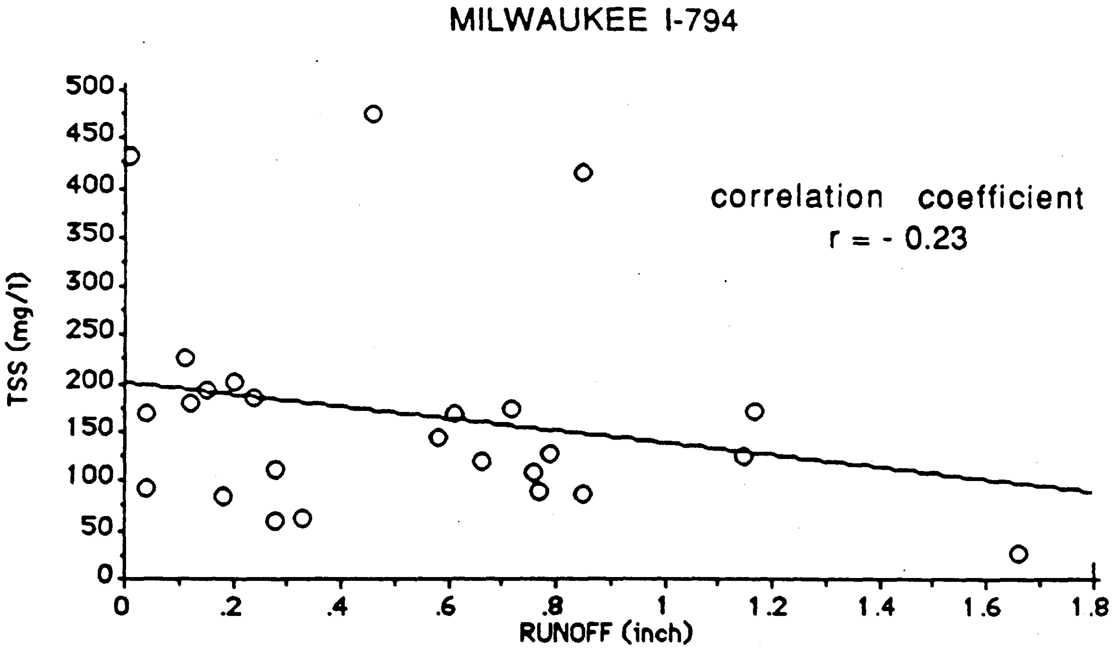
To examine the possible relationship between the event mean concentrations of a particular constituent and the corresponding event runoff volumes at a highway site, linear correlation coefficients were calculated. The null hypothesis that the two variables are uncorrelated was tested using that distribution at both the 90 and 95 percent confidence levels. Since it is possible for correlation to be either positive or negative, the two-tailed test was used. Failure to reject the null hypothesis means that linear dependency between the two variables in the population has not been shown. The rejection of the null hypothesis means that there is evidence of a linear dependency between the two variables in the population, but it does not mean that a cause-and-effect relationship has been established.

General guidelines for the use of this test suggest that it be used with caution for values of N less than 10 due to the high uncertainties associated with estimates of population variance with small samples. Furthermore, when N = 2 a perfect correlation will result, but the finding is meaningless. To include as many highway sites as possible in this examination, all constituents for which N was greater than 5 were included. At the other extreme, when N is very large, say over 100, correlation coefficients are almost always significant but can be so weak that they are meaningless from a practical standpoint. For N = 100 the critical value of r at the 90 percent confidence level is 0.164, meaning that the correlation explains less than 3 percent of the concentration variability. Figure 27 presents an example of the correlation analysis. Shown are TSS and Lead versus runoff for the Milwaukee I-794 site. In this example, both correlation coefficients were not significantly different from zero. Therefore, no relationship between runoff and these two parameters can be shown.

Volume-concentration correlations were determined for a total of 184 paired data sets, representing eight different pollutants at each of 23 highway sites. The results, presented in table 15, indicate that there tends to be little if any significant correlation between constituent concentration and runoff volume at highway sites. Correlation coefficients (r) that are statistically significant at the 95 percent confidence level are indicated by the values printed in bold type, while normal type is used to designate significance at the 90 percent confidence level. Only 10 or 15 percent of the 184 data sets examined show statistically significant correlations, depending on the confidence level selected. All others are not significantly different from zero.

Note that even for the relatively few sets for which there is a statistically significant correlation, the magnitudes of the coefficient (r) indicate that runoff volume can only explain about 20 percent of the concentration variability, on average. As a practical matter, since the correlations are mostly zero or otherwise weak, pollutant EMCs can be considered to be independent and unrelated to runoff volume, and by extension to storm size.

This finding is important for several reasons. First, in stormwater monitoring projects there is a natural and appropriate bias that favors emphasizing resource allocation to larger storm events. This was generally the case at the various highway sites as well. However, because of differences in local meteorological conditions, degree of site imperviousness, and other factors, there are appreciable differences in the average sizes of storms monitored by site in the FHWA data base. Since little significant linear correlation was found, such biases and differences are not expected to influence site comparisons to any appreciable extent.



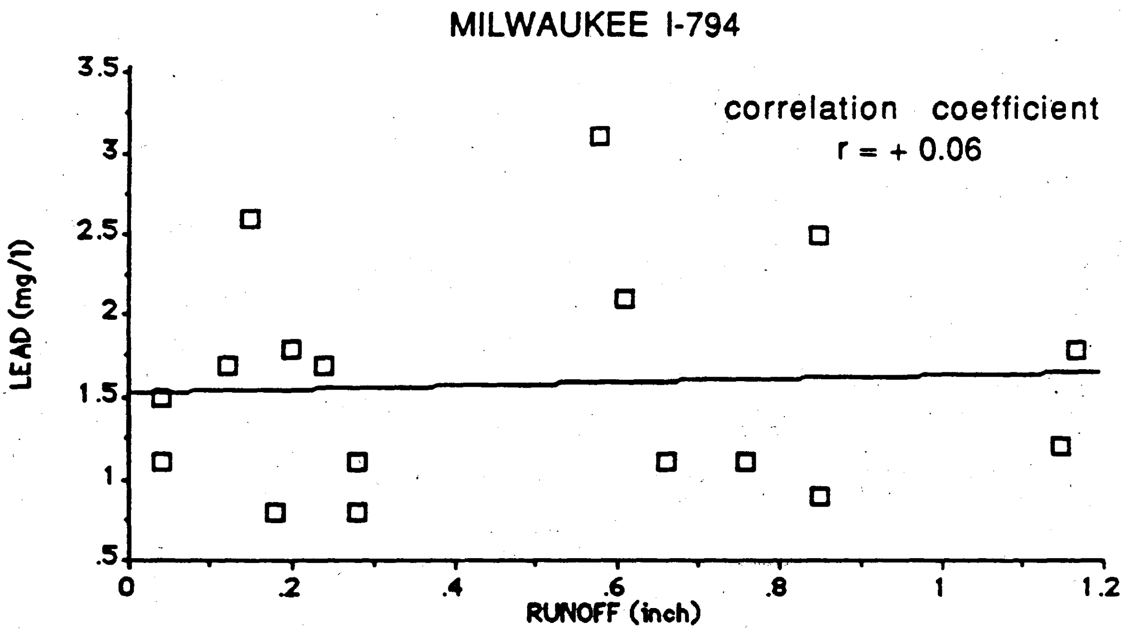


Figure 27. Correlation between EMC and runoff volume.

Table 15. Significant correlations coefficients with runoff.

		SS	N	COD	N	NO2+3	N	TKN	N	PO4-P	N	Cu	N	Pb	N	Zn	N
AR-1	Little Rock I-30		13		14		14		0		0		14		14		14
CA-2	Sacramento Hwy 50		34		12		18		17		17		28		34		34
CA-3	Walnut Creek I-680		9		9		0		8		8		0	-.63	10	-.73	10
CO-1	Denver I-25		15	-.64	15		0		15	-.51	15		15		15	-.60	15
FL-1	Broward Co. Hwy 384		40	-.42	40	-.29	41	-.39	41	-.34	41		40	-.26	40	-.39	39
MN-1	Minneapolis I-94		66		0		0		64		64		64		64		0
MN-2	St. Paul I-94		26		0		0		23		26		25		26		0
NC-1	Efland I-85		32		0		2		3		3		15		15		15
PA-1	Harrisburg (I) I-81		18		16		1		17	.66	18		18		18		18
TN-2	Nashville I-40		27	-.67	21		0		21		20		21		27	-.45	27
WA-5	Montesano SR-12		18		17		7		7		16		11	-.54	13	-.56	11
WA-6	Pasco SR-12		23	-.41	24		7		1	-.48	13		18		16		18
WA-9	Pulman SR-270W		34	-.32	33		11		7		28	-.36	26		26		26
WA-1	Seattle I-5		92	.19	92	-.37	59	-.39	50		67		84	-.24	84		84
WA-11	Seattle I-5*		25	-.43	25		6		5		23		19		19	-.49	19
WA-4	Snoqualmie Pass I-90		31		31		18		9		17		23		21		19
WA-3	Vancouver I-205		85		87		56		52		69		63		66		56
WI-1	Milwaukee I-94		99		35	-.48	37	-.30	37		36		40		41		41
WI-2	Milwaukee Hwy 45		22		22		3		22		22	.45	21		22		22
WI-3	Milwaukee I-794		25	-.49	18		1	-.42	19		19		18		17		18
	No. Sites Where N > 5	100%	20	1.00	17	1.00	11	1.00	17	1.00	18	1.00	19	1.00	20	1.00	18
	No. Significant @ 90%	0%	0	.47	8	.27	3	.24	4	.22	4	.11	2	.20	4	.33	6
	No. Significant @ 95%	0%	0	.35	6	.18	2	.12	2	.11	2	.05	1	.05	1	.28	5

Second, although the probabilistic methodologies that have been developed for examining receiving water impacts can properly account for correlations between concentration and runoff volume, the computation becomes more complicated. The use of the more complicated form does not appear to be warranted for highway runoff, and the simple form that assumes that concentration and runoff volume are independent can be used.

It is interesting to compare the present results with those from the Environmental Protection Agency's Nationwide Urban Runoff Program (NURP) (17), especially in view of the latter's much larger data base (nearly 70 sites). The results are summarized in table 16, which shows that, overall, the percentage of sites with significant correlations between concentration and runoff volume are comparable between the two data bases. If anything, there are fewer significant correlations at the highway sites.

Table 16. Comparison of correlation significance at FHWA and NURP sites.

Sites Significant	SS	COD	NO2+3	TKN	PO4-P	Cu	Pb	Zn
FHWA @ 90%	0%	47%	27%	24%	22%	11%	20%	33%
NURP @ 90%	19%	38%	30%	30%	30%	35%	25%	34%
FHWA @ 95%	0%	35%	18%	12%	11%	5%	5%	28%
NURP @ 95%	10%	30%	23%	22%	22%	27%	20%	29%

An examination of possible correlations between EMCs and rainfall volume was also performed. If they had proved to be significant, a method of predicting constituent concentrations in highway runoff from rainfall records could be developed. Following the same procedures as described above, correlation coefficients were calculated between constituent concentration and rainfall volume on a site-by-site basis. The results are summarized in table 17. As can be noted, the correlation pattern is weak and similar to that for runoff volume. On a constituent basis at the 95 percent confidence level, only COD has a significant correlation at as many as one-third of the sites. The others are much lower, suggesting little basis for using rainfall volume for EMC prediction.

These findings suggest that attempts to develop linear regression relationships between rainfall or runoff volume and constituent concentration, as a means of predicting the latter, will not provide satisfactory results.

4.5 EFFECT OF AVERAGE DAILY TRAFFIC LEVEL

The vehicular traffic carried by a highway is an obvious source of pollutants found in the runoff from such sites. Most previous studies actively evaluated relationships between traffic density and pollutant levels in runoff. This subsection examines this question using the comprehensive data base that has been assembled, by comparing "Total" Average Daily Traffic

Table 17. Significant correlations with rainfall.

		SS	N	COD	N	NO2+3	N	TKN	N	PO4-P	N	Cu	N	Pb	N	Zn	N
AR-1	Little Rock I-30		17		18		17		0		0	-.43	18		18		18
CA-2	Sacramento Hwy 50		34		12		18		17		17		28		34		34
CO-1	Denver I-25		15	.67	15		0		15	-.57	15		15		15	-.62	15
FL-1	Broward Co. Hwy 384		40	-.43	41		41	-.35	41	-.28	41		40		40	-.38	39
MN-1	Minneapolis I-94		46		0		0	-.26	45		45		45		45		0
MN-2	St. Paul I-94		30		0		0		25		30		29		30		0
NC-1	Efland I-85		32		0		0		0		0		15		15		15
PA-1	Harrisburg (I) I-81		18		16		0		17	.63	18		18		18		18
TN-2	Nashville I-40		27	-.60	21		0		21		20		21		27		27
WA-5	Montesano SR-12		24		23		12		10		21		14	-.51	16	-.69	14
WA-6	Pasco SR-12		35	-.33	36		18		6		20		30		28		30
WA-9	Pulman SR-270W		37		36		13		8		30		29		29		28
WA-1	Seattle I-5		97	.18	97	-.41	63	-.36	53		69		88	-.23	89	-.34	89
WA-11	Seattle I-5*		25	-.37	25		6		5		23		19		19	-.49	19
WA-2	Seattle SR-520	.43	37	.34	37		34		31	.36	35	.31	36	.45	36	.30	36
WA-4	Snoqualmie Pass I-90		31		31		18		9		17		23		21		19
WA-7	Spokane I-90		11	.77	10		8		6		9		10		8		9
WA-3	Vancouver I-205		85		87	-.26	56		52		69		63		66		56
WI-1	Milwaukee I-94		98		35	-.47	37	-.29	37		36		40		41		41
WI-2	Milwaukee Hwy 45		22	-.40	22		3		22		22	.37	21		22		22
WI-3	Milwaukee I-794		25	-.42	18		0	-.40	19		19		18		17		18
	No. Sites Where Meas.	100%	21	100%	18	100%	13	100%	18	100%	19	100%	21	100%	21	100%	19
	No. Significant @ 90%	5%	1	56%	10	23%	3	28%	5	21%	4	14%	3	14%	3	32%	6
	No. Significant @ 95%	5%	1	33%	6	23%	3	11%	2	16%	3	0%	0	14%	3	26%	5

(ADT) in 1000 vehicles per day with "Site Median" concentrations of pollutants.

Since all pollutants in runoff from highways have been shown in section 3.6 to have a comparable degree of variability from event-to-event at any particular site, the median EMC for a site, designated the Site Median, can be adopted as a single value which characterizes a pollutant's level in runoff for each site. These values are compared with reported values for ADT, tabulated earlier in table 4. The "total" ADT levels listed follow the conventional practice which reports ADT as the total number of vehicles which pass by the highway segment in question in both directions. The number used is a daily average value, and averages out differences based on hour of the day, day of the week, or season of the year.

The procedure used for this evaluation was described previously in section 2.7, and involves an examination of the linear correlation between ADT and site median concentrations for each of the pollutants monitored. The demonstrated lack of correlation between storm or runoff volume eliminates any concern for possible bias because of possible differences in the size of monitored storms at different study sites. However, since it was shown in section 3.5 that there are significant differences for all pollutants between the groups representing "nonurban" sites with ADTs less than 30,000 vehicles per day and "urban" highways with higher ADTs, we have focused the following analysis on the latter group.

It is not clear whether the distinctly different groups result primarily from the traffic levels, or from the ambient conditions resulting from the character of the surrounding area. Since the two factors are so strongly correlated themselves, it is impossible, and unnecessary, to distinguish them. These results support previous study results which conclude that rural highways have much lower pollutant levels in runoff, and as a result, a substantially smaller potential for receiving water problems. This is one reason why it was concluded to be most appropriate to focus here on only the urban highways. The other reason is technical in nature. As discussed in section 2.5, there are only eight rural sites, five of which are in the State of Washington, and two of these are relatively atypical in that they are in semiarid or desert areas. There is some uncertainty about how representative our nonurban data set is, compared with all rural highways. Even so, the fact that pollutant levels are significantly lower would tend to introduce a bias in correlations if all sites were pooled for analysis.

The results of the correlation-regression analyses for the urban highway sites are presented in the series of plots that follow. Regression analysis is a useful, but relatively crude form of data analysis. For a good understanding of the relationships being examined, and to avoid either faulty conclusions or a failure to appreciate the reliability of predictions produced by a regression equation, it is important to examine plotted data, and consider the influence of individual elements of the data set.

Consider first the results for BOD and Oil & Grease shown by figure 28. The upper of the two sets shows results for all of the data, which are only four or five values, one of which in each case is an outlier, substantially higher than all other values in the set. Whether these values are valid ones for the site or due to measurement error cannot be determined, but they are clearly not consistent with all the remaining data, and at best suggest an unusual or nontypical situation. Since the objective is a general relationship for the majority of highway sites, the inclusion of these outliers becomes an issue, particularly since their deletion (shown by the lower set of plots)

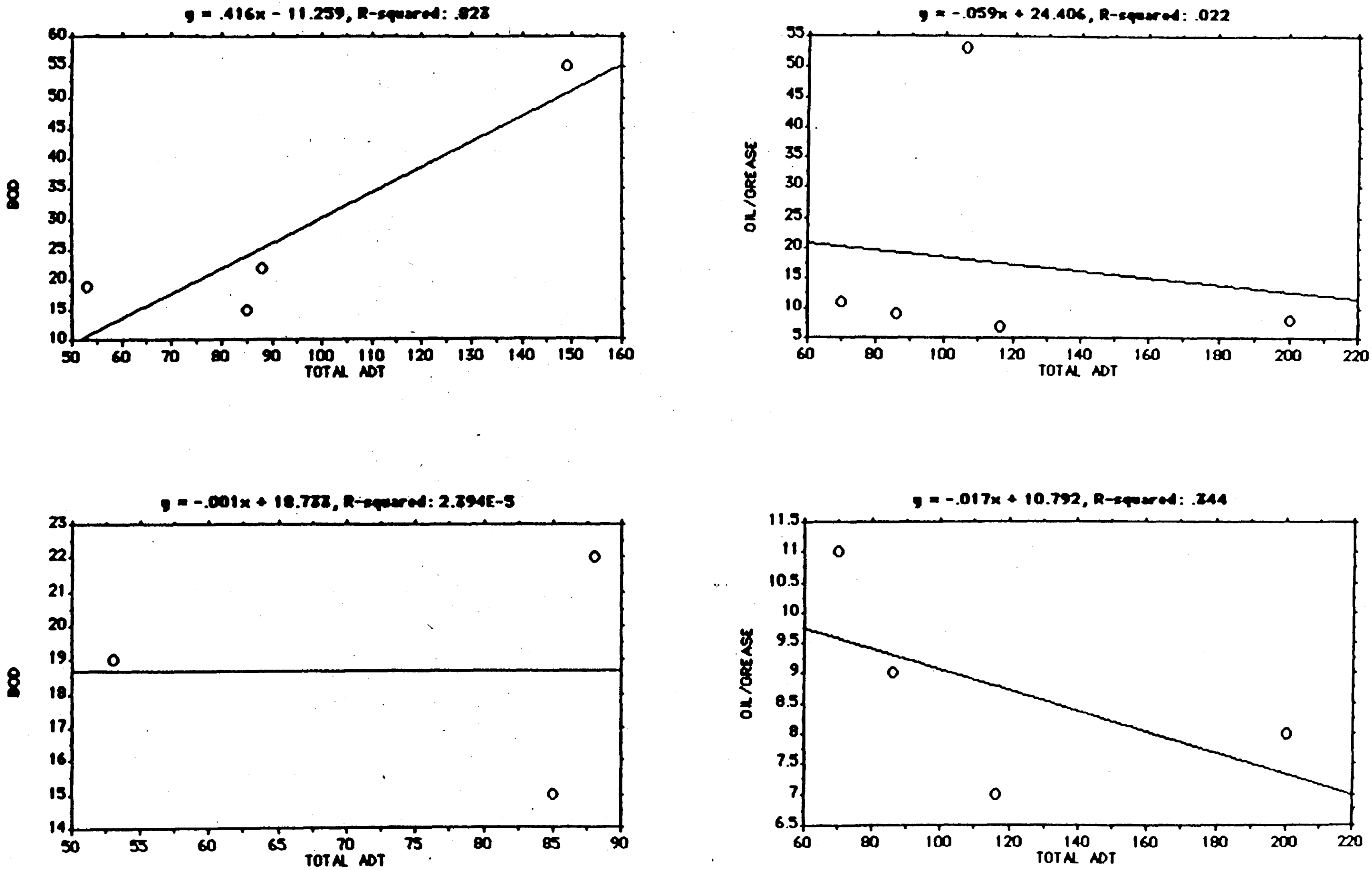


Figure 28. Site median EMC vs traffic density - BOD and Oil & Grease.

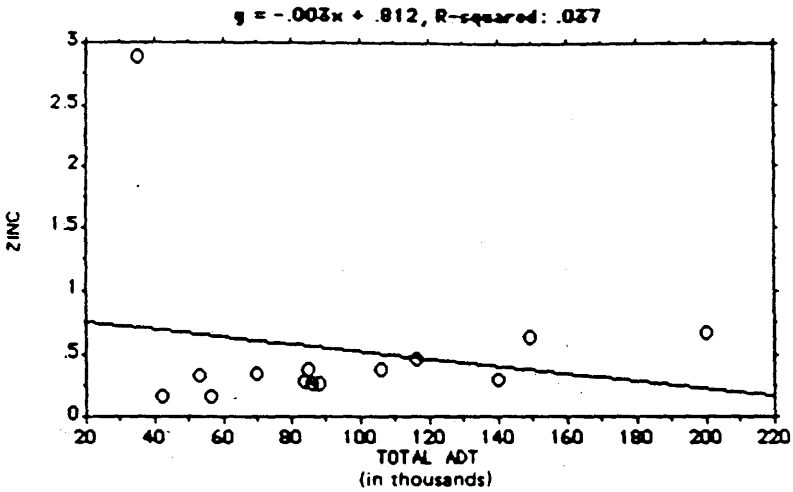
significantly changes the indicated relationship between ADT and pollutant level. In the case of BOD it changes a rather strong relationship, in which ADT explains over 80 percent of the differences in BOD concentrations in runoff from different sites, to one that indicates that ADT has no influence whatever on BOD discharges. For oil and grease levels, the elimination of one outlier increases the strength of a negative correlation, but since we do not accept the indication that higher traffic levels would improve runoff quality, the only rational conclusion is that the data do not demonstrate any influence of the level of ADT on the amount of oil and grease in highway runoff. On a more fundamental basis we conclude that limited data sets do not provide reliable results, and that we have no basis for deciding that ADT influences the runoff quality for these two pollutants. The regression equations shown are, as a practical matter, totally meaningless. If the BOD data were just mechanically processed by a regression analysis, a totally unwarranted conclusion of the effect of ADT might be drawn.

A similar situation is shown for zinc site medians by figure 29. The regression analysis for the upper plot indicates that there is no significant correlation with ADT, but indicates a dramatic outlier. In this case we know that it represents a highway segment adjacent to a smelter. The data are real, but not typical of the vast majority of highways. Elimination of this site from the analysis radically changes the results (lower plot), producing, of all the pollutants examined, the strongest relationship between runoff quality and ADT.

Figure 30 shows the correlations between ADT and site median concentrations for total suspended solids (TSS), total solids (TS), and for chloride ion with and without a possible outlier. In all cases, the results provide no basis for attributing a quantitative influence on pollutant level to ADT. The regression equations are meaningless, since the "R-squared" values shown reflect the fraction of the observed variation in site median concentrations that is explained by ADT. For these pollutants, it amounts to between 1 and 4 percent. This finding is informative, but not particularly significant for TSS, because it can be reasoned that other sources of TSS from surrounding areas could well be significant contributors to accumulations on highway surfaces, and contributors to the runoff loads. Total Solids (TS) may be more significant, only because some prior analyses selected it as a surrogate for the levels of other pollutants in highway runoff, and this analysis indicates ADT to have no influence on TS levels in runoff.

The class of pollutants most commonly associated with highway runoff is heavy metals, which are potentially toxic to aquatic life and likely to relate to vehicular traffic. Figure 31 shows their correlation with ADT. The upper two plots show the relationships for copper and lead to have positive correlations, as might be expected. However, the correlation is very weak, accounting for only 12 to 14 percent of the variance, and is not significantly different from zero. Traffic density is suggested to have a small but not practically significant influence on levels of these metals in highway runoff. Iron (the middle left plot) is not environmentally significant, but would be expected to be strongly associated with traffic levels. It shows no significant correlation with traffic density. For cadmium, chromium and mercury, shown by the remaining plots, results are presumed to be influenced by test accuracy at the very low concentrations present. The negative correlations indicated should (as indicated by the R-squared values shown) be interpreted as an inability to demonstrate that there is any correlation between heavy metal levels in the runoff from urban highway sites and the traffic level. The one exception to this is zinc.

Nutrient relationships are shown by figure 32. TKN shows a slight but not particularly



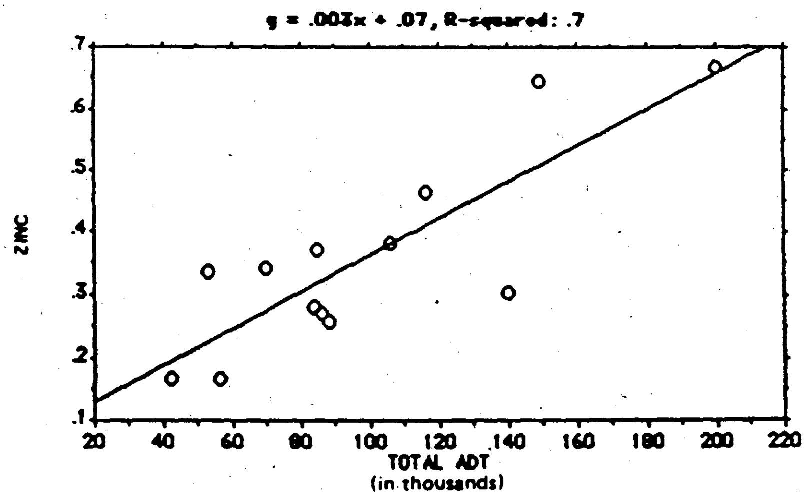


Figure 29. Site median EMC vs traffic density - Zinc.

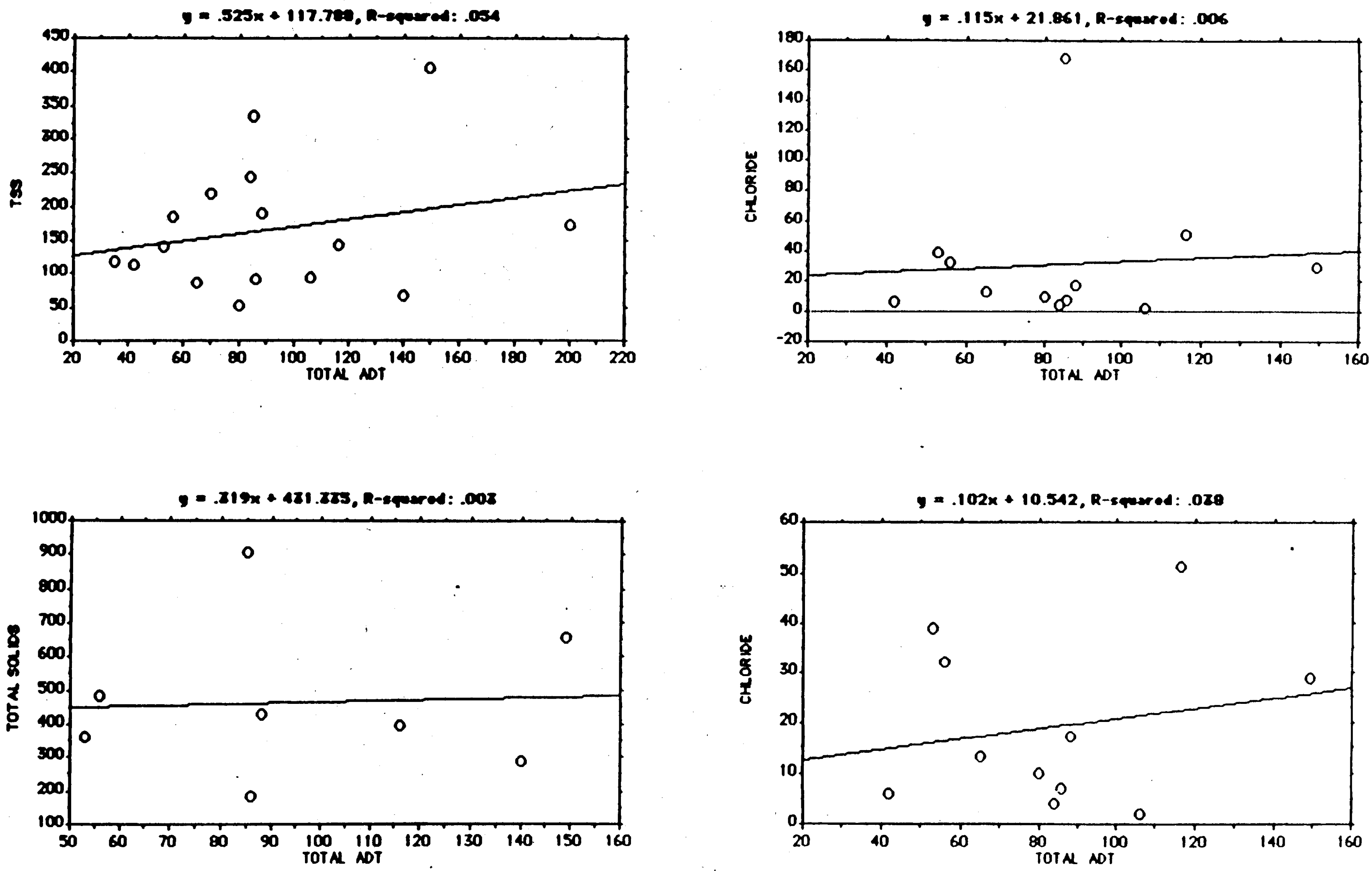


Figure 30. Site median EMC vs traffic density - TSS, TS, and Chlorides.

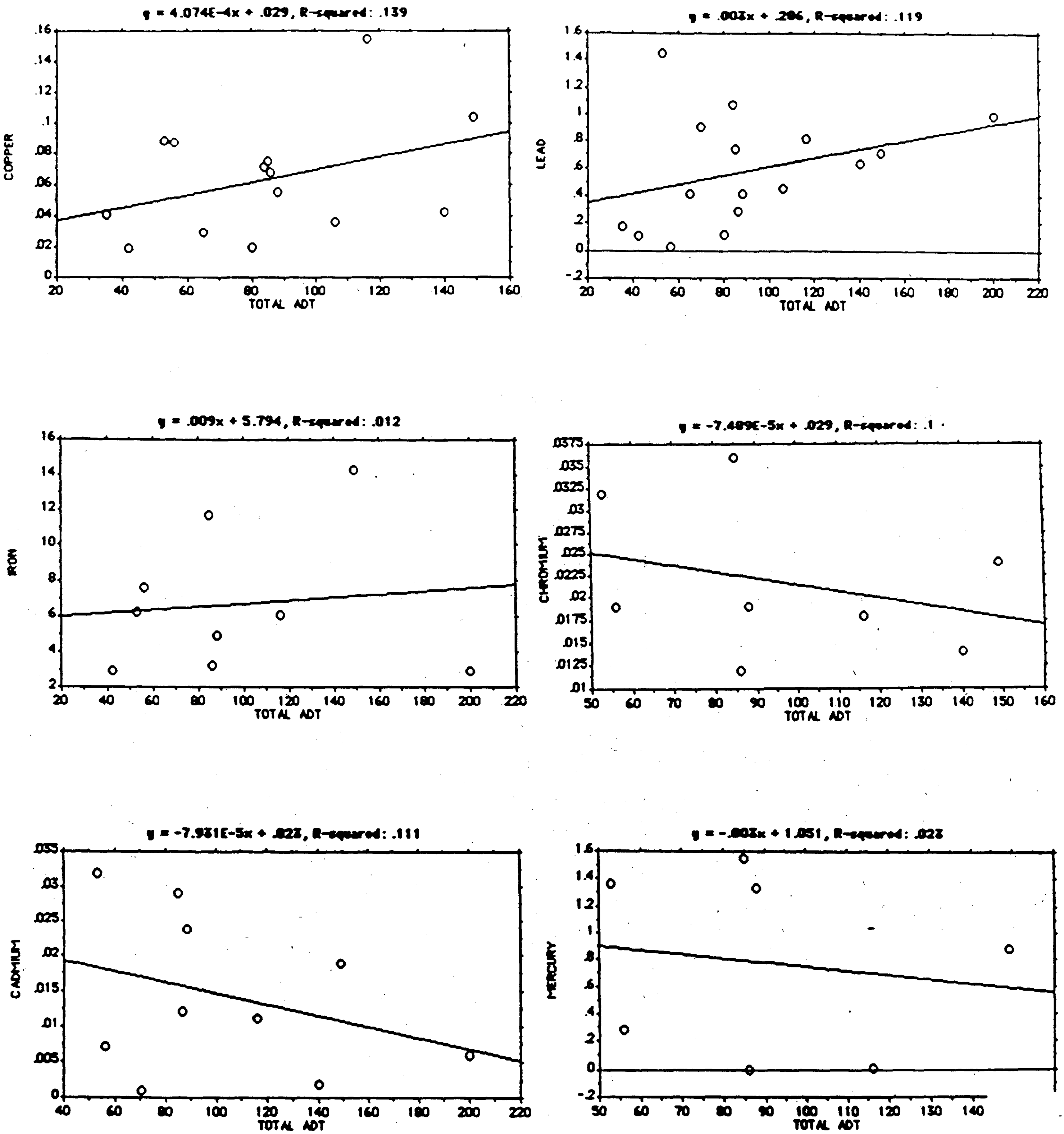


Figure 31. Site median EMC vs traffic density - Heavy Metals.

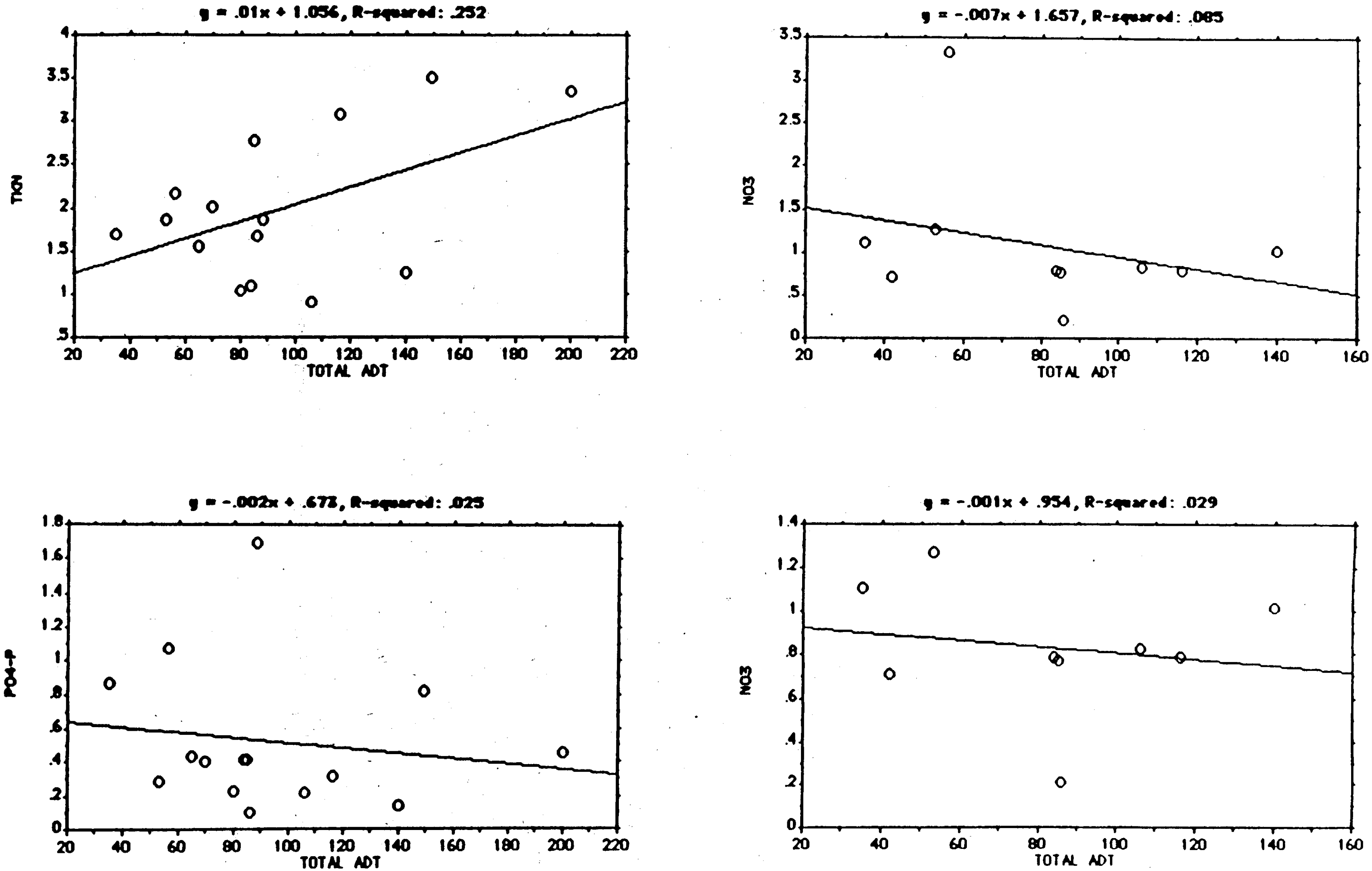


Figure 32. Site median EMC vs traffic density - Nutrients.

significant positive correlation, while phosphorus and nitrate (whether or not the apparent outlier is considered) show negative correlations that are not significantly different from zero.

Organic pollutants, including volatile suspended solids (VSS), chemical oxygen demand (COD), and total organic carbon (TOC), surprisingly show the most consistent degree of correlation with traffic density, as illustrated by figure 33. All show a positive, though not particularly strong, correlation with ADT. The TOC relationship is not substantially influenced by whether or not the possible outlier is included. For each of these pollutants, ADT explains about 40 percent of the site differences in runoff concentrations.

We also considered the possibility that traffic density reported as ADT per lane might be a more useful measure than the total daily value that was used. The correlations did not change significantly, though the Total ADT formulation provided slightly better coefficients. An additional consideration in the selection of Total ADT for the comparisons is the uncertainty over how to interpret the results. For example, there is some question whether one lane of an undivided two lane highway, two lanes from a four lane road with a concrete barrier divider, or a road with a wide vegetated median, should all be treated the same. The site mix that was available for analysis does not permit a determination as to whether a traffic per lane formulation would be superior, but it does provide a satisfactory basis for examining the relationship between traffic and pollutant levels.

In summary, when the group of "urban highway" sites was considered, there appeared to be no strong and definitive relationship between differences in traffic density and the pollutant level for a site. For VSS, COD, and TOC a positive but relatively weak correlation was shown. Although zinc showed a strong positive correlation, this result must be evaluated in the context that all other heavy metals (and particularly lead) show runoff concentration levels that appear to be uncorrelated with traffic density. We conclude that, other than the use of ADT as a surrogate measure to distinguish between "urban" and "non-urban" highways, further use of ADT to refine estimates of pollutant levels in runoff has no supportable basis. Stotz [22], in a report on the properties of runoff from three highways in West Germany, also concludes that "the amount of pollutants discharged is not dependent on the traffic frequency, but much more on the characteristics of the area".

4.6 RELATION OF OTHER POLLUTANTS TO SUSPENDED SOLIDS

The examination of possible correlations between other pollutant EMCs and suspended solids concentrations is of interest because such a relationship could provide a method of estimating the concentrations of unmeasured constituents in highway runoff from suspended solids data. The rationale for such an approach is that some constituents are adsorbed onto suspended solids particles and, thus, might be closely associated with them. It must be realized, however, that the suspended solids determination is a gravimetric one, and hence volume dependent, while adsorption is a surface phenomenon. Following the same procedures as were indicated for correlations with runoff volume, correlation coefficients were calculated between constituent concentration and suspended solids concentration on a site-by-site basis. The results are summarized in table 18. There it can be seen that there is some promise, at least at the 90 percent confidence level, for all but the nitrogen constituents, suggesting that the latter exist largely in dissolved form.

A second benefit from the association of other constituents with suspended solids is that one

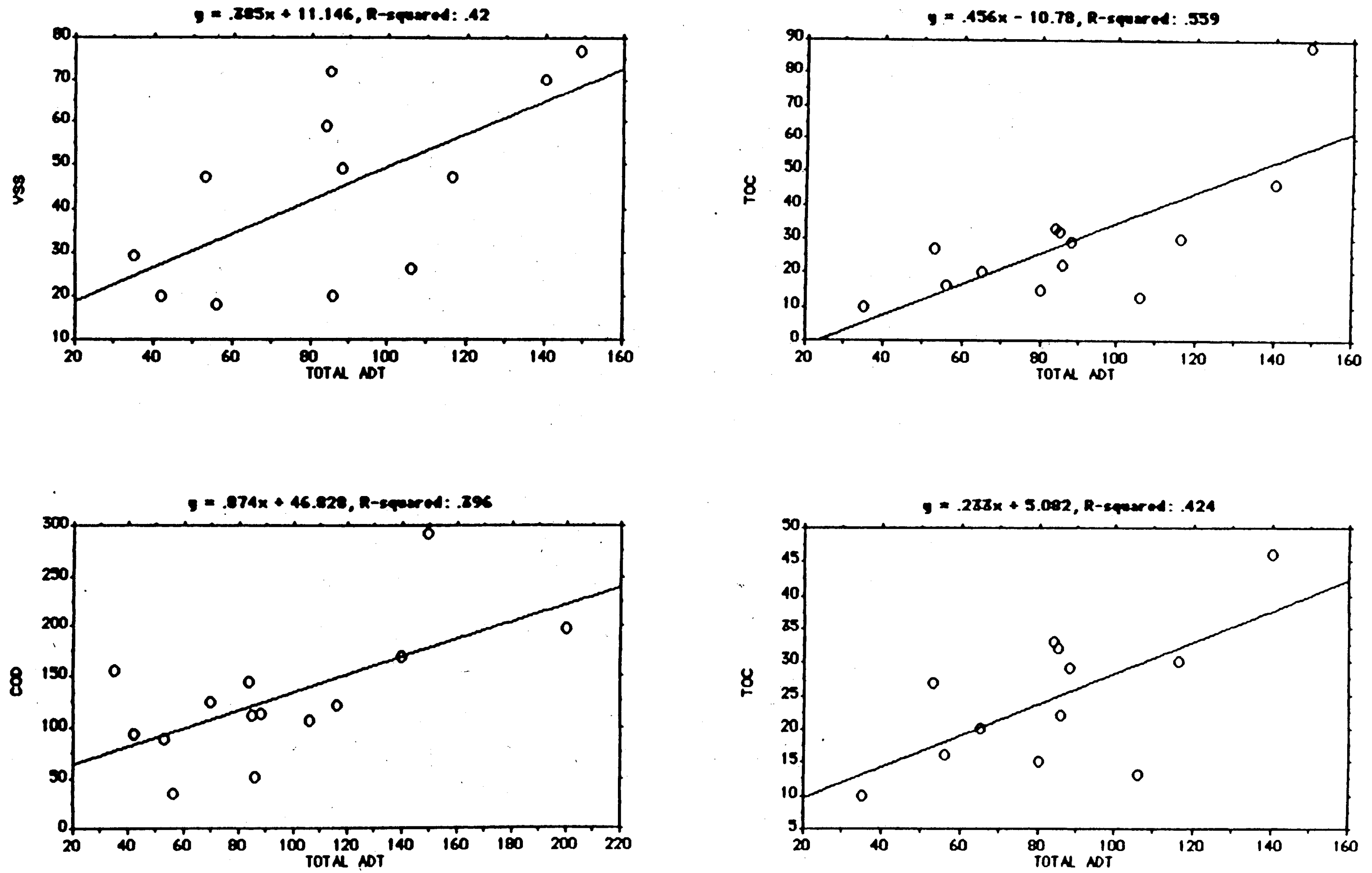


Figure 33. Site median EMC vs traffic density - Organics.

Table 18. Significant correlation coefficients with suspended solids.

		COD	N	NO2+3	N	TKN	N	PO4-P	N	Cu	N	Pb	N	Zn	N
AR-1	Little Rock I-30		18		17		0		0	.42	18		18		18
CA-2	Sacramento Hwy 50	.67	12	.44	18		17	.52	17		28	.83	34		34
CA-3	Walnut Creek I-680		9		0		8		8		0		9		9
CO-1	Denver I-25		5		0		15		15		15		15		15
FL-1	Broward Co. Hwy 384	.46	40	.52	40	.65	40	.62	40		39	.47	39	.31	38
MN-1	Minneapolis I-94		0		0	.51	65	.45	65	.58	65	.57	65		0
MN-2	St. Paul I-94		0		0		26	.42	31		30		31		0
NC-1	Efland I-85		2		2		3		3	.55	15		15		15
PA-1	Harrisburg (I) I-81		16		1		17	.49	18		18		18	.57	18
TN-2	Nashville I-40	.40	21		0		21	.83	20		21	.75	27	.70	27
WA-5	Montesano SR-12	.76	23		12	.88	10	.83	21		14	.86	16	.80	14
WA-6	Pasco SR-12	.48	34		17		6	.43	20	.55	29	.47	27	.41	29
WA-9	Pulman SR-270W		38		16		10	.30	32		32		32		31
WA-1	Seattle I-5		97		63		53	.47	69		88	.62	89		89
WA-11	Seattle I-5*	.83	25		6		5	.89	23	.81	19	.94	19	.65	19
WA-2	Seattle SR-520	.73	37		34	.35	31	.81	35	.71	36	.87	36	.65	36
WA-4	Snoqualmie Pass I-90	.30	31		18		9	.93	17	.34	23	.67	21		19
WA-7	Spokane I-90	.64	9		8		6	.83	9		10		8		9
WA-3	Vancouver I-205		85		56		52	.64	69		63		66	.60	56
WI-1	Milwaukee I-94	.89	35		37		37	.83	36	.82	40	.95	41	.90	41
WI-2	Milwaukee Hwy 45		22		3		22	.93	22		21	.82	22	.55	22
WI-3	Milwaukee I-794		18		0		19	.55	19	.40	18	.65	17	.50	18
	No. Sites Where N > 5	100%	19	100%	13	100%	19	100%	20	100%	21	100%	22	100%	20
	No. Significant @ 90%	53%	10	15%	2	21%	4	90%	18	43%	9	59%	13	55%	11
	No. Significant @ 95%	37%	7	8%	1	16%	3	80%	16	29%	6	59%	13	50%	10
	Average r @ 90%	.62		.48		.60		.65		.58		.73		.60	
	Average r @ 95%	.69		.52		.68		.69		.67		.73		.63	

obtains a sense of the degree of removal that different control practices might have. Those that are effective in removing solids by sedimentation or filtration would be expected to be effective in removing those constituents that are associated with suspended solids. On the other hand, there is no basis to expect similar removals for constituents that are not associated with solids.

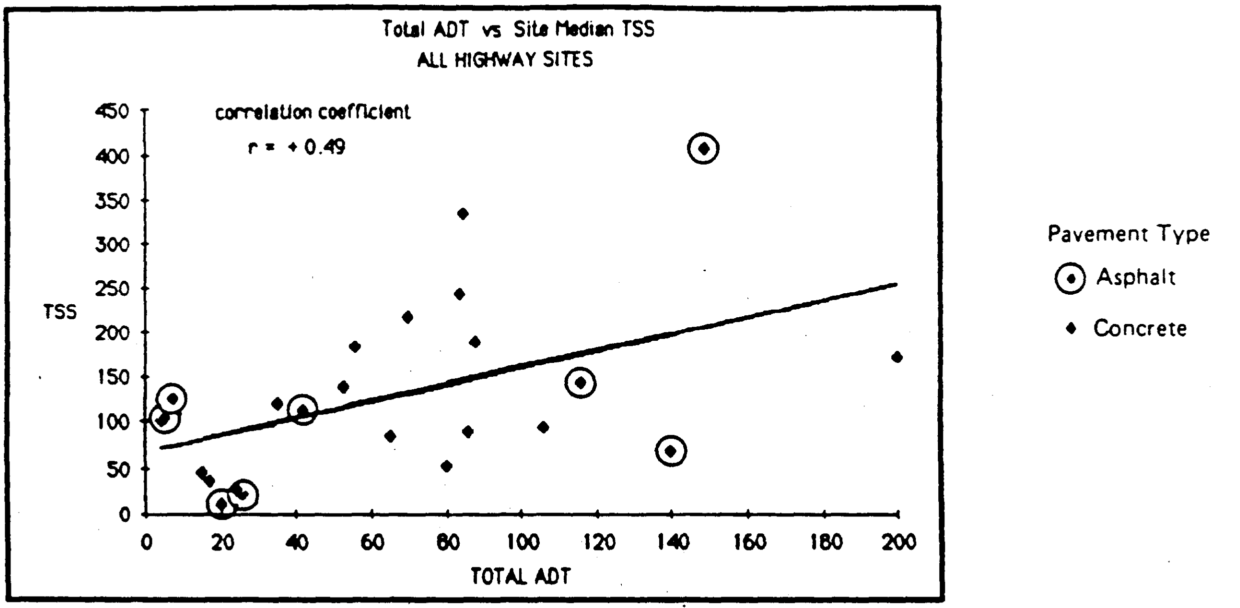
4.7 SUMMARY - FACTORS INFLUENCING HIGHWAY POLLUTANT LOADS

A variety of factors have been or can be postulated to influence the pollutant loadings that will result from highway stormwater runoff. The most commonly identified factors, including those discussed in detail earlier in this section, are identified and discussed below for the following reasons. They provide information on general causal relationships and can be used to guide estimates on site median concentration estimates either initially or after reconsideration. They may also provide a guide for regression or simulation analyses that might be considered as backup approaches in some situations. Finally, the discussions will provide useful perspective on the overall analysis and consideration of mitigation measures. Each of the factors is addressed in the particular contexts of 1) what could be concluded or inferred from the data base that was assembled for analysis, and 2) whether a factor has a practical utility for contributing to the basic objective of this study, which is a procedure for predicting pollutant loadings from highway sites in general. An illustration of each of these points is appropriate.

With regard to item 1), the inability of the data base to support the determination (for general predictions) of the magnitude of the effect of a particular factor, the following example indicates the situation. The 24 sites and the large number of events in the WDF provide a substantial data base, but it proves to be much too small to confirm, much less quantify, effects and possible interactions across all of these possible explanatory variables. To illustrate the lack of obvious relationships with other site factors, figure 34 presents plots of TSS vs ADT. Data summarized earlier in tables 4 and 5 (section 3) are used to assign a site characteristic tof interest to each of the plotted points. The upper plot compares pavement type, while the lower plot compares percent impervious area. In both cases no obvious influences by these possible factors are indicated. Furthermore, data on many of the factors are not uniformly available for all the sites, further reducing the available pollutant concentration data base available for such analyses. Some earlier studies did develop regression models that included a number of factors in the prediction scheme. However, as discussed later in section 5.2, these formulations proved to be not at all appropriate for other highway locations

The end result of many frustrating attempts at multivariate regression, ANOVA, and factor analysis, is the conclusion that there does not appear to be a way to meaningfully incorporate any of the possible factors into a better predictive model (with the notable exception of surrounding land use).

This does not mean that all other things being equal, a change in a particular factor would not affect the pollutant discharge. It means that this study was not able to quantify such an effect for use as a general predictor of highway runoff loads. For example, the absence of curbs is generally, and properly, considered to have a beneficial effect on reducing the level of pollutant discharges in highway runoff. At least one individual study suggested its benefit. However, only three of the study sites in this data base were without a curb of some sort. Among all the competing influences



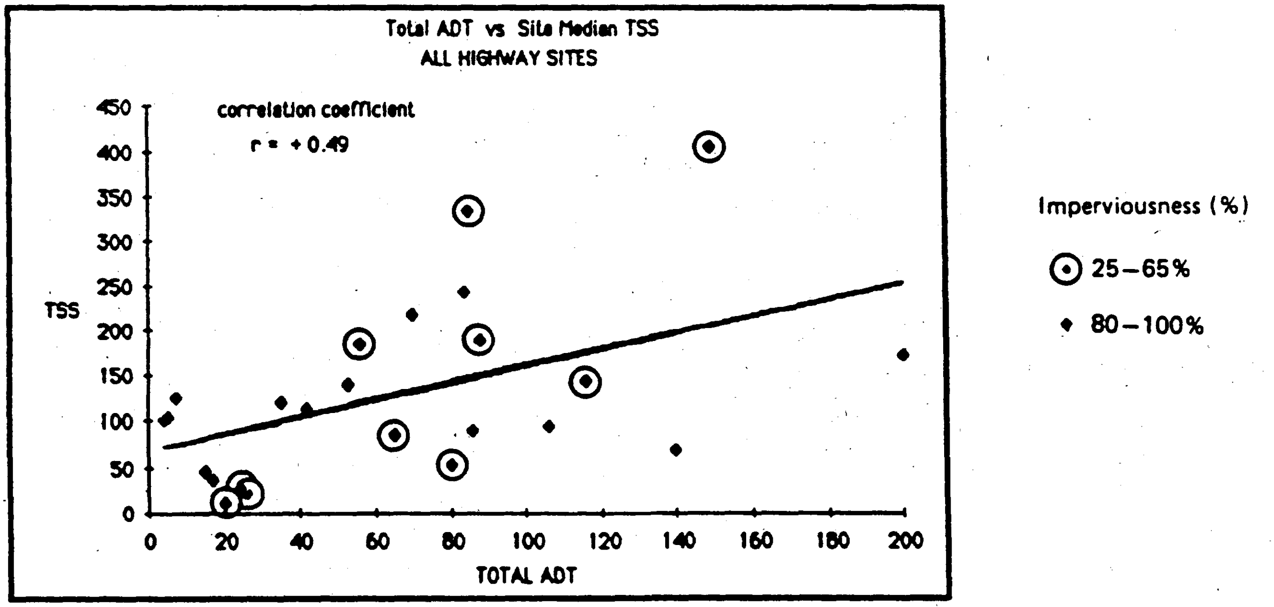


Figure 34. Influence of other site factors.

that contribute to variability and the median EMC concentration at highway sites, the overall effect of the absence of a curb structure is lost in the "noise" resulting from all other influences. Thus this data set does not provide a basis for confirming the beneficial effect of this practice, nor for quantifying its magnitude. It is accordingly not used in the predictive procedure subsequently presented. However, neither do the results provide a reliable basis for concluding that such a practice, where feasible, will not be useful. The size of the data base that would be required to positively confirm and quantify all of the factors that are plausible influences on pollutant levels is well in excess of any that can be expected to be developed.

With regard to item 2), the practical utility of a factor for use in a general predictive model, consider the following. One study (Washington State) apparently encountered the same lack of success as this study did, in attempting to define a deterministic relationship between combinations of factors and pollutant loads. They developed a relationship between loads and "traffic during storms". While this provides some insight into possible mechanisms, it is not really useful in a predictive method for the following reason. Traffic levels vary with time of day, with day of the week, and in many places seasonally as well. Storms do not occur at predictable times. If, as is the case in this study, the purpose is to predict loads so that receiving water impacts and problem potential can be determined, then the most appropriate estimate is the loading over some extended period, and not one for a unique several hour time period. The overall loading will be the result of storms that occur at random for the whole spectrum of actual traffic levels that combine to produce the average traffic density (ADT) for the site.

Keeping the foregoing considerations in mind, our summary evaluation of factors that are involved in pollutant loadings from highway runoff are presented below.

CLIMATE

When dealing with meteorogically-driven events such as highway stormwater runoff, the local climate, particularly the precipitation pattern, is one of the most important factors. Apart from the precipitation form, e.g., rain, sleet, snow, there are important regional differences in precipitation amount, average intensity, duration, and interval between storms, all of which influence the characteristics of highway runoff and related receiving water effects. To determine these precipitation characteristics and how they vary regionally, we analyzed a large number of long-term rainfall records at locations throughout the country using the SYNOP (Synoptic Rainfall Data Analysis Program), which was developed earlier for the U. S. Environmental Protection Agency. Section 6.1.7 provides additional discussion on this topic. Because of the major importance of local rainfall patterns on stormwater runoff loads, a microcomputer version of this analysis program was developed and provided to FHWA. It will provide a State highway agency with a convenient means of assembling reliable local data on this important factor.

Precipitation form, frequency, intensity, duration - The predominant effect on pollutant loading is the precipitation volume either on a storm event or an annual scale. Intensity and duration (whether for a particular event, or as annual average values have not been demonstrated to exert any significant modifying influence on pollutant loadings. However these factors do influence the performance of certain types of control measures. Their particular effect is reflected by the procedures for estimating performance of such devices, and are addressed in the relevant documents either produced by or referenced in this study. Frequency of rainfall is closely related to either annual volumes (in most areas of the country), or to seasonal volumes (in areas in the western and southwestern part of the country, which experience pronounced wet and dry seasonal distributions of rainfall). The SYNOP program provides the necessary information on these features.

Surface wind speed and direction - There are two possible competing influences that this factor could have on runoff loads. Wind could either blow deposits off the roadway, reducing the amount available for washoff by a storm event, or it could increase the amount of material on the road surface by carrying in dust and dirt from the surrounding area. As indicated further below, the characteristics of the surrounding area appear to have a major influence on runoff loads. The available evidence suggests that localized wind currents generated by vehicle-induced turbulence are much more important than the general wind pattern in the dispersion of pollutants. Studies at a major urban highway in Great Britain (Warren and Birch, 1987) confirm other investigations and indicate that concentrations of four heavy metal in soils adjacent to the highway vary considerably among test sites, and that soil contamination is restricted to a narrow band bordering the highway. Background levels are reached approximately 30 meters from the roadway. Studies on US highways (Lord 1987) indicated that the impact area was within 35 meters of the edge of the pavement for urban highways and 15 meters for rural highways. Comparable data developed for a Belgian highway (Derouanne-Bauvin, et. al.,1987) also showed elevated lead concentrations to be present in a relatively narrow zone along either side of the road. Soil concentrations drop an order of magnitude over the first 10 meters, and thereafter quite gradually. Noticeable increases were found out to 120 meters. The deposition of lead in soil adjacent to a highway was reported to be influenced by prevailing winds. The data presented indicate the magnitude of the effect to be relatively minor and influenced slightly (as discussed further below) by the highway cross section. The concentration versus distance profiles appear roughly as peaked bell-shaped curves. Wind effects are indicated by a slight skew to the spatial distribution pattern, but in all cases within the general range of influence indicated above.

Temperature - The effect of temperature on the density and viscosity of the runoff water and its possible ultimate effect on the washoff of pollutants is considered to be insignificant in relation to the other factors that influence pollutant runoff loads. The major temperature effect on pollutant discharges is related to it's influence on the form of the precipitation (rain, sleet, snow). Snow or sleet will often result in the application of sand or de-icing chemicals, and will thereby significantly influence the quality of the runoff during a small number of subsequent runoff events. The data presented in this study indicates the significant elevation of chloride levels that occur in these circumstances. The other significant effect of temperature on runoff quality shown by this study is that resulting from a rainfall event during a thaw period when there is an accumulated snow pack on the roadside. In such cases the concentrations of most pollutants in the runoff resulting from melting and washoff, are about three times higher that normal levels for a site.

Atmospheric Deposition and Removals - This is most likely the fundamental mechanisms by which pollutants in stormwater from any impervious surface are generated. It applies also to pervious surfaces, but in this case erosive effects must also be considered. As a result, algorithms for these mechanisms have been incorporated in most, if not all, of the physically-based runoff models that have been developed (for example, Huber, et. al., 1981b). Unfortunately, the amount of specialized data that has been collected to support estimates of buildup-washoff coefficients has been very limited, and inadequate to reliably quantify these parameters in the face of the inherent variability resulting from hydrological and local site factors. Given the cost and difficulty of monitoring programs, virtually all of the substantial number of studies that have been conducted (for urban as well as highway runoff) over the past ten years, have measured the equivalent of end-of-pipe runoff. All of the studies that contributed to the highway runoff data base used in this study developed this kind of data. Accordingly, we conclude that although accumulation and washoff are probably the basic underlying physical mechanisms that influence pollutant discharge levels in highway runoff, the available data does not provide a reliable basis for using these factors for general predictive purposes.

HIGHWAY SITE SITUATIONS

Configuration (elevated, ground level, depressed) - The topographic cross-section of a highway segment in considered to have a potential influence on pollutant loads based on whether it tends to enhance or to restrict the wind-induced dispersion of pollutant accumualtions on the road surface. For example, one might expect a greater net accumulation of deposits for cut sections and less for fill sections. Detailed information developed for a Belgian highway study (Deroanne-Bauvin 1987) provides useful information on the degree of significance of this factor. Lead accumulation profiles for the three types of cross-sectional configuration indicate that differences in maximum accumulations (at the road surface) are minor; an excavated section is 10 percent lower than a flat section, and an embanked section is about 5 percent higher. For both the cut section and the fill section, the impact area is closer to the centerline than for the flat highway configuration. Again, these differences are not substantial. These results appear to support the previous conclusion that vehicle turbulence is a more important factor than prevailing wind patterns.

Pavement composition, quantity, condition - The quantity of paved surface (in relation to to the total drainage area of the right-of-way) has an obvious and important influence on the pollutant loadings that will be generated by stormwater runoff. It's dominant influence is on the amount of runoff that will result from a particular amount of precipitation, and this factor is incorporated in the predictive model. As indicated in the example presented above, the available data provide no indication that pavement composition (concrete, asphalt) has any influence on runoff quality and pollutant loads. A more limited data base at three highway sites (2 asphalt and 1 concrete) in the FRG (Stotz 1987) supports the evidence from this study. Pavement condition can be expected to have some influence on pollutant runoff loads, but the study data available provides no basis for quantifying it's potential effect. Pavement deterioration could, in fact, either increase runoff loads by contributing decomposition products, or reduce loads by permitting part of the runoff to percolate through cracks and pot holes and be subjected to filtration in the road base materials. In any event, pavement condition is not considered to be an appropriate factor to include in the type of general predictive model that is the object of this study. The use of the loading prediction will be to determine whether they are likely to be sufficient to create water quality problems, and thereby guide decisions on the need for the consideration of control measures. the most appropriate loading estimate would be on that has a long term basis, and integrates any changes that might result from the repeating cycle of pavement condition between resurfacing activities.

Design, geometrics, cross-sections - In terms of highway design, the most important factor appears to be whether or not the possible layout options will permit the inclusion of vegetated or other control features, or the diversion of runoff from a sensitive water body. As discussed earlier, orientation relative to prevaling winds, pavement composition or type of cross-section have no significant influence on runoff loads and need not be considered to be design constraints or preferences.

Vegetation types on right-of-way - The presence of vegetation in the right-of way has an important influence on the pollutant levels that escape from a highway site. Trees and shrubs have been shown to trap air-borne pollutants (Douanne-Bauvin 1987), which are retained as leaf surface deposits. Precipitation ultimately washes these deposits off, and they are then incorporated into the soil, with limited root zone uptake into plant tissue. Grassed areas using species appropriate for the region and properly maintained, effectively remove pollutants in the runoff from paved surfaces (Versar 1986).

Drainage features - Pollutant discharges to a receiving water, as opposed to the edge of the pavement, will be strongly influenced by whether runoff is immediately collected by a system of piping and rapidly and directly conveyed to an overflow point, or whether it reaches its eventual discharge point after passage through vegetated drainage channels. Wherever site conditions permit, the latter is the preferred drainage feature to employ (Maestri and Lord 1987). The avoidance of curb and gutter drainage design where possible, is preferred.

OPERATIONAL SITUATIONS

Traffic characteristics (density, speed, braking) - Traffic density is commonly suggested to be the major operational consideration affecting highway runoff pollutant loads. Adequate information on overall average traffic density was available in the data base that was analyzed, and will be available for projections at any study site. Most previous studies (Lord 1987, Mar et al 1982) have incorporated average daily traffic (ADT) in a predictive procedure or recorded ADT levels in studies on highway runoff (Stotz 1987). Attempts to quantify correlations between highway pollutant loads and traffic density have been less than satisfying, and the regressions developed have not proved reliable when applied to locations that were not embodied in the data set used to develop the correlation (see section 5.2 Of this report). In this study we found ADT to be a significant and quantifiable factor only on a very broad scale (ADT greater or less than 30,000 vehicles per day), and this we conclude to be more the effect of the surrounding area than the ADT per se, as discussed further below. Traffic density levels are clearly a factor in pollutant load levels, but they do not appear to be sufficient to dominate the site to site variations produced by the combined effect of all other variable factors. For the secondary traffic characteristics, average speed and braking frequency, which might modify the general effect of ADT on pollutant loads, there is evidence that vehicle speed and braking influence exhaust emissions and mechanical wear. However, this study does not provide adequate data to quantify these potential influences on runoff quality.

Vehicle characteristics (type, emission,age,maintenance) - The data base assembled for analysis in this study does not include the detail that would be required to evaluate the influence of this factor on the pollutant loads generated by a predictive model. Moreover, while the condition of a particular vehicle can be expected to influence its contribution to pollutant discharges, the general loading predictions that are the primary objective of this study are most appropriately a reflection of the net effect of the overall combination of vehicle types and conditions that use the highway section being evaluated.

Vehicular transported, generated and deposited inputs - Clearly, the type of material transported in significant amounts over a particular stretch of highway, and deposited on the road surface in transit, can have an important influence on the quantity of specific pollutants that are discharged in the stormwater runoff. For example a highway segment at the convergence of multiple access routes to a municipal garbage transfer station may have non-typical runoff levels for organic pollutants. The data base analyzed in this study and the predictive procedure developed from it is considered to apply to a "typical" highway situation. The user should recognize that where unique or unusual local conditions are present, the estimates should be adjusted.

Maintenance practices (sweeping, mowing, weed control, repair) - Maintenacge practices, and the efficiency with which they are applied will have some influence on pollutant loads. For example, maintaining the height of grassed areas at levels that result in the most efficient operation for overland flow and grassed swales, will enhance the retention of pollutants present in the runoff. Unnecessary or excessive use of weed control chemicals could result in their presence in the runoff. The available data provide no basis for quantifying the effect of maintenance practices on the level of pollutant discharges from a highway site, and they are not included as a factor in the predictive model.

Institutional characteristics (litter laws, speed limit enforcement, car emission regulations) - These factors may be presumed to have some undefined degree of favorable influence on pollutant discharge levels, but they are very likely minor. More importantly, there is no basis fordetermining the degree of influence they might have from the data that is available, and these factors have not been considered for use in the predictive model.

SURROUNDING LAND USE CHARACTERISTICS

Surrounding land use is indicated by the results of this study to be the most important general factor that influences the level of pollutant loads in highway runoff. Runoff quality differed significantly, (as discussed in section 4.5) between highways in urban areas versus those in rural areas. Traffic densities are markedly different between thes two categories of surrounding land use, but the lack of a clear correlation with ADT within each grouping, leads to the conclusion that the general atmospheric quality differences between urban and rural areas is the most important influence. This is supported by an independent study of runoff from highways in West Germany (22) which concluded that ADT is not a dominant factor determining pollutant levels, and that surrounding area characteristics is a more important influence. The available data also suggest that unusual local factors can result in abnormal levels for specific pollutants. An example is the non-typical zinc concentrations found in one of the Washington State sites adjacent to a smelter. This, however will reflect isolated localized situations influencing a limited segment of highway. Such conditions are ignored in the general predictive scheme, but should be considered for local estimates whenever appropriate.

5.1 INTRODUCTION

A review of the literature addressing the characteristics and prediction of pollutants in stormwater runoff from highways and land uses that respond similarly to runoff, indicated that three analysis/predictive approaches be given consideration for the purposes of this study effort. These methods can be grouped into the following categories:

- REGRESSION METHODS - These provide a relatively simple approach, and have been used on a number of earlier studies dealing specifically with runoff from highways. They are discussed in section 5.2 below.

- SIMULATION MODELS - A number of deterministic simulation models have a significant history of application in highway runoff or analogous situations. These are discussed in section 5.3 below.

- STATISTICAL TECHNIQUES - Methods of this type were successfully applied to urban runoff in a recent EPA program, and are directly applicable to highway runoff. This approach is discussed in section 5.4 below.

This section presents a brief discussion of well-documented and tested examples of the foregoing procedures, and evaluates their potential use in predicting pollutant discharges from highway sites. This synopsis is based on the more detailed description and evaluation of each procedure prepared as an interim task report on this project.

5.2 REGRESSION METHODS

Regression equations provide a quick and simple means for estimating highway runoff quantity and quality. Although most sampling studies perform some elementary statistical analysis on their data, there were only a few studies combining comprehensive data bases and regression analysis. These include three FHWA studies, by Envirex (33), the University of Washington (34), and the California Department of Transportation (4), and a U.S. Geological Survey study on a highway site in south Florida (5) containing regression equations on constituent loads in the stormwater runoff (35). Finally, the Midwest Research Institute (36) performed a regression analysis on highway data as part of an EPA study on estimation of nonpoint source runoff quality. The "Student Workbook" prepared by the FHWA for its Highway Runoff Water Quality Training Course summarizes and discusses results from some of the above sources.

The Envirex predictive equations estimate the total solids (TS) load in runoff from individual storms, and have two major components: accumulation of the pollutant (TS), followed by pollutant washoff. Accumulation (build-up) is modeled as a linear function of accumulation period and traffic volume, and washoff is expressed as an exponential function of the runoff rate. Pollutants other than TS are predicted by linear regression from TS. Results are based on sampling in four cities (Milwaukee, Harrisburg, Nashville, and Denver) for three different types of interstate highway sites: a) urban elevated bridge, b) urban with mountable curb and paved and nonpaved roadside drainage, and c) rural.

In the Washington State procedure, traffic volume, observed when the highway pavement is still wet, is the major independent variable in determining the quantity of suspended solids in the stormwater runoff. This is in contrast to the Envirex method where buildup time and runoff rate determine the amount of pollutants found in runoff and follows from fundamental differences in the precipitation patterns at the sites providing the data bases [34]. The Envirex sites generally experience relatively intense but brief storms, whereas Washington State has extended rains of low intensity. In the Pacific Northwest, transport of highway contaminants was suggested to be more a function of kinetic energy provided by moving vehicles than of rainfall [34]. Again, other pollutants are computed as a fraction of the suspended solids load. As Miracle [37] and McBean and Burn [38] point out, some of the Washington State regression results exhibit spurious correlation because of regression analysis inappropriately applied to double mass curves.

The California and USGS South Florida studies used multiple linear regression to predict pollutant loads (dependent variables) using different independent variables. Examples of independent variables tested in these studies include average daily traffic, dry days before the storm, runoff volume, and storm duration.

The Midwest Research Institute study developed an equation to predict the deposition rate of pollutants on highway surfaces (but not the washoff). The loading function is dependent on the length of the highway and the amount of traffic. This equation is for the accumulation of traffic related materials on roadway surfaces and does not represent the discharge of pollutants to the roadside.

<u>Comparison of Regression Equations</u>

Measured rainfall, runoff, and quality data were used to evaluate the five groups of predictive equations. Results of this analysis by Miracle (37), an interim study product, are presented below.

Predicted loads were estimated for each method using site-specific rainfall, runoff, traffic, and inter-event data, and were compared with measured loads. Unfortunately, an independent data set was not available, and the rainfall, runoff, and pollutant load data were selected from the data base for the highway site in Broward County, Florida (5,39). These are the same site and data used by Miller et al. (35) to develop regression equations and will therefore bias the results in their favor.

All of the rainfall, runoff, and quality data needed to predict pollutant loads using the predictive equations were available for 42 storm events from the period 1975-1977 in the EPA rainfall-runoff-quality data base [39]. Most of the site data (i.e., area of the site, ADT, and length of highway) were available from Mattraw [40] and Miller [41]. Assumptions were made for any inputs not given for the site, including the daily distribution of average daily traffic (ADT).

The Envirex method required a choice of the site type, for which Type II (paved and unpaved with curbs and inlets along the paved area) was used. Other parameters of the method could be estimated from the data base.

The only assumption needed for the Washington State and California equations was the number of vehicles during the storm (VDS). This value was estimated using an assumed hourly distribution of the known ADT for the site. The VDS value could then be estimated from the known time of day of the storm. Loading equations for both eastern and western Washington were available and both were used for the comparison.

The loading equations contained in the Midwest Research Institute study are for the deposition rates of pollutants, not their washoff. In lieu of a better assumption, we used the common exponential washoff assumption incorporated into most simulation models (originating with reference 42), discussed later. The method was applied arbitrarily such that a rainfall of 0.5 inch would remove 90 percent of the pollutants accumulated. Another necessary assumption was the value for the average number of axles per vehicle; 2.5 was used.

Results

A graph of measured versus predicted load gives a qualitative view of the accuracy of a predictive method. If the predicted load equals the measured load, the graph will plot as a straight line. On the other hand, scattered data points away from the line indicate that the predictive equations are not accurately predicting the measured loads. Comparisons for all constituents and methods are shown by Miracle (37) along with computed percent differences from measured values. A typical poor fit and a nontypical good fit are shown by figures 35 and 36. Results from this comparison are summarized for each regression method, and for all pollutants, in table 19.

Table 19. Broward County, Florida highway site - USGS runoff data.

Mean Percent Difference for Measured vs Predicted Pollutant Loads

Constituent	USGS S. FL	Envirex	Wash. St. (W. WA)	Wash. St. (E. WA)	Calif.	Midwest Res. Inst.
Total Solids	-27	-69	--	--	--	--
Suspended Solids	--	100	16	-243	-18	--
Total Filt. Res.	--	--	--	--	77	--
TKN	--	-320	97	94	-6	84
NO3-NO2	--	--	94	73	--	--
Nitrate-N	--	--	--	--	--	75
Nitrite-N	--	--	--	--	--	-192
Total Nitrogen	-19	-71	--	--	--	--
BOD	--	-678	--	--	--	79
COD	-80	-1108	93	72	60	20
TOC	--	-235	--	--	--	--
Total Carbon	-39	--	--	--	--	--
Total Phosp.	-29	96	80	16	--	-439
Lead	-43	64	96	90	74	-2722
Zinc	-86	-153	94	-131	23	-1061
Copper	--	-1824	86	43	--	-1065
Cadmium	--	-3402	--	--	--	--
Iron	--	100	--	--	--	--
Chromium	--	-359	--	--	--	-286

Discussion

The South Florida and California methods generally have the best results when compared to actual pollutant loads. However, the graphs of predicted versus measured loads were much better for the USGS South Florida method than for the California method. The strength of the USGS

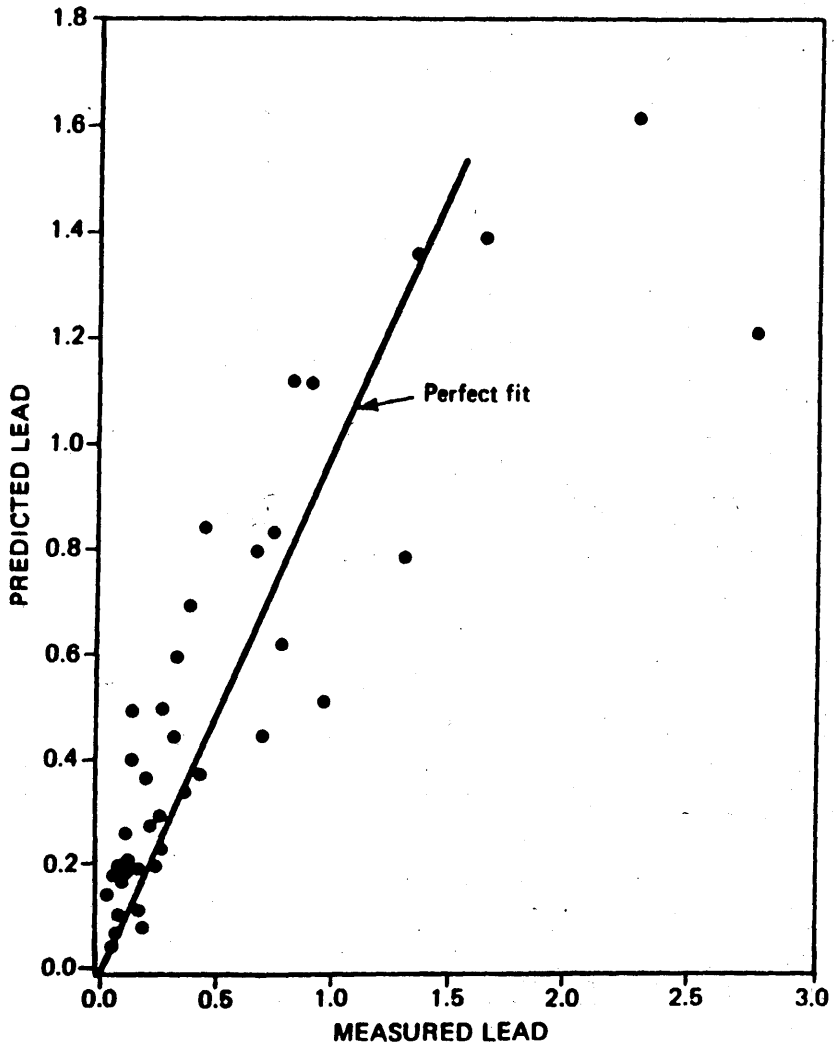


Figure 35. A good fit (very unusual) of predicted vs measured lead (lbs) by USGS South Florida method.

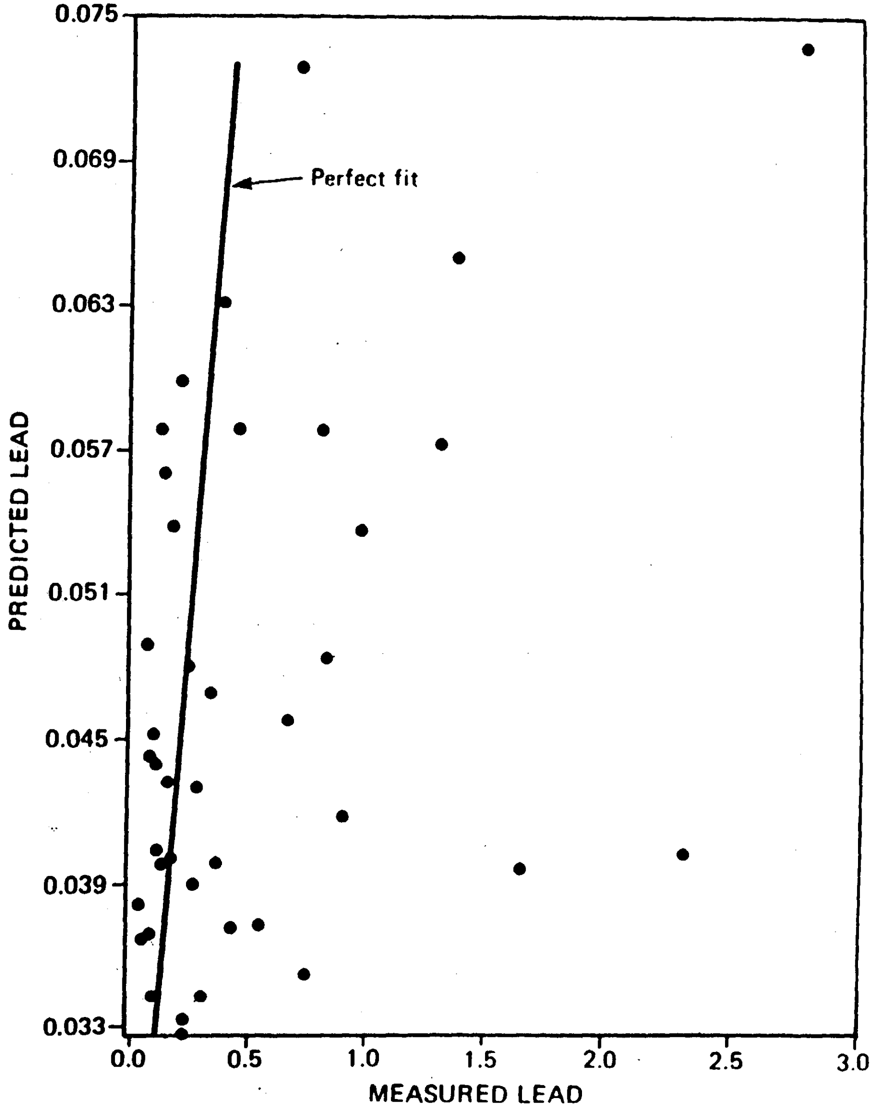


Figure 36. A poor fit (typical) of predicted vs measured lead (lbs) by California method.

equations would be expected since the storm events selected were from the same data base used to derive the USGS South Florida regression equations.

Generally, the predictive equations were not very accurate when compared to the actual runoff loads, for a number of reasons. First, only 42 of the 108 storms monitored by Hardee et al. (5) contained constituent load data. Second, the VDS assumption can be questioned in light of no VPH (vehicles per hour) data for the test site. Third, the California and Washington State studies were conducted in different climates than South Florida. These two studies might give better results for highways in their respective region of the country, but there is no way to check this at this time. Nor can the four Envirex cities be considered to be in the same region as South Florida. Finally, the Midwest Research Institute loading equations were for accumulation rates and not for washoff loads.

In summary, the USGS South Florida regression equations generally gave the best results when compared to actual data. It is noted that both the USGS South Florida and California methods used only "pure" multiple regression analysis (i.e., no assumption as to functional form other than linear or log-linear) in the predictive procedure. Conversely, the other studies used a combination of regression methods. For example, Envirex also used linear buildup and exponential washoff equations while Washington State modeled TSS loads which were then regressed against other constituents. No final conclusions or recommendations concerning these simple methods can be made based upon data from only one site.

5.3 SIMULATION MODELS

Numerous models have been developed to simulate stormwater runoff quantity and quality from urban and non-urban areas. A number of these models can be used to estimate pollutant loads from highway stormwater runoff. However, this review concentrates on only those models which are operational, that is, models that have documentation, user support, support by a government agency, and are widely used by other than just the model developers. Models meeting these requirements are SWMM, STORM, and HSPF. The FHWA Urban Highway Storm Drainage Model was also included in our review because it specifically models highway sites. SWMM and STORM include routines to compute the effect of certain controls.

Another possibility is the USGS model developed for urban quality predictions by Alley and Smith (43). However, it has seen considerably fewer applications than SWMM, STORM or HSPF, and its quality routines are basically subsets of those in SWMM and HSPF (Huber 1985). Hence, it is not included in this review.

Generally, these models simulate the buildup of pollutants during dry periods, followed by washoff during storms. This was first implemented in the original EPA Storm Water Management Model, SWMM (42). The functional form of the buildup and washoff equations varies from model to model, ranging from highly flexible in SWMM to rigid in STORM. Another approach besides modeling buildup and washoff is the use of a rating curve methodology. Some urban runoff data exhibit a linear relationship on log-log paper of flow versus concentration. This may be easily programmed and is an option in SWMM.

Although it might be assumed that complex simulation models should represent an improvement over simple regression equations for prediction of runoff quality, it should be remembered that simulation models are the most demanding of site-specific data, <u>including measured runoff quality data</u>, of any method. These models might be viewed as "very complex regression equations" which must be calibrated in the same way that least squares is used to fit ordinary regression relationships to data. The advantage is not that the simulation models provide a better prediction of storm event loads, since they do not necessarily do so. Rather, the models provide a more physically realistic predictive mechanism which, when calibrated, may more easily be altered to examine the effects of changes and abatement practices. Also, simulation models provide a temporal and spatial distribution that is unavailable in simple regression techniques. For example, continuous simulation models may be used to generate a time history of pollutant loads from which a frequency analysis may then be conducted. This permits an analysis on the basis of pollutant characteristics rather than on rainfall or runoff characteristics. (The EPA statistical method, to be described later, approaches this same end by means of a derived distribution, rather than simulation.)

In addition to the interim project report by Miracle [37] that has been used for this summary discussion, model reviews are provided by Huber and Heaney [44] and EPA [17]. A detailed review of physically based mechanisms for prediction of urban runoff quality, including highways, is given by Huber [45]. Only brief summaries of model characteristics can be given below.

5.3.1 Storm Water Management Model (SWMM)

The current Version 3 of SWMM [30,46] performs single event or continuous simulation of quantity and quality over the entire range of an urban catchment, including surface areas, the drainage system, and storage/treatment facilities. Runoff is generated from rainfall and routed in the Runoff Block using a nonlinear reservoir method. Flow routing may also be performed by this method or by the kinematic wave method in the Transport Block or by using the complete dynamic wave equations in the Extran Block. Reservoir routing is accomplished in both the Transport and Storage/Treatment Blocks. Of course, flow routing must be performed prior to quality routing in all of the simulation models.

Overview. On an impervious surface it is usually assumed that a supply of constituents builds up on the land surface during dry weather preceding a storm due to the combined effects of all processes that occur during that time period, such as traffic flow, dry fallout, wind erosion, and street sweeping. This concept is based strongly on early sampling of street surface material in Chicago by APWA [47]. During a storm event the material is then washed off into the drainage system. The physics of the washoff may involve rainfall energy, as in some erosion calculations, or may be a function of bottom shear stress, as in sediment transport theory; however, it is most often treated by an empirical equation with slight physical justification [45]. Nonetheless, well-known experiments performed by Sartor and Boyd [48] have long justified the "exponential washoff" formulation described below.

From a predictive point of view, quality loads may be generated equally well by a rating curve approach in which loads are proportional to flow to some power. This approach, an option in SWMM, may also be justified physically and is often easier to calibrate using available data.

Up to 10 arbitrary constituents may be simulated in the Runoff Block of SWMM, either individually or as functions of other pollutants (e.g., a pollutant could be calculated as a fraction of suspended solids). Input data may include several parameters for each pollutant as well as land use data.

Although the conceptualization of the quality process is not difficult, the reliability and credibility of quality parameter simulation is very difficult to establish. In fact, quality predictions by SWMM or almost any other surface runoff model are almost useless without local data for the catchment being simulated to use for calibration and verification [30]. This is in contrast to quantity prediction for which reasonable estimates of hydrographs may be made in advance of calibration.

Buildup. SWMM provides three options for constituent buildup as a function of time: power-linear, exponential, or Michaelis-Menton. Linear buildup is simply a subset of a power function buildup. The shapes of the three functions are compared in figure 37 using strictly arbitrary numerical values of the parameters. Exponential and Michaelis-Menton functions have clearly defined asymptotes or upper limits. Upper limits for linear or power function buildup may be imposed if desired. Guidelines for parameter estimation are provided in the documentation and from sources such as Manning et al. [49].

Washoff. It is assumed that the amount of pollutant that can be removed during a rainfall is dependent on the storm duration and initial quantity of the pollutant. This is modeled in the SWMM by a modified first order differential equation of the form

$$-POFF(t) = dP/dt = -K\,r^{W}P \tag{9}$$

where

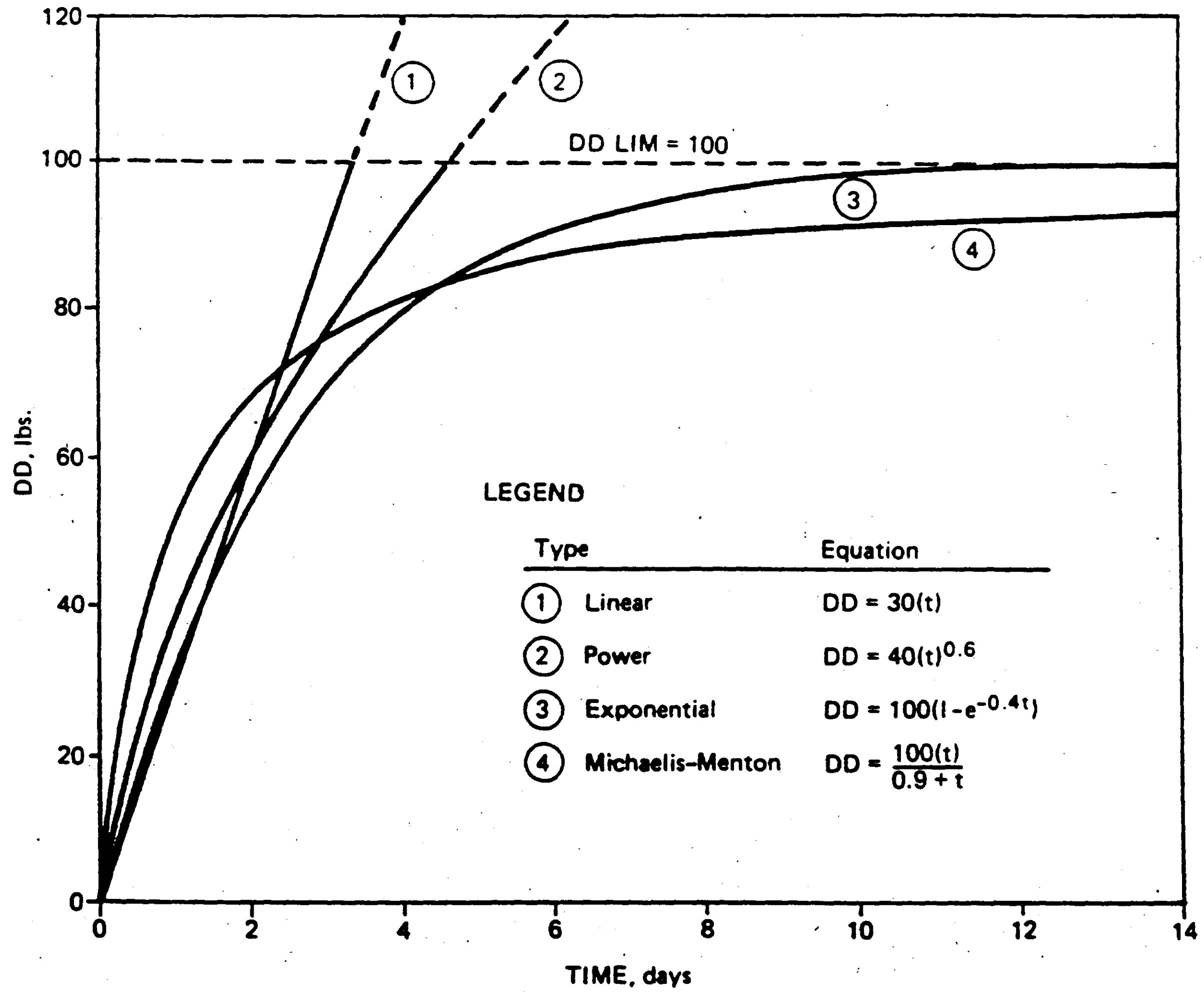
POFF = constituent load washed off at a time, t, quantity/sec
P = quantity of constituent available for washoff at time, t
K = washoff coefficient, $(1/sec)(in./hr)^{-W}$
W = exponent
r = runoff rate, in./hr

Although the load remaining on the surface, P, decreases in an approximate exponential fashion, loads and concentrations in the runoff may vary significantly during the storm. It may seem that if equation 9 is divided by area and runoff rate to obtain concentration, then concentration is proportional to r^{W-1}. Hence, if the increase in runoff rate is sufficient, concentrations can increase during the middle of a storm even if P is diminished [30], as long as W is greater than 1. The original SWMM methodology used W=1 which prevented this.

The washoff equation has two parameters, K and W, that usually must be obtained through calibration. However, they provide sufficient flexibility such that the use of "availability factors" (which were included in the original SWMM formulation) may be avoided, since they are empirical functions derived from site-specific data to enable better fits of predicted and measured washoff data. See the ensuing discussion of the STORM and FHWA models for examples of availability factors.

Rating Curve. That the load rate of sediment in streams is proportional to flow rate is supported by both theory and data [50,51]. In addition, many urban runoff event mean data (loads and average concentrations from a complete storm event) are analyzed in this fashion, that is, as a power function of flow. In SWMM, buildup and washoff calculations may be completely avoided and load rates computed for each subcatchment at each time step by a rating curve method

$$POFF(t) = a\,Q^{b} \tag{10}$$



Note: "Dust and dirt", DD, is used as an example.
Numerical values have been chosen arbitrarily.

Source: Huber et al., 1981b

Figure 37. Comparison of linear and three non-linear buildup equations.

where

> Q = subcatchment runoff, cfs
> POFF = constituent load washed off at time, t, quantity/sec
> a = coefficient (quantity)$(ft^{-3})^b(Sec)^{b-1}$
> b = exponent

The rating curve methodology works well for parameters that do not exhibit hysteresis in a plot of load versus flow during a storm (30). If hysteresis is present, the washoff method of equation 10 works well. A disadvantage of the rating curve is that it is harder to simulate control options and changes in the catchment; such effects can more readily be simulated with buildup and washoff parameters.

5.3.2 FHWA Urban Highway Storm Drainage Model

Most of the components of the FHWA model (52) are based on SWMM; hence, it is very similar in most of its quantity and quality methods to the SWMM model (and also to the STORM model). The model is divided into four related but independent modules. The Precipitation Module can perform a variety of statistical analyses on long-term hourly precipitation data and generate design storm hydrographs. The Hydraulics/Quality Module (based on the SWMM Runoff Block) simulates time-varying runoff quantity and quality, locates stormwater inlets, and sizes the conduits of the major drainage system. The Analysis Module (based on the SWMM Extran Block) simulates unsteady gradually-varied flow in the drainage system and can be used to analyze complex hydraulic conditions, such as surcharge and backwater, that may be encountered during extreme storm events. The Cost Module can be used to estimate construction, operation and maintenance, and total annual costs associated with the drainage system.

Overview. The FHWA model is a single-event model that can simulate up to 13 pre-specified pollutants. Most of the quality procedures are a subset of those available in SWMM. Although the model has not been applied much in practice, the techniques used in the model are based upon much experience with SWMM and STORM.

Buildup. Buildup of suspended solids is a function of dry-weather days preceding a storm by the Michaelis-Menton relationship shown for SWMM in figure 37. All other pollutants are computed as fractions of suspended solids.

Washoff. This is computed similarly to equation 9, except that an "availability factor," AVAIL, is used on the right-hand side instead of r^W. AVAIL is given as

$$AVAIL = 0.33 + 33\, r^2 = 33(.01 + r^2) \qquad (11)$$

where

> AVAIL = empirical availabilty factor
> r = runoff rate, in./hr

So for washoff, equation 9 becomes

$$-POFF(t) = -(K)(AVAIL)P \qquad (12)$$

with AVAIL calculated as shown above.

The model structure is such that this formulation can only be changed by altering the code and not by adjustment of input variables. The indicated functional form is based on experience with the model in Detroit.

5.3.3 Storage, Treatment, Overflow, Runoff Model (STORM)

The STORM model of the Corps of Engineers, Hydrologic Engineering Center [53,54] was the first continuous simulation model to be developed primarily for urban areas and was developed for planning for control of stormwater and combined sewer overflows in San Francisco. It has since seen wide usage as a screening tool for urban water quantity and quality control.

Hourly runoff values are generated by either a weighted runoff coefficient plus depression storage, or by the SCS method. The resulting runoff is routed to a storage-treatment facility where runoff less than or equal to the treatment rate is treated (by a constant removal rate) and released. Runoff exceeding the capacity of the treatment plant is stored for treatment at a later time. If storage is exceeded, the untreated excess is wasted through an overflow directly into the receiving waters (for easy simulation of CSOs). Statistics of the overflows and treated outflows are maintained.

Overview. The computations for the stormwater runoff quality are based on formulations used in the first version of the EPA Storm Water Management Model [42]. Up to six pre-specified pollutants may be simulated.

Buildup. The buildup of "dust and dirt" is a linear function of dry days preceding a storm, with allowance for street sweeping. The six pollutants are constant fractions of dust and dirt. Default values for surface loadings are based on the APWA Chicago study [47].

Washoff. Washoff is accomplished by means of equation 9 with the exponent, W, equal to 1.0. However, for two model parameters (suspended solids and settleable solids), the resulting load is multiplied by availability factors. In addition, variable fractions of suspended solids and settleable solids concentrations are added to the concentrations of BOD, nitrogen, and phosphate to account for the insoluble portion of these parameters not present during the APWA Chicago study. (No such addition is made for the sixth parameter, total coliforms.) Unfortunately, this parameter interaction makes it more difficult to calibrate STORM to measured data.

5.3.4 Hydrological Simulation Program - FORTRAN (HSPF)

HSPF [55] is an outgrowth of the widely-used Stanford Watershed Model (for its hydrology) and early EPA non-point source quality models, such as NPS and ARM. It is suitable for both urban and non-urban (completely pervious) land surfaces, and may be used in both a continuous and single event mode. A considerable strength of the model is its ability to manipulate the input and output time series involved in continuous simulation.

To simulate a highway surface, the impervious land segment module, IMPLND, of HSPF would be utilized. On such a surface, there is no infiltration, but storage, evaporation, and runoff do occur, and up to 10 water quality constituents accumulate and are removed. Water and pollutants then move downstream to a stream reach or reservoir segment for further routing.

Overview. A variety of methods exist for quality generation depending on whether impervious or pervious surfaces are being considered and on whether or not the pollutants are to be linked with "solids" (computed as a fraction of solids concentration).

Buildup. Solids and/or individual pollutants can be accumulated and removed by processes as a function only of dry-weather days preceding a storm. For example, buildup of solids uses the following relationship on a daily time step basis,

$$\text{SLDS} = \text{ACCSDP} + \text{SLDSS}\ (1.0 - \text{REMSDP}) \tag{13}$$

where

ACCSDP = accumulation rate of the solids on the surface, tons/acre/day

SLDS = solids stored on surface at end of time interval, tons/acre

SLDSS = solids in storage at start of interval,tons/acre

REMSDP = unit removal rate of solids in storage (i.e. fraction removed per day)

The removal rate, REMSDP, can account for factors such as wind erosion and street sweeping. If no runoff occurs, equation 13 implies that solids storage approaches an asymptotic, SLDSL, given by equating SLDS and SLDSS:

$$\text{SLDSL} = \text{ACCSDP} / \text{REMSDP} \tag{14}$$

Other pollutants may be computed as fractions of "solids" or by using equivalent forms of equation 12 for individual pollutants.

Washoff. Washoff of solids or pollutants can be performed using the same exponential washoff equation 9 (with exponent, W, equal to 1.0) that is available in the SWMM, FHWA, and STORM models. In addition, a form of rating curve approach is available in which washoff capability of solids is proportional to runoff to a power. The actual amount is limited to a maximum equal to the amount available through buildup.

5.3.5 Summary - Simulation Models

SWMM, FHWA, STORM, and HSPF can all be utilized for highway sites. The buildup and washoff algorithms of the STORM and FHWA models are basically less flexible versions of the general routines available in SWMM. Hence, SWMM might be preferred for its many options, including rating curves, unless the specific hydrology (or availability factors) of one of the other two models is desired. HSPF is almost as flexible as SWMM except for its exponential washoff (equation 9) which is limited to the exponent, W, equal to 1.0. On the other hand, its solids washoff equations are probably more sophisticated than those in SWMM, being based on data from pervious areas.

All four models have been used in urban areas, including highway surfaces, and a choice might be made on the basis of personal preference or familiarity. However, the ability to perform both continuous and single event simulation, plus the several modeling options available in SWMM and HSPF would probably place these two at the head of the list. Thus, both models can be used for both planning and screening purposes, as well as for detailed design simulations. Their general parameter options also make them easier to calibrate.

Whichever modeling choice is made, the importance of local, site-specific data for calibration and verification should always be remembered. Although prediction of relative changes in concentrations or loads (e.g., due to control options) might be reasonable with minimal data, prediction of absolute values of concentrations and loads will not be credible without such local data.

5.4 STATISTICAL TECHNIQUES

During the EPA sponsored nonpoint source studies in the late 1970's that were initiated in response to the requirements of section 208 of the Clean Water Act, a need arose for a screening methodology for estimates of stormwater quality loads and concentrations and their impact on receiving waters. The initial methodology [56] was developed by Hydroscience, Inc. and later refined [57] for application as a screening tool by the EPA Nationwide Urban Runoff Program (NURP). The NURP results [17] also included further models for application to streams [58]. The underlying idea of the method is to derive the moments (e.g., mean and variance) of the stormwater runoff event mean concentrations and loads and then to use these moments to derive the moments of the concentrations in the receiving water. Thus, the probabilty distribution is available for analysis, instead of just the mean values that a regression-type analysis would produce.

Underlying probability distributions for rainfall, runoff, concentrations, and loads are assumed to be gamma or lognormal, depending on the portion of the theory being applied. For example, the overwhelming majority of event mean concentration data from the NURP studies and elsewhere (including receiving water quality data) appear to fit a lognormal distribution very well. This observed fact, plus the ability to manipulate it analytically [58] has lead to the application of the lognormal distribution as the primary choice for the screening methodology. The gamma distribution is applied for studying the effectiveness of control options [59,60]. A gamma distribution characterizes a data set having a very large number of small values, and a very small number of large values. Rainfall data are generally considered to be well represented by a gamma distribution [57]. The mathematically convenient exponential distribution is a special case of the gamma, and results when the coefficient of variation is equal to 1.

In addition to the references listed above, reviews and comparisons of the methodology are given by Nix [61] and Goforth et al. [62]. The method has also been described in general terms in an earlier project report to the FHWA [63]. The following discussions will deal only with the approximate method for obtaining the moments of runoff quality concentrations and loads.

5.4.1 Characterization of Rainfall and Runoff Events

The Time Series. The rainfall or runoff may be viewed as a series of independent, randomly occuring events as shown in figure 38(a). This representation is further simplified by schematizing each event as a uniform, rectangular hydrograph, figure 38(b). Each event is characterized by its duration, volume, average flow rate or intensity, and the time elapsed since the last event (interevent time). The interevent time is measured between event midpoints.

The required statistics for this method are summarized in table 20. Here, the coefficient of

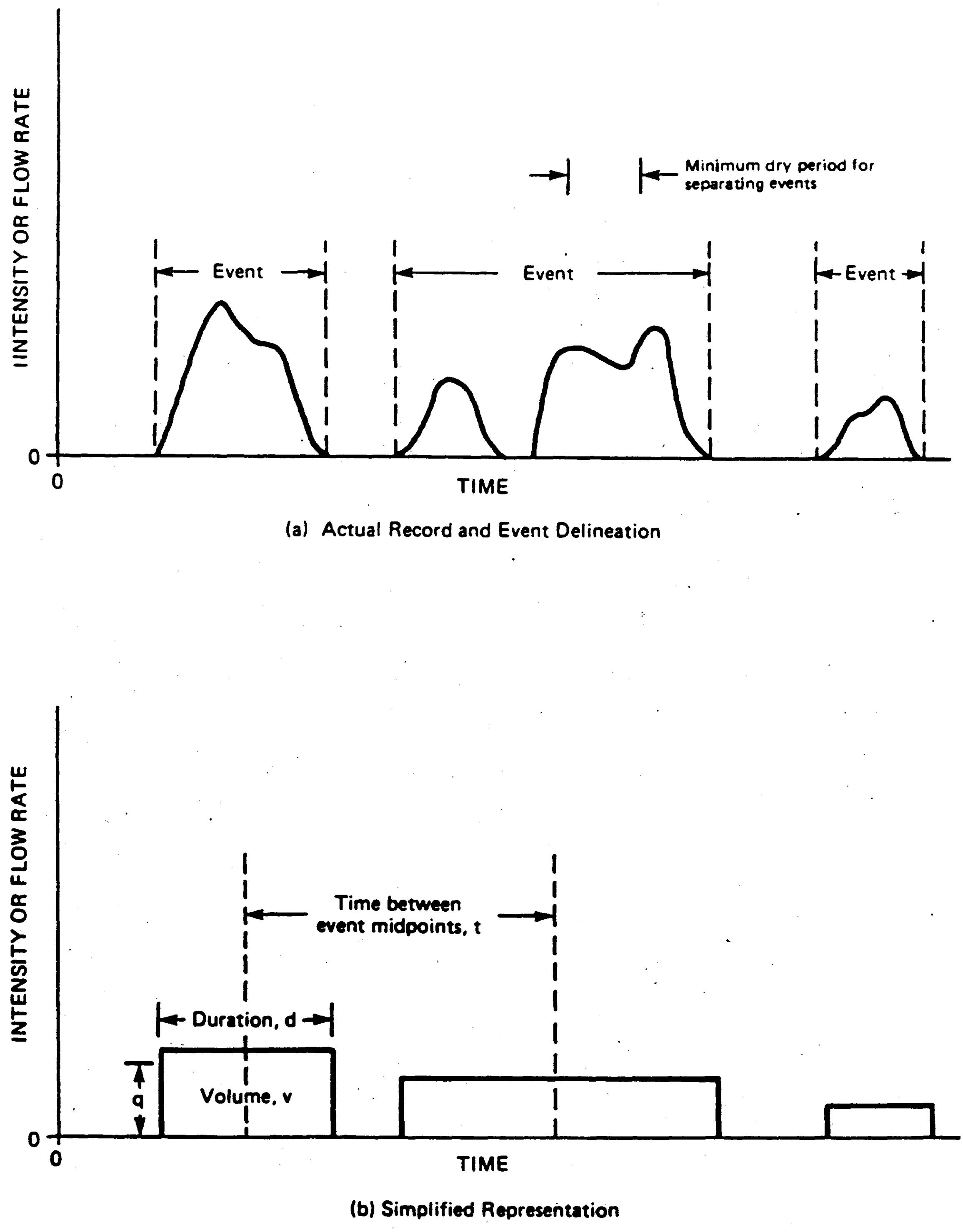


Figure 38. Simplified representation of independent rainfall or runoff events.
(HYDROSCIENCE, INC., 1979)

variation (ratio of standard deviation to the mean) is used in place of the standard deviation in order to have a convenient dimensionless parameter representing variance.

The parameters may be estimated from historical records. For instance, the SYNOP program (56) was developed to compute the four required statistics from hourly rainfall data. For example, representative values showing regional differences for these rainfall statistics are shown in table 21.

Definition of an Independent Event. The usual approach used for convenience in processing hourly rainfall data is to choose a minimum interevent time, MIT, such that rainfall values separated by less than MIT are considered part of the same storm. Values separated by times greater than or equal to MIT are considered to be independent. Several methods for choosing MIT exist [64], but the most common is to assume that interevent times are exponentially distributed, a common occurrence [57,65]. The exponential distribution has the property that its coefficient of variation equals one. Thus, trial values of MIT are chosen until the coefficient of variation of time between event midpoints (table 20) equals 1.0. Resulting values of MIT are usually in the range of 3 to 24 hours [57].

5.4.2 Runoff Statistics from Rainfall Statistics

Quantity Statistics. A simple runoff coefficient method is used to calculate the mean runoff event volume and flow from the corresponding rainfall statistics. For volume,

$$VR = Rv * VP \tag{15}$$

where

VR = mean runoff event volume
Rv = average runoff coefficient
VP = mean rainfall event volume

The runoff coefficient, Rv, represents the average runoff to rainfall ratio and neglects depression storage. Of course, this ratio varies from storm to storm, but for preliminary analyses the estimate is probably adequate [61]. The value of Rv can be estimated by an analysis of local rainfall/runoff data or estimated from one of several simple techniques [57].

The mean runoff flow rate is calculated as

$$QR = Rv * QP * (DP / DR) \tag{16}$$

where

QR = mean runoff event flow rate, volume/time
QP = mean rainfall event intensity, volume/time
DP = mean rainfall event duration, time
DR = mean runoff event duration, time

The ratio DP/DR is included to account for runoff continuing after the rainfall event has subsided. A method for estimating DR using unit hydrograph analysis is presented by Hydroscience [57].

The mean interevent time for runoff events, TR, is assumed to equal the rainfall value, TP. The coefficients of variation for runoff event flows, CVQR, and volumes, CVVR, are also assumed

Table 20. **Rainfall/runoff event parameters and statistics.**

PARAMETER (a)	SYMBOL FOR EACH EVENT (b)	EVENT MEAN (b)	COEFFICIENT OF VARIATION (b)
INTENSITY or FLOW RATE (L^3/T)	q	QP QR	CVQP CVQR
DURATION (T)	d	DP, DR	CVDP, CVDR
VOLUME (L^3)	v	VP, VR	CVVP, CVVR
TIME BETWEEN EVENT MIDPOINTS (T)	t	TP, TR	CVTP, CVTR

(a) Event intensities/flow rates and volumes are often normalized over the catchment area. When this is done, the units become L/T and L.

(b) The letters "P" and "R" will be used to denote a rainfall or runoff event parameter or statistic, respectively.

Table 21. **Regional differences in typical rainfall statistics.**

REGION	VOLUME (inch) MEAN	CV	INTENSITY (in/hr) MEAN	CV	DURATION (hours) MEAN	CV	INTERVAL (hours) MEAN	CV
NORTHWEST	0.45	1.5	0.02	0.9	20	1.3	100	1.0
ROCKY MT	0.20	1.6	0.04	1.0	4	1.2	100	1.0
NORTHEAST	0.40	1.5	0.08	1.1	6	1.0	80	1.0
SOUTHEAST	0.45	1.6	0.12	1.3	5	1.3	72	1.0

to equal their rainfall counterparts.

<u>Quality Statistics</u>. The mean pollutant load for all runoff events is determined by the mean pollutant concentration and the mean runoff event volume:

$$MR = CR * VR \tag{17}$$

where

MR = mean runoff event pollutant load, mass
CR = mean runoff event concentration, mass/volume

This equation assumes that the pollutant event mean concentrations are independent of runoff volumes; if not true, an adjustment is available below. Similarly, the mean pollutant load rate is found by

$$WR = CR * QR \tag{18}$$

where

WR = mean runoff event pollutant load rate, mass/time

Again, the assumption of independence between pollutant concentrations and runoff flow is made. If the independence assumptions are inadequate, the following corrections can be made [57].

$$MR = CR * VR * (1 + CVCR * CVVR * r_{cv}) \tag{19}$$

$$WR = CR * QR * (1 + CVCR * CVQR * r_{cq}) \tag{20}$$

where

CVCR = coefficient of variation for runoff event mean pollutant concentrations

r_{cv} = linear correlation coefficient between pollutant concentrations and runoff volumes (ranging from -1 to +1)

r_{cq} = linear correlation coefficient between pollutant concentrations and runoff flow rates

A positive value of r_{cv} or r_{cq} indicates that higher flows or volumes produce higher concentrations. A negative value indicates that the dilution effect of large runoff events is dominant.

Finally, it is assumed that all the variation in loads is due to variation in runoff volumes. Thus,

$$CVMR = CVVR \tag{21}$$

and

$$CVWR = CVQR \tag{22}$$

where

CVMR = coefficient of variation of runoff pollutant loads
CVWR = coefficient of variation of runoff pollutant load rates
CVVR = coefficient of variation of runoff volume
CVQR = coefficient of variation of runoff flow

The probability distribution of loads and concentrations is assumed to be gamma for application to storage-treatment analysis [59,60] and lognormal for application to stream water quality impacts [58]. A derived distribution for suspended solids in Rapid Creek, downstream of Rapid City, South Dakota is shown in figure 39 [17,58]. The fit of downstream concentrations is seen to be good.

5.4.3. Summary - Statistical Technique

The statistical method has been applied broadly as part of the NURP program [17] and is well suited for screening of impacts of stormwater runoff on streams due to its simplicity and availability of regional parameters (i.e., the statistics of rainfall may be described regionally.) It has the considerable advantage over regression methods of producing the frequency distribution of quality parameters instead of just the mean. However, it cannot simulate the interactions of flow and concentration nor the effect of abatement actions as well as simulation models can. For example, simulation models avoid the assumption that the coefficient of variation of the runoff and quality time series is the same as for the rainfall time series. But the method has proven itself as a screening tool at several locations around the country and can be applied without extensive computer facilities or as much input data as are needed by simulation models.

5.5 SUMMARY - PRIOR APPROACHES

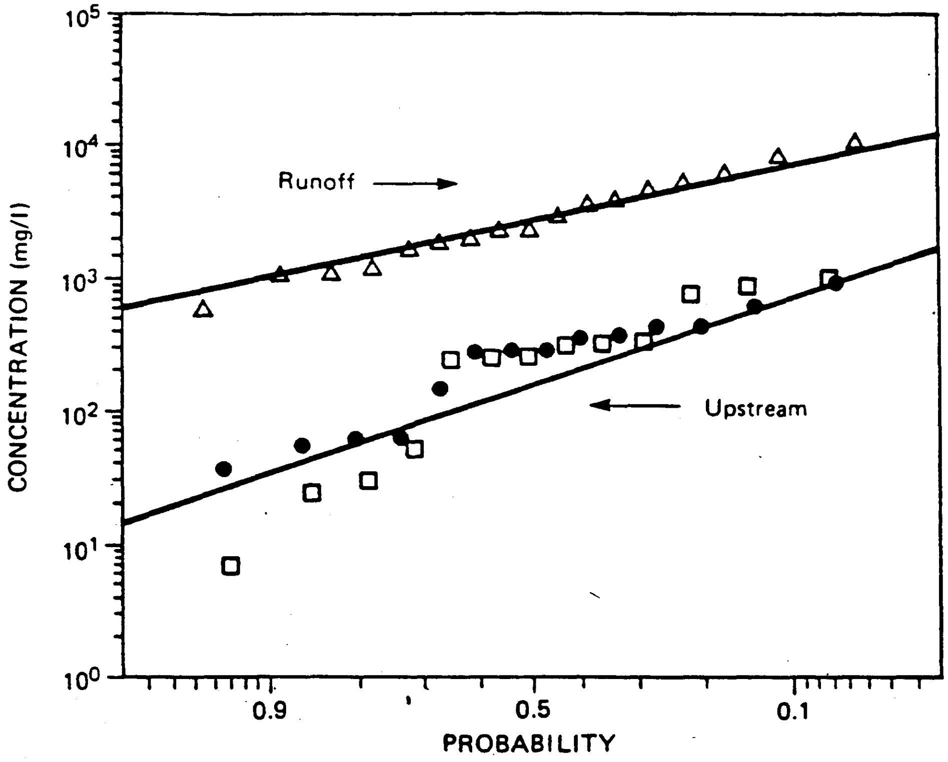
Regression equations, simulation models, and the statistical method are analytical tools for predicting pollutant loads from highway runoff. The primary advantage of the regression and statistical methods is that both allow a relatively quick, simple, and inexpensive screening of stormwater problems. This is particularly useful in the early stages of the planning process [57].

Each method has its own particular advantages and disadvantages. The regression methods are simple and include causative mechanisms such as rainfall characteristics, traffic counts, highway lengths, etc. On the other hand, only the mean is predicted for a given set of inputs. Furthermore, regression relationships are notoriously difficult to apply beyond the original data set from which they were derived.

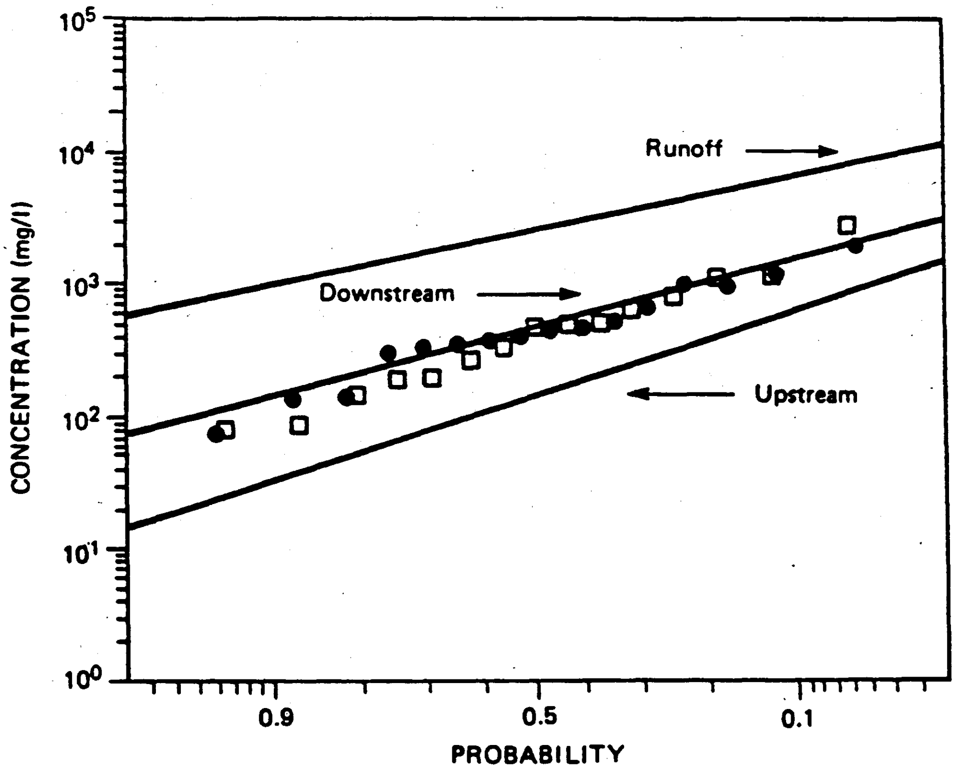
The statistical method requires rainfall statistics (readily available) and known mean concentrations of pollutants in the runoff (somewhat harder) as input variables (plus streamflow statistics, if that extension of the methodology is used). The output of a frequency distribution for water quality is tremendously useful, however, since assessments of risk and return periods can be made, e.g., what is the probability that a given concentration level will be equalled or exceeded? The method makes many approximations in the interest of obtaining an analytical solution, however, some of which may be important in individual cases [66]. The other difficulty with the method is that it is difficult to determine the effectiveness of control options or changes in the catchment with it.

Finally, simulation models require the most work, especially in terms of calibration and verification data requirements, but also produce the most varied output. For instance, continuous

RAPID CITY – STORM AVERAGES



a) TSS Distributions



b) Downstream TSS Verification

NOTE: Upper panel: Observed upstream(squares and dots) and runoff(triangles) total suspended solids(TSS) and fitted lognormal distribution(lines). Lower Panel: Observed downstream TSS distribution(squares and dots) and computed downstream distribution.

Figure 39. Methodology verification.

simulation can be used to derive the same statistics as produced by the statistical method and without as many limiting assumptions (but considerably more effort). The models are the most versatile in terms of assessing the effectiveness of control options and runoff changes due to changes in the catchment or other input variables, especially at the design phase. But they are practically useless for predictions of absolute values of concentrations and loads without adequate, site-specific water quality data for calibration and verification.

In summary, the various methods are complementary to each other and represent varying levels of complexity that may be applied as appropriate. Each can provide insight and direction for use of the other. All may be applied to the prediction of highway runoff quality with essentially no modifications. For example, although the selected statistical method has been selected as the most appropriate choice for use in predicting pollutant loads at a site based on general information from all other sites in the data base, additional flexibility results when circumstances or local preferences result in the development of a site-specific data set on highway stormwater runoff.

Regression models tend to be poor when applied to sites other than those on which they are based, but could provide a simple, convenient and useful method for comparing alternatives at the particular site whose data were the basis for the equations developed. The reliability of the projections will depend on whether all of the decision factors can be incorporated into the regression equations, and whether the "ranges" for data used in the projections are compatible with the "ranges" represented by the data used to formulate the equations. Regressions tend to be unreliable when their predictions are applied to conditions beyond the range of the data used in their formulation.

Simulation models, which can provide more detailed output predictions, could be based on either local monitoring data, or keyed to the predictions generated by the statistical technique. Sensitivity analyses by a simulation model could be used to address some of the simplifications and assumptions associated with the statistical approach. Conversely, the statistical approach can be used to reduce the number of more costly and time-consuming analyses that might be called for in a situation where a simulation model was selected for use in a local analysis.

There are obviously a variety of ways in which the three techniques can be used in complementary, mutually supportive roles, in cases where this is either appropriate or determined to be desirable by a user.

6.0 SELECTED APPROACH TO PREDICTIVE MODELING

6.1 INTRODUCTION

We selected a statistical technique as the preferred approach for predicting pollutant discharges by highway runoff. The success of a similar approach for urban runoff applications in EPA's Nationwide Urban Runoff Program (NURP) encouraged this choice, and results of the highway runoff data analysis activities described earlier in sections 3.0 and 4.0 provide additional support. Another factor considered in the selection was the ease of application, making it suitable for planning level evaluations or screening analyses. Further, the output format for the runoff pollutant predictions is compatible with available planning level procedures for evaluating receiving water impacts and the performance of controls subjected to intermittent and variable stormwater discharges.

Another merit of the statistical approach is that the user is reminded of, and provided with, a means of easily dealing with the inherent variability of the stormwater process. It also makes evident the impossibility of reliably predicting the pollutant loads from a particular individual storm event, a fact recognized by experienced practitioners using regression or simulation models, but easy to overlook by other, less experienced users. Finally, the user is explicitly made aware of the fact that, while overall site pollutant runoff characteristics can be estimated with reasonable reliability, there is uncertainty involved. A probabilistic format for characterizing the available data base provides a basis for evaluating the confidence level of a planning decision.

The previously developed regression models, as discussed in section 5.0, were not adopted because analysis against a broader data base indicated that, although they may give reasonable estimates for the small group of sites used in the formulation, they do not produce reliable predictions for most other locations. Simulation models were not selected for several reasons, though it is emphasized that they may be appropriate choices for more detailed studies to follow up a planning level analysis in certain situations. Simulators were considered less suitable for either the evaluation of the data base assembled for this study, or for use as a planning level screening model. The level of effort associated with application of these models, and the type and amount of data required for them to produce more reliable estimates than the simple statistical technique, were considered to be greater than available for this or for most local planning studies which the predictive model from this study is intended to support.

The important elements associated with the selected statistical approach are discussed below.

6.1.1 Separate Treatment of Flows and Concentrations

Consider the "pollutant loading" from a particular highway site. Data can be analyzed and summarized so that results are expressed in terms of a unit area loading rate (for example, as kilograms per hectare per year). On the other hand, one could choose to analyze the data and present the results in terms of unit area discharge flow and concentration. The former might be appropriate if, for example, one is assessing the impact of highway runoff to a lake and nutrients are the pollutants of concern. Such areal unit loads are not as useful, however, when one is dealing with a river or stream as the receiving water, since in such cases the ecological response to pollutant inputs is primarily driven by the transient concentrations resulting from individual, discrete events, rather than cumulative total mass loads over an extended period. This point is discussed in greater detail in section 7.0 of this report.

In addition, presenting data in the form of flows and concentrations is generally superior for making comparisons among different sites, and for evaluating the significance of different factors that may influence the runoff characteristics from a particular site. There are several reasons for this. Runoff flows are dominantly influenced by the size of a storm event, and as a result, so is the mass load of a pollutant. Monitoring programs are generally biased toward larger storms, so that load estimates derived from a limited number of events will often provide a distorted (and usually overstated) value for the long-term unit loading potential for a site. Further, because of the significant regional differences in precipitation characteristics, and the possibility that different site studies monitored different mixes of storm sizes, site comparisons and factor evaluations based strictly on monitored areal loads are at least faulty, and quite possibly misleading.

The data analysis results reported in sections 3.0 and 4.0 indicate that runoff flows and concentrations are, for all practical purposes, uncorrelated, and that event mean concentrations of pollutants in the runoff from any site are approximated well by a lognormal probability distribution. Because of this, it is the concentrations in runoff that provide the most useful parameter on which to base site comparisons, evaluate the significance of influencing factors, and base predictive methods. Since precipitation characteristics are readily available for any site, and rainfall/runoff relationships can be independently defined, this approach provides a useful way to deal with differences in storm characteristics associated with different studies, or different regions of the country.

6.1.2 <u>Site Factors Incorporated</u>

Consider the level of detail at which one should define the way runoff characteristics are influenced by site factors. If one's goal is to conduct basic research to develop a fundamental understanding of the process mechanics involved, one might need extremely detailed data and information. On the other hand, if one's task is to produce planning level procedures for estimating highway pollutant loads and receiving water effects, as in this project, such a high level of detail is unnecessary. A detailed study may even be detrimental to sound decision making by obscuring the essential elements that should properly influence the decision.

If the available data base does not permit quantifying the effect of interest, the "factor" has no place in a predictive technique. Similarly, however well established a given relationship may be, if the necessary data pertaining to the factors involved will not be available or obtainable within the resources that can be committed for a subsequent local analysis, the relationship has little practical value.

There are a number of factors which are thought to have an important influence on highway stormwater runoff loads and which, additionally, are elements of the available data base. As the highway stormwater runoff data reported in section 3.0 indicate, there is a high degree of variability in the data (e.g., flows and concentrations). Much of this variability is not explained very well, if at all, by factors identified as probable influences. This variability should be dealt with as a random process, with confidence bounds set on projections rather than using simple point estimates. It should also be noted that where the effect of a particular "factor" could not be quantified with an acceptable level of confidence, that factor was not used in this predictive model, even though the general conventional wisdom may suggest some positive or negative influence to it.

For example, it is widely assumed that highway sections without a curb or barrier will produce lower pollutant levels in runoff because they will permit a greater dissipation of road surface accumulations. This is reasonable to expect; however, the available data base is unable to confirm this, much less provide a basis for quantifying the magnitude of a potential effect. Only three of the 31 sites represented in the data base represent highway segments without curbs, so there is hardly a sound basis for conclusion one way or the other. Accordingly, the predictive model does not incorporate this factor. However, since the model develops a range of possible values, a planner convinced of the positive influence of the absence of curbs, may elect to assign greater weight to values in the lower end of the range.

Of all the potential site factors that one might reasonably expect to have an influence on highway runoff pollutant discharges, very few proved to be quantifiable from the available data base, and therefore considered suitable for use in the predictive model. Pollutant concentration levels in runoff have been shown to be significantly influenced by whether or not the highway is in an urban area. Also runoff concentrations are significantly different during periods when snow accumulations are being washed off. Total mass loads discharged are dominantly influenced by the overall volume of stormwater that runs off a highway site. This in turn is influenced by local rainfall patterns, which vary regionally, and by the total drainage area and its impervious fraction. The use of these factors in the predictive model is discussed below.

6.1.3 Surrounding Land Use

Surrounding land use has a number of different aspects for the prediction of highway runoff pollutant levels. Site specific factors may influence the pollutants deposited on a specific highway segment and washed off during storms. An example is the abnormally high zinc concentrations found at the Spokane site in Washington State which is adjacent to a zinc smelter. This site reflects a case where a local situation influences a limited segment of highway and a specific pollutant. Such influences are not covered by the predictive model. A user will be required to make appropriate adjustments to model predictions based on knowledge of, and information on, unusual local conditions.

A more generalized regional influence associated with dry, semi-arid areas, is suggested by the data base, but with insufficient information to define a formal quantitative relationship. The highway sites in Denver, and at Spokane and Pasco in the eastern part of Washington State do not produce runoff concentrations that appear abnormal, though they consistently fall in the higher end of the range of all highway sites. An analyst may elect to bias local estimates accordingly for sites in comparable surroundings.

The most important demonstrated effect of surrounding land use on highway runoff quality characteristics lies in whether the segment is located in an urbanized area, or in a rural area. Land use descriptions tend to be subjective and rather general. The more specific measure, average traffic density (ADT), is strongly related to whether a highway segment is in an urban or rural area. Our data analysis confirms earlier work that indicated that a break point at 30,000 vehicles per day provides a good separation of the two categories, and results in statistically significant differences in pollutant runoff levels. Accordingly, the predictive model uses a 30,000 vehicle per day division as a surrogate measure for assigning a site to an urban-type or non-urban-type (rural and suburban) setting, each of which is assigned different runoff characteristics.

The poor correlations between runoff quality and traffic density that were obtained after the segregation of the data base into urban and rural sub-sets, together with an expectation of poorer air quality in urban areas, leads us to believe that the land use characteristics of the surrounding area is the more important factor. In most cases, the ADT will provide a suitable basis for this distinction. However, there will be some locations where this is no so, for example a heavily travelled interstate highway in the rural link between two large urban areas. for estimates of runoff quality in such cases (rural surroundings but very high ADT, or vice-versa) the user may make note of the fact (see table 6) that there is an overlap between the pollutant levels in the low range of urban highway sites, and the high range of rural highways. Predictive estimates should preferably select a value in the area of overlap in such cases.

An additional important aspect of the surrounding land use is unrelated to predictions of the pollutants discharged by highway runoff. It is related to the pollutants contributed by other land uses in the same drainage catchment to the receiving water body they share in common with the highway drainage. Table 22, based on information presented in the FHWA Student Workbook for the Highway Runoff Training Course, presents some approximate concentration levels for a few of the pollutants found in stormwater runoff, contributed by different land uses. There will be site differences, so the values are not correct for all sites. They are, however, reasonable estimates of the order of magnitude of typical average concentrations from the indicated land use.

In many watersheds, the amount of runoff and the pollutant contribution from land uses other than highways will be much greater than from the highway runoff. This occurs despite the fact that a highway catchment, with its high impervious fraction, tends to convert a greater fraction of the rainfall to runoff (75 or 80 percent in many cases) than is generated by the non-highway areas of the basin. The fact that these other uses usually occupy the dominant portion of the watershed area tends to reduce the significance of the highway runoff as a source of pollutants, even when highways may carry higher concentrations of specific pollutants. Where typical highway pollutant concentrations are significantly lower, as with nutrients, highway runoff could be essentially excluded from the analyses in cases where water quality issues are related to nutrient loads.

Table 22. Land use influence on runoff quality.

POLLUTANT	REPRESENTATIVE RUNOFF CONCENTRATIONS milligrams per liter			
	HIGHWAYS		URBAN	AGRICULTURAL
	URBAN	RURAL	STORMWATER	RUNOFF
LEAD	0.400	0.080	0.150	---
ZINC	0.329	0.080	0.160	---
COPPER	0.054	0.022	0.034	---
PHOSPHORUS	0.400	0.160	0.330	0.800
NO_{2+3} - N	0.760	0.460	0.700	3.000

6.1.4 Snow Washoff Periods

The data indicate that during periods of the year when accumulated snow is being washed off, runoff concentrations of most pollutants are significantly higher than during all other times of the year. The procedure for predicting highway pollutant loads segregates such periods for independent treatment. For areas of the country that either never, or very rarely, have significant snow accumulations, all runoff predictions should be derived from the basic data set. For those areas that routinely experience the accumulation of roadside snowpack and its eventual washoff, usually during a relatively short period in late winter, separate pollutant loading estimates should be made for both the normal rain periods and for the snow washoff periods.

A separate analysis may be made to examine potential receiving water impacts resulting from the higher load levels associated with snow washoff events, but such an analysis should take into account the fact that there are usually only a few of these each year. In addition, the appropriate values for stream flow and temperature (which at such times will normally be well outside critical ranges) should be used for such analyses. Where the impact evaluation should use annual mass loads (as for a lake), a properly weighted estimate based on the proportion of the two kinds of events should be used.

6.1.5 Impervious Area Fraction

The impervious area fraction will influence total pollutant mass loads as it has a direct influence on the amount of runoff volume produced by rainfall events. This has a much greater effect on mass load than the potential range of differences in site median concentrations. Impervious area fraction remains the best available factor to combine with local rainfall patterns for developing predictions of the volume of runoff, and therefore mass loading, from a site.

6.1.6 Total Drainage Area

The total drainage area of a highway segment that directly contributes storm runoff to a receiving water body will have a direct influence on the potential for adverse impacts. Taken together with local rainfall characteristics, the impervious fraction, and the concentrations present in the runoff, the overall drainage area contributing runoff has a major influence on whether the runoff loads are quite large or relatively small in relation to the diluting capacity of the receiving water body in question.

A segment crossing a stream at right angles, or tangentially passing the shore of a lake, will normally tend to have a reduced potential for adverse impact, because the extent of the highway area that contributes will be limited. A greater potential for significant impact is present when a highway runs generally parallel to a stream (or circles a lake), so that runoff enters at multiple locations from a number of different road segments. Finally, the significance of highway runoff will depend strongly on the comparative relation of highway source pollutant loads to other sources that contribute, or to the background quality of the water body.

6.1.7 Regional Climate Effects

There are important regional differences in average precipitation amount, intensity, duration, and interval between storms. Storm size has been shown to have no significant influence on pollutant concentrations in runoff (see section 4.4). However, the substantial differences in regional rainfall amounts will have an important influence on the total loads discharged on an annual or seasonal basis. Also, regional differences in the average interval between storms may possibly influence concentration levels and hence the effect highway runoff exerts on a receiving water body. Overall volume (e.g., inches per year) relates to water bodies such as lakes, which respond to total mass loads. The average intensity and interval between storms, that determine runoff rate and the number of events an area experiences during a year, influence the impact on streams. These relationships are discussed in more depth in section 7.0 of this report.

Local values for precipitation characteristics can be determined from the analysis of long-term rainfall records for various locations across the country. An available computational procedure for doing so is the computer program SYNOP (Synoptic Rainfall Data Analysis Program), which was developed for the U.S. Environmental Protection Agency. An IBM-PC compatible microcomputer version of this program has been developed as part of this study, and was provided to FHWA on folppy disk.

SYNOP is a tool that can be used to efficiently summarize and characterize a rainfall record. Hourly rainfall data, readily available from the National Climatic Data Center in Asheville NC on floppy disks, form the input to SYNOP. The program organizes and summarizes rainfall data by individual storm events, and for each event determines its volume (inches), duration (hours), average intensity (inches/hour), and time since the previous storm (hours) measured as the interval between midpoints of sucessive storms. SYNOP delineates storm events as rainfall periods separated by a minimum number of consecutive hours without rainfall. From the list of synoptic storm events the statistics of the relevant storm parameters are then computed, and the mean and coefficient of variation of each parameter are determined. For each of the parameters (volume, intensity, duration, and interevent time), SYNOP computes:

- Storm event statistics stratified by month of the year
- Storm event statistics stratified on an annual basis for each year of record
- Storm event statistics for all storms in the period of record

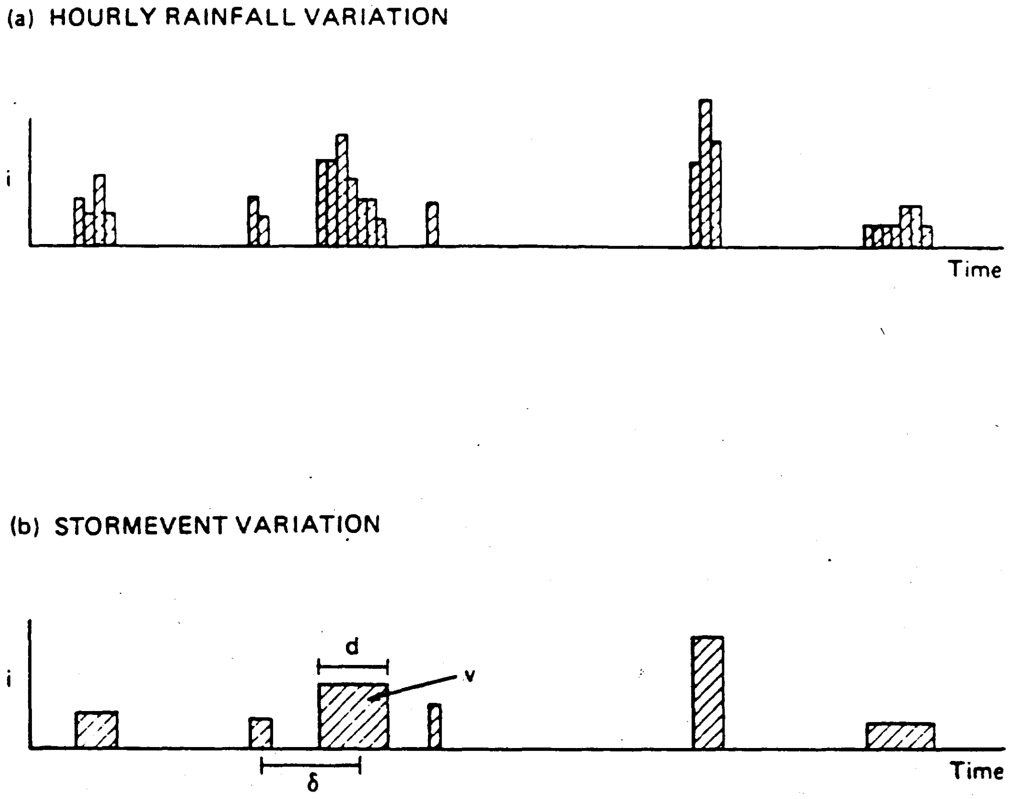
The analysis procedures used in this report are based on the statistical characteristics of storm "events" as developed by this program. Figure 40 illustrates how the hourly record is converted to an "event" record by the specification of a minimum number of dry hours that define the separation of storm events. Routine statistical procedures are then used to compute the statistical parameters (mean, standard deviation, coefficient of variation) of all events in the record, for the rainfall properties of interest.

Figure 41 provides a basis for preliminary estimates of storm event characteristics for broad regions of the country, based on about 60 different rainfall records that have been analyzed. This table provides a reasonable indication of gross regional differences, but it is emphasized that there are often significant localized differences within a region due to orographic or other effects. Final determinations should always be based on the analysis of an appropriate local rain gage having a long-term record.

From the statistics of the basic storm event parameters, other values of interest may be determined. The ratio of mean storm duration (D) to the mean interval between storms (Δ) reflects the percentage of the time that storm events are in progress.

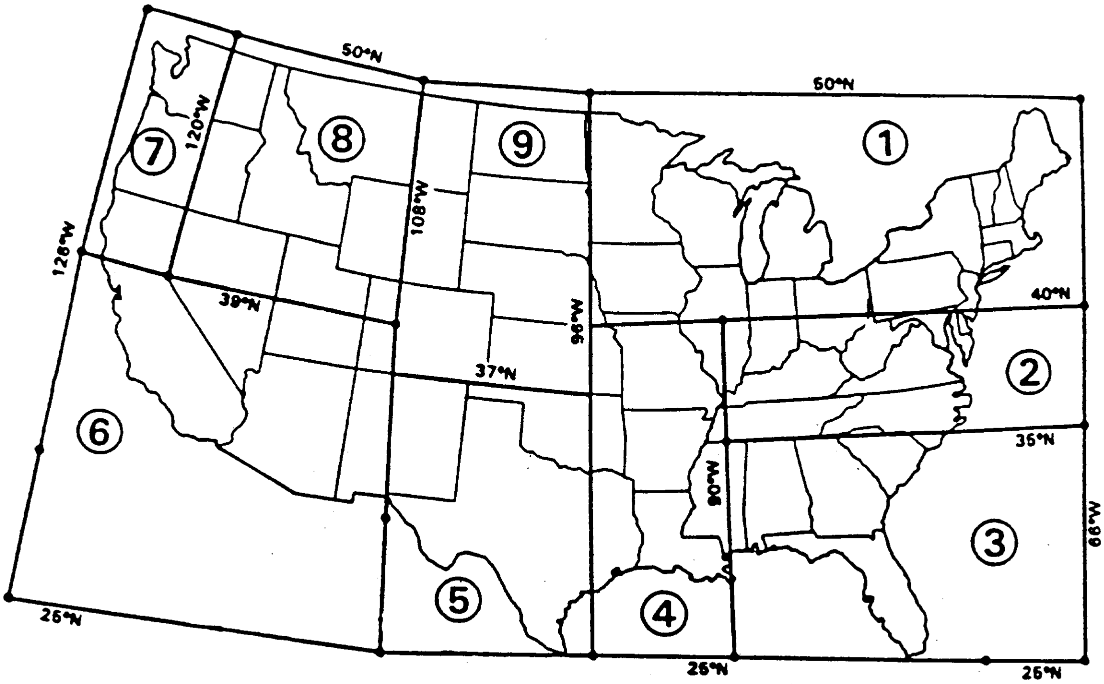
$$\%\ \text{time that it is raining} = \frac{D}{\Delta} \qquad (23)$$

The average number of storms during any period of time is defined by the ratio between the total number of hours in the selected period and the average interval between storms (Δ) in hours. For example, on an annual basis:



	PARAMETER			
	For Each Storm Event		For All Storm Events	
			Mean	Coef. Var.
Volume	v	(inches)	V	ν_v
Duration	d	(hours)	D	ν_d
Average intensity	i	(inch/hour)	I	ν_i
Interval between event midpoints	δ	(hours)	Δ	ν_δ

Figure 40. Characterization of a rainfall record.



ZONE	PERIOD	RAINFALL STATISTICS							
		VOLUME (IN)		INTENSITY (IN/HR)		DURATION (HR)		INTERVAL (HR)	
		MEAN	C.V.	MEAN	C.V.	MEAN	C.V.	MEAN	C.V.
1	ANNUAL	0.26	1.46	0.051	1.31	5.8	1.05	73	1.07
	SUMMER	0.32	1.38	0.082	1.29	4.4	1.14	76	1.07
2	ANNUAL	0.36	1.45	0.066	1.32	5.9	1.05	77	1.05
	SUMMER	0.40	1.57	0.101	1.37	4.2	1.08	77	1.06
3	ANNUAL	0.49	1.47	.102	1.28	6.2	1.22	89	1.05
	SUMMER	0.48	1.52	.133	1.34	4.9	1.33	68	1.01
4	ANNUAL	0.56	1.46	.087	1.35	7.3	1.17	98	1.00
	SUMMER	0.52	1.54	.122	1.35	5.2	1.29	87	1.06
5	ANNUAL	0.33	1.74	.080	1.37	4.0	1.07	106	1.41
	SUMMER	0.38	1.71	.110	1.38	3.2	1.08	112	1.49
6	ANNUAL	0.17	1.51	.045	1.04	3.6	1.02	277	1.48
	SUMMER	0.17	1.81	.060	1.16	2.6	1.01	425	1.26
7	ANNUAL	0.46	1.81	0.024	0.84	20.0	1.23	101	1.21
	SUMMER	0.26	1.35	0.027	1.11	11.4	1.20	188	1.15
8	ANNUAL	0.14	1.42	.031	0.81	4.5	0.82	94	1.38
	SUMMER	0.14	1.51	.041	1.13	2.8	0.80	125	1.41
9	ANNUAL	0.15	1.77	.036	1.35	4.4	1.20	94	1.24
	SUMMER	0.18	1.74	.058	1.44	3.1	1.14	78	1.13

Figure 41. Representative regional rainfall statistics for preliminary estimates.

$$\text{Avg. number of storms per year} = \frac{365 * 24}{\Delta} \tag{24}$$

The storm event parameters of interest have been shown to be well represented by a gamma distribution (57), and the results listed in figure 41 indicate that the coefficient of variation of the event parameters generally falls between 1.0 and 1.5. Figure 42 plots the probability distribution of gamma distributed variables with coefficient of variation of 1.0, 1.25, and 1.5, in terms of probability of occurrence versus the magnitude (expressed as a multiple of the mean). This plot can be used to approximate the magnitude of an event with a specified frequency of occurrence.

For example, at a location where storm events have volume statistics for MEAN and CV of 0.4 inch, and 1.5 respectively, figure 42 can be used to estimate that 1 percent of all storm events have volumes that exceed about 7.5 times the mean (or 7.5 * 0.4 = 3 inches). If the same location has an average interval between storms (Δ) of 87.5 hours, there will be an average of:

$$(365 * 24) / 87.5 = 100 \text{ events/year}$$

and the 1 percentile event (3 inches) reflects a storm volume exceeded, on average, once per year.

6.2 FINAL MODEL FORMULATION

The model described and discussed in this section is different from models that have previously been prepared for predicting loadings from highway runoff. It does not result in a single value, or in a regression equation that produces a specific value, or even in a complex mathematical model that requires multiple input values or estimates, and then produces a specific predicted output value. The user will have to consider a number of values within a range of likely possibilities. The procedure provided is a realistic approach that is easy to apply, and helps the user to maintain an awareness of the inherent variability of storm runoff discharges, and an appreciation of the degree of uncertainty in predicting pollutant loads.

The predictive procedure consists of the following steps, which are simply listed here, and then discussed in greater depth in the remainder of this section:

- Estimate runoff flow rate and volume characteristics. This requires a determination of local rainfall properties, and an estimate of the runoff coefficient for the site.

- Estimate a "site median" concentration for each of the pollutants of interest for the planned evaluation.

- Compute annual or seasonal mass loads in cases where mass loads are desired, either to evaluate impacts on a lake, or because of user preference for comparing alternatives. Convert the site median value to the concentration for the mean event, and multiply by the mean value for runoff volume and the number of storms based on the selected period for analysis.

The remainder of this sub-section presents a brief outline discussion of the elements in the procedure used to define pollutant discharges in highway runoff. The user is referred to the Design Procedures report for a detailed step-by-step description of the practical application of the

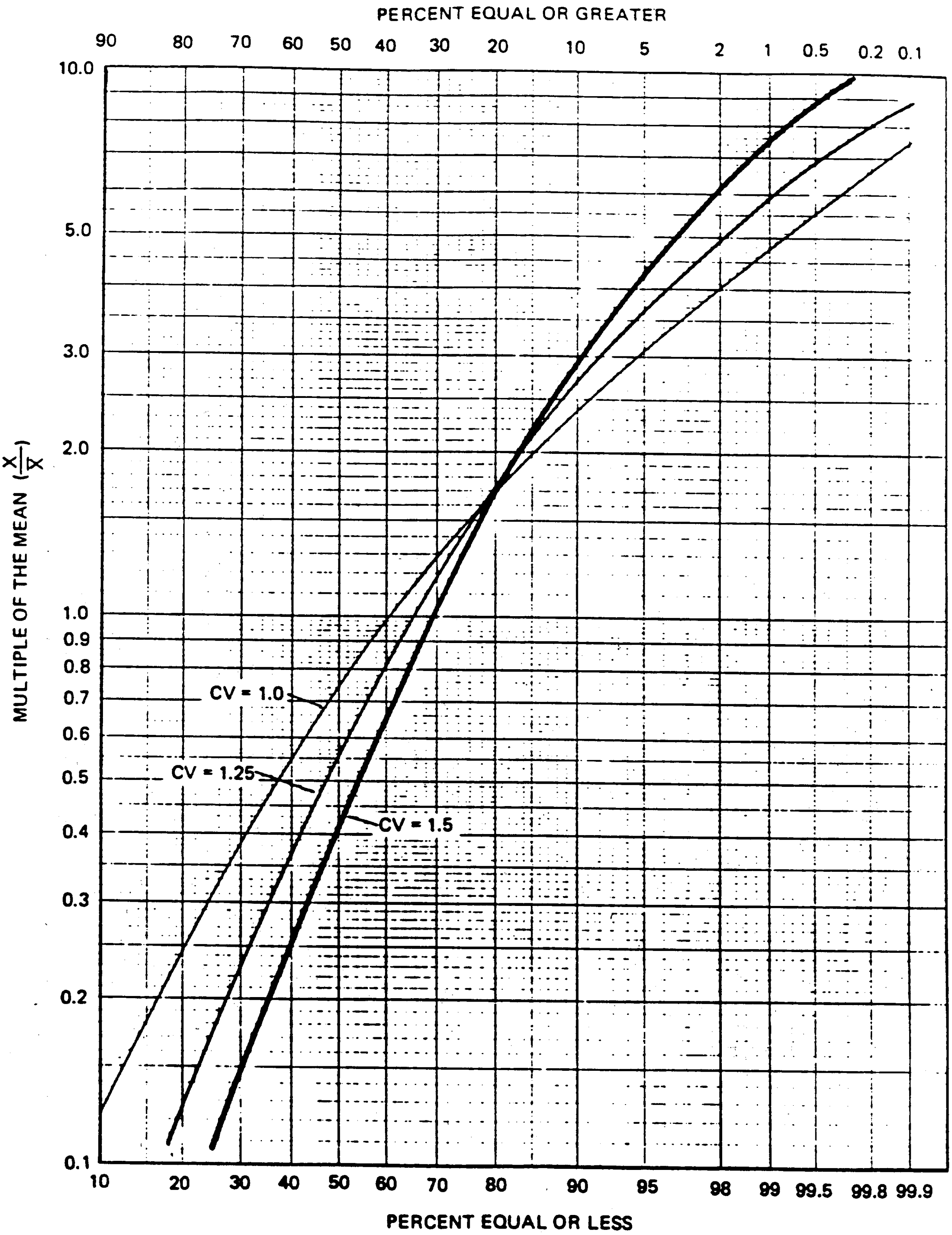


Figure 42. Probability distribution for a variable with a gamma distribution.

procedure.

6.2.1 Estimating Runoff Quantity

The major variables for such estimates are the local rainfall characteristics and the degree of imperviousness of the highway drainage area.

Preliminary estimates of rainfall statistics can be obtained from figure 41, but the user should recognize that significant local variations can exist within the broad areas shown. The preferred approach would be to perform an analysis of the rainfall record of a gage having a long-term record (preferably 10 years or more), that is in the same general area as the highway site being examined. As indicated previously a microcomputer program for performing this analysis is available from FHWA through this study. Alternatively, a State Highway Department may elect to develop the SYNOP statistics for all rain gages within the State.

In most cases the analysis should be based on the statistics using all storms in the record. In cases where a seasonal analysis is determined to be appropriate (because the receiving water has a distinct critical period (e.g., low flow and high temperature), the analyst can elect to use the results that apply to that season.

In either case, the information of interest is the mean and coefficient of variation of storm event volumes, intensities, durations, and intervals between successive events. These properties are then converted to corresponding values for runoff by applying a runoff coefficient (Rv) to the mean value for volume and intensity. The general relationship is shown by the following equations. Their more complete form with drainage area terms and dimensional conversion constants are presented in the Design Procedures report.

$$\text{Mean Runoff event VOLUME} = Rv * \text{Mean Rain Volume} \tag{25}$$

$$\text{Mean Runoff event FLOW RATE} = Rv * \text{Mean Rain Intensity} \tag{26}$$

The variability from event to event is assumed to be the same for both rainfall and runoff, so the coefficient of variation for the appropriate rainfall parameter is applied for the corresponding runoff parameter.

The runoff coefficient (Rv) is estimated from the impervious fraction of the overall drainage area of the highway segment being evaluated. Either the relationship shown in report section 3.7, or that tabulated in the student workbook for the FHWA training course, can be used. Both result in similar estimates. The user will note from the plots or tabulated ranges a precise estimate of Rv is not possible. At a later point in the analysis, sensitivity tests can be used to determine whether the uncertainty associated with this parameter estimate has a significant effect on conclusions.

The runoff estimates produced are thus expressed as the statistics of individual discrete storm events. These values are used directly in a number of subsequent analyses, as discussed later in section 7.0 for receiving water impacts. For an estimate of the total volume of runoff over some extended period of time (a year, or a summer season), first compute the average number of storms for the period. This is given by the total number of hours in the period of interest divided by the mean interval between storm midpoints. Then multiply the volume for the mean storm by the number of storms to obtain the total volume from all storms during the period. For example, consider an area with a mean storm volume of 0.4 inch, a mean interval between storms of 80 hours and a runoff coefficient of 0.5.

Volume for mean runoff event = 0.5 * 0.4 = 0.2 inches

Average number of events per year = (365 * 24) / 80 = 109.5

Average volume of runoff in a year = 0.2 * 109.5 = 21.9 inches

6.2.2 Estimating Runoff Pollutant Concentrations

The data analysis presented in section 3.0 indicates that highways in non-urban settings having traffic densities below 30,000 vehicles per day, have significantly lower runoff concentrations of all pollutants than do urban highways. Individual highway sites within each general group were shown to have different median EMCs (site medians), which for most pollutants correlated poorly with traffic density. A quantitative influence on pollutant levels in runoff could not be shown from the available data, for the other potential site factors such as pavement type, presence of curbs, or the impervious fraction.

Accordingly, the predictive model assumes that the recorded differences in the median EMC concentrations for different sites within each grouping are best treated as random in nature. This does not challenge the existence of actual cause and effect relationships between pollutant levels in runoff and specific site factors such as traffic density or curbs. It merely acknowledges the fact that the quantitative relationships, necessary for reliable predictions, cannot be demonstrated from the available data. This is probably due to the limitations of even a quite large data base in considering the effect of multiple factors, where the influence of any one factor may be modest enough to be lost in the "noise" produced by a combination of other factors.

Although the differences between sites are random, the site medians were shown to have a lognormal probability distribution. This applies to all the pollutants analyzed, and provides a basis for using the data for planning level predictions. Table 23 summarizes the pertinent characteristics of the site differences by listing, for both urban and rural highways, the median of the highway site median EMCs, and coefficient of variation (CV) that quantifies the site to site variation. The column on the right lists, for each pollutant, the ratio between the urban and non-urban median of the highway site median EMCs. Urban highways produce runoff that has two to five times the pollutant levels present in the runoff from rural highways. Because of the magnitude of this difference, and the fact that it was shown previously in section 3.0 that the differences are statistically significant, the predictive procedure calls for this distinction to be made as the first step in estimating concentration levels in runoff.

Urban Highways. If the highway segment of interest is located in an urban environment, which will usually correspond with traffic densities of more than 30,000 vehicles per day, the predictions will be based on the distribution parameters (median and COV) listed in table 23 for urban highways. Note that this tabulation merely summarizes the information previously shown graphically by figures 7 through 16.

Since the site medians can be represented as lognormally distributed, the listed values for median and CV completely describe the distribution or the probability of a highway site having a specific concentration level. The discussion of lognormal relationships that is presented in sections 2.4 and 2.5 of the report will provide the user with the information needed to compute the concentration for any specified percentile, or the percentile for any specified concentration. Table

Table 23. Summary of highway site median concentrations.

POLLUTANT		URBAN HIGHWAYS MEDIAN	COV	No. SITES	NONURBAN HIGHWAYS MEDIAN	COV	No. SITES	RATIO URB/NURB
TOTAL SUSPENDED SOLIDS	TSS	142	0.62	16	41	1.17	8	3.5
VOLATILE SUSPENDED SOLIDS	VSS	39	0.58	12	12	0.62	7	3.3
TOTAL ORGANIC CARBON	TOC	25	0.62	13	8	1.02	8	3.1
CHEMICAL OXYGEN DEMAND	COD	114	0.58	14	49	0.45	8	2.3
NITRATE + NITRITE	NO3	0.76	0.56	9	0.46	0.57	8	1.7
TOTAL KJELDAHL NITROGEN	TKN	1.83	0.45	15	0.87	0.83	8	2.1
PHOSPHORUS	PO4-P	0.40	0.89	15	0.16	1.02	8	2.5
TOTAL COPPER	CU	0.054	0.68	14	0.022	0.72	8	2.5
TOTAL LEAD	PB	0.400	1.45	16	0.080	1.22	8	5.0
TOTAL ZINC	ZN	0.329	0.44	13	0.080	0.73	8	4.1
AVERAGE SITE MEDIAN COV =			0.69			0.84	AVG RATIO=	2.99
COV OF SITE MEDIAN COV's =			0.43			0.31	COV OF RATIOS=	0.34

24 illustrates the results of such a computation, for several selected percentiles. Its use for a site-specific prediction is straightforward, but requires the user to apply some professional judgement. Following are some considerations that may be applied.

If no other information is known about a highway site, other than that is in an urban area, the most probable pollutant level is defined by the concentration for the median urban highway site (for example, 142 mg/l for TSS). However, as part of a sensitivity analysis, the user may elect to choose a site median concentration of 295 mg/l TSS. Only one urban highway segment in ten is expected to have a median concentration that exceeds this level, but if the segment in question is the only one contributing runoff to a water body, this or the 80th percentile level might be more appropriate to use than the median site value. On the other hand, if a number of different highway segments contribute runoff to the same water body, the evidence is that they will all have different pollutant levels, so an estimate closer to the median (as the average for all contributing segments) would tend to be more realistic.

Sites in relatively dry, semi-arid areas of the country appear from the data to tend toward higher concentrations of many pollutants compared with sites in humid regions. The data base wasn't large enough to confirm or quantify such an influence; however, estimates for such a site might preferably favor using values from the higher end of the distributions.

Where estimates of traffic density are available, this information may be used to guide an estimate. Although most pollutants levels did not show correlations significantly different than zero, based on ADT, several showed the positive trends that are intuitively expected. While the correlations were too weak to justify the formulation of a reliable formal mathematical relationship, the traffic density projected for the site might, for certain pollutants, be used to weight the prediction toward the higher or lower ends of the probability distribution.

The regression equations for the correlations between site median concentrations (SMC) of a pollutant and traffic density are of the form:

$$SMC = a * ADT + b \tag{27}$$

where

SMC = site median concentration of pollutant (mg/l)
ADT = average daily traffic (1000 vehicles per day)

The values for coefficients "a" and "b" are shown in table 25 for those pollutants that showed a statistically significant correlation in the analyses that were presented in report section 4.5. The square of the correlation coefficient, R, (R-squared in the table below and expressed as a percentage) indicates what percentage of the variation in the observed SMC values, is explained or accounted for by ADT.

Table 24. Range of site median concentrations in urban highway runoff.
(site median concentration in mg/l)

URBAN HIGHWAYS
AVERAGE DAILY TRAFFIC MORE THAN 30,000 VEHICLES PER DAY

PERCENT OF HIGHWAY SITES HAVING A MEDIAN EMC
LESS THAN INDICATED CONCENTRATION

POLLUTANT		10%	20%	50% MEDIAN SITE	80%	90%
	Z=	-1.280	-0.842	0.000	0.842	1.280
TSS		68	88	142	230	295
VSS		20	25	39	61	78
TOC		8	12	25	51	74
COD		57	72	114	179	227
NO2+3		0.39	0.49	0.76	1.18	1.48
TKN		1.06	1.27	1.83	2.62	3.17
PO4-P		0.15	0.21	0.40	0.76	1.06
COPPER		0.025	0.032	0.054	0.091	0.119
LEAD		0.102	0.163	0.400	0.980	1.562
ZINC		0.192	0.231	0.329	0.469	0.564

Table 25. Regression coefficients for significant correlations between ADT and various pollutant concentrations.

POLLUTANT	a	b	R-squared
VSS	0.385	11.	42 %
TKN	0.01	1.06	25 %
COD	0.874	47.	40 %
TOC	0.233	5.	42 %
ZINC	0.003	0.07	70 %

The pollutants TSS, copper, and lead showed weak positive correlations, but the r-squared values corresponded to only 5 to 12 percent. These levels are not significantly different from zero, and the use of a regression equation would not improve the estimate. For all of the other pollutants analyzed, site median concentrations bear no relationship to traffic density.

The logical procedure described above would be used in association with the pertinent data tables and plots to estimate a value (or a range of values for sensitivity analyses) for the site median concentration of a pollutant. It will be recognized that individual storm events will have higher and lower EMCs than the median for the site. This variation is defined by the CV for EMCs at any site, for which the most probable value is 0.71 for urban highway sites. This is in accordance with the analysis presented in report section 3.6. Sensitivity analyses might examine the effect of values in a range of 0.5 to 1.0 for event CV.

Rural Highways. The same basic approach would be applied for developing estimates of site median concentrations for highways in this group. Here, however, the small number of sites in the data base prevents a reasonable use of regressions against ADT to provide a basis for guiding estimates. Estimates for this group should rely primarily on the lognormal distribution of what are presumed to be random variations in site median concentrations.

Table 26 lists the 10th, 20th, 50th, 80th and 90th percentiles of the distribution of rural highway site median concentration values. They can be used to develop either most probable estimates, or conservative ones. It should be noted that two of the eight sites in the list are located in semi-arid or desert areas in the eastern part of the State of Washington, and for most pollutants, are associated with site medians in the higher end of the range. The remaining six rural sites are in humid areas, and three of these are also in the State of Washington. The geographical distribution of rural sites is not as broad as for the urban highway sites, and has a larger proportion of arid areas represented than is typical of the country as a whole. These considerations should be recognized when the distributions are used to guide a local estimate. The user may wish to favor higher percentile values for highways in semi-arid regions, and the lower percentile values for most other areas.

The variation that individual storm events will have (higher and lower EMCs than the median) for the site is defined by the CV for EMCs at any site. The most probable value is 0.84 for rural highway sites as shown by the analysis presented in report section 3.6. Rural sites have slightly higher event-to-event variability than urban highways. Sensitivity analyses to examine the

Table 26. Range of site median concentrations in nonurban highway runoff.
(site median concentration in mg/l)

NONURBAN HIGHWAYS
AVERAGE DAILY TRAFFIC LESS THAN 30,000 VEHICLES PER DAY

PERCENT OF HIGHWAY SITES HAVING A MEDIAN EMC LESS THAN INDICATED CONCENTRATION

POLLUTANT	10%	20%	50% MEDIAN SITE	80%	90%
Z =	-1.280	-0.842	0.000	0.842	1.280
TSS	12	19	41	90	135
VSS	6	7	12	19	25
TOC	4	5	8	13	17
COD	28	34	49	70	85
NO2+3	0.23	0.29	0.46	0.72	0.91
TKN	0.34	0.47	0.87	1.59	2.19
PO4-P	0.06	0.08	0.16	0.33	0.48
COPPER	0.010	0.013	0.022	0.038	0.050
LEAD	0.024	0.036	0.080	0.179	0.272
ZINC	0.035	0.046	0.080	0.139	0.185

effect of uncertainty in the actual values might examine event-to-event CVs in a range of 0.6 to 1.2.

Other Highway Situations. There will be some situations where a highway segment in a rural area will have traffic densities well above 30,000 vehicles per day, or where an urban highway has a low ADT. For estimates of site median concentrations for such situations, the user is referred to the data presentations in section 3 which indicate that there is a degree of overlap in the pollutant concentrations from urban and rural highways. The cleanest urban highway sites exhibit lower site median concentrations than the dirtiest rural highway sites.

In cases where the ADT and surrounding area do not conform with the 30,000 vehicle per day division reflected by the data base that was analyzed, the estimate can be based on a concentration level in the lower end of the urban range, and/or the higher end of the rural range.

An independent check on this guidance is provided by the results presented by Stotz (22) on the runoff characteristics of three West German highways. For the pollutants he measured that can be compared directly with the results from this study (TSS. phosphorus, copper, lead and zinc) the German highway stormwater runoff concentrations have a comparable variability between sites and fall within the range for US highways reported in this study. To make the comparison, the site mean values reported by Stotz were converted to site median values by assuming a lognormal distribution and a coefficient of variation comparable to that indicated by the US data, for his event mean concentrations.

The German sites are reported to be in rural areas, but have ADTs of 40 to 50 thousand vehicles per day. With the exception of copper, which falls in the upper end of both the urban and rural range for US sites, the other pollutant SMCs support the above guidance quite well. That is, they tend to fall in the upper end of the rural range and toward the lower end of the urban range.

6.2.3 Estimating Mass Loads

The preceding two subsections describe the procedures for developing estimates of runoff volumes and pollutant concentrations. Results are expressed as a coefficient of variation (CV) and either a MEAN (in the case of runoff), or a MEDIAN (in the case of concentration). Mass load is the product of concentration and volume, so that while we have the basic information for computing mass loads, some care and interpretation is required to ensure that the two sets (runoff and concentrations) are combined properly.

For predictive purposes, estimates of runoff volume should be based on the long-term rainfall for the area, and not on the measured volumes of the monitored storms from a study program. This is because the storms selected for measurement in any study are virtually never a representative sample of all storm sizes for the area. This bias (usually toward larger storms) does not bias the concentration data because there has been shown to be essentially no significant correlation between concentration and volume. Monitoring data on rainfall and runoff would be used to define the runoff coefficient for the site. But runoff volume (and subsequent load) predictions should be based on the long-term rainfall record and the runoff coefficient.

As described earlier, the appropriate rainfall analysis will provide an estimate of the mean (M) and CV of storm volumes. The predictive procedure assumes that the mean runoff volume is provided by Rv times the mean storm volume, that the CV is the same, and that whereas rainfall has a gamma distribution, the runoff becomes lognormal due to the physical processes associated with overland flow.

For concentrations, however, the data analysis and summaries that have been developed deal with median, rather than mean values. The lognormal distribution assignment for EMCs at a site allows the computation of the mean runoff event concentration, using the relationship:

$$M = T * SQRT(1+CV^2) \tag{28}$$

Since a typical value for the CV of pollutant concentrations in highway runoff is 0.75 (or 0.71 for urban, 0.86 for rural sites), the right hand term has a value of 1.25. The mean event concentration will thus be 25 percent greater than the site median value.

The mean storm event mass load is given by the product of the means of the runoff volume and concentration.

$$M(MASS) = M(VOL) * M(CONC) * 0.227 \tag{29}$$

where the conversion factor (0.227) produces a mass loading expressed as pounds per acre, using runoff volumes expressed as inches, and pollutant concentrations expressed as mg/l. Other dimensional conversion factors would be used when the volume term is expressed in terms other than inches of runoff.

To estimate the total mass load discharged over an extended period, multiply the load for the mean event by the number of events during the period. Annual mass loading rates are most often desired, so the period of interest is usually one year. The average number of storm events per year can be estimated from the rainfall statistics (the mean interval between storm midpoints), as indicated in section 6.2.1 and elsewhere in this volume. The annual mass load is then:

$$ANMASS = M(MASS) * NST \tag{30}$$

where:

ANMASS = annual mass load (mass / year)
M(MASS) = mass load for the mean event
NST = number of events per year

7.0 EVALUATION OF PROBLEM POTENTIAL

7.1 GENERAL

The purpose of this section is to discuss the issues associated with the potential for highway stormwater runoff to create, or significantly contribute to, receiving water quality. References for the theoretical basis for the procedures discussed are provided at appropriate places in the text that follows. Additional information on the use of the procedures are provided in other products of this study, the Design Report and the interactive computer program.

This report section discusses the application of the procedures in initial screening analyses, where they may be used to determine whether there is any significant potential for a highway site to cause water quality problems. Where screening results indicate a problem (or cannot confidently dismiss the possibility), the next step would be to evaluate the degree of mitigation that would be provided by runoff control, or to refine the analysis using additional local monitoring data. Environmentally sensitive sites may warrant local monitoring and/or a more detailed analysis.

The results of some generalized screening analyses are also presented. These are based on the ranges of quality characteristics developed for highway runoff by this study, and representative characteristics of receiving water bodies. These general analyses are designed to provide an initial indication of the problem potential for different conditions.

7.2 OVERVIEW

There are two basic elements that combine to determine the circumstances where highway runoff creates water quality problems and, of equal importance, where highway runoff can be eliminated from consideration as a significant contributor to adverse receiving water effects.

POLLUTANT LEVELS IN RUNOFF - Both the specific pollutants that are present at significant levels and their magnitudes in runoff are important. The previous sections described procedures for predicting the characteristics of pollutant discharges from highway sites.

RECEIVING WATER CHARACTERISTICS - Whether or not a discharge has the potential to cause a pollution problem depends not only on the type and amount of pollutants present, but also on the characteristics of the receiving water body it enters. Different water body types (e.g., streams, lakes) tend to have different beneficial uses and sensitivities to different groups of pollutants. The size of the receiving water body relative to the discharge has a dominant influence on whether a significant water quality impact will occur. Further, the significance of highway stormwater runoff discharges will be influenced by the background quality of the water body, which is determined by all the sources that contribute pollutant loads.

To assess the actual potential for highway pollutant discharges to create "pollution problems" and to evaluate the significance of reported "pollutant loads" from highways, several factors are relevant. The magnitude of the concentration of a pollutant is the important factor in impact analyses rather than mere presence. Furthermore, some forms of a pollutant are more objectionable than others (e.g., soluble vs particulate). It is appropriate to apply different water quality criteria, depending upon the designated use of the water body affected. Finally, potential effects should be considered in terms of the intermittent nature of highway runoff discharges.

All of the above elements must be considered if one is to develop a realistic and practical perspective on water pollution from highway stormwater runoff. Practicality requires that we distinguish between situations where the discharges constitute a trivial or insignificant threat from a human health or ecological aspect and those where the pollution potential is sufficient to dictate attention to serious efforts at control in order to mitigate loads and impacts.

7.3 PERSPECTIVES ON POTENTIAL FOR ECOLOGICAL AND HUMAN HEALTH EFFECTS

Water is never found "pure" in nature; it always carries impurities. These impurities, which may occur in either dissolved or suspended form, vary quite widely in both type and concentration. Substances present in water may also be referred to as "contaminants" or as "pollutants," but there is normally little or no semantic precision to the choice of term. In dealing with water quality issues, the term "pollutant" is commonly used, and so we have adopted this terminology in this report. As generally used, the term "pollutant" should be considered synonymous with contaminant or impurity. The issue is not whether natural waters contain impurities; they all do, but whether or not a particular impurity (pollutant), or group thereof, is present at a high enough level to create an adverse environmental effect.

In later parts of this section, we discuss the factors that influence the concentration level that a pollutant can reach in a water body receiving highway stormwater runoff. However, in order to properly assess whether or not any such concentration level would be expected to create, or significantly contribute to an adverse environmental impact, it is necessary to consider several additional factors. These factors which must be considered in making a responsible decision on whether or not a situation can reasonably be expected to be a problem are as follows.

7.3.1 Specific Pollutants

As noted earlier, runoff from highways can carry a variety of pollutants with it. It is important to realize at the outset, however, that they are not unique. Rather, it is a case of highway stormwater runoff carrying a different mix of specific pollutants that are found in all load sources, point as well as nonpoint. For example, highway runoff tends to carry higher concentrations of heavy metals than does agricultural runoff or municipal treatment plant discharges. At the same time, agricultural runoff carries much greater levels of nutrients and suspended solids, while domestic sanitary wastes contribute much higher levels of oxygen consuming organic compounds.

Just as different water bodies tend to have different beneficial uses, these uses in turn are affected by different pollutants. For example, probably the most common water quality issue in streams is the suppression of aquatic life, and in such instances, the possible toxic effects of heavy metals are an important concern. In contrast, by far the most common environmental issue in lakes is the overstimulation of aquatic life, and nutrients rather than heavy metals are the pollutant types of greatest significance. There are two essential points that the decision maker must understand at the outset:

- DEPENDING UPON THE WATER BODY TYPE AND ITS DESIGNATED BENEFICIAL USE, DIFFERENT SETS OF POLLUTANTS WILL HAVE THE MOST SIGNIFICANCE

- VARIOUS LOAD SOURCES DIFFER IN THE RELATIVE MIX OF POLLUTANTS THAT THEY CONTAIN, AND THEREFORE SOME SOURCES WILL BE INHERENTLY MUCH MORE SIGNIFICANT THAN OTHERS, DEPENDING ON THE WATER BODY TYPE AND ITS DESIGNATED BENEFICIAL USE

It is important to recognize that it is the not mere presence of a pollutant in a given discharge or water body that is important, but rather the magnitude of the mass load or concentration. Although there are many illustrations of this basic fact, it often tends to be overlooked or ignored. To cite one of the most common examples, all of the water that we drink has some salt in it. On the other hand, over-consumption of excessively saline water can be fatal, as evidenced for example, in instances of shipwreck victim deaths attributable to drinking sea water. Even those of us who have never been to sea, have no difficulty understanding the lament ". . . water, water everywhere, nor any drop to drink . . ." from Coleridge's "The Rime of the Ancient Mariner."

There can be no argument that all heavy metals are toxic at high enough concentrations. However, they are not only innocuous at sufficiently low concentrations, but many are recognized nutritional factors whose total absence from the human diet is detrimental to health. This observation is not to suggest that highway stormwater runoff has a possible role as a diet supplement, but to emphasize the point that "the right dose differentiates a poison and a remedy" and not the substance itself, as Paracelsus observed in the sixteenth century. Furthermore, the important environmental consideration is the "dose" in the receiving water at the point where the desired uses are situated and not at the edge of the pavement. The beneficial use of highway road surfaces is to safely and efficiently carry vehicles, and one of the important beneficial uses of the adjacent area is to carry stormwater away from the road surfaces efficiently, so that the primary "use" of the road surface is not adversely impacted. These uses are not influenced by runoff contaminant levels in the slightest. The relationship between contaminants in the runoff and a designated beneficial use begins only when the runoff water has been conveyed to some receiving water body whose legitimate beneficial uses (actual or potential) are in fact impacted by the presence of the pollutants. Thus, we come to a third point that is essential to keep in mind when dealing with water quality issues:

- IT IS THE QUANTITY OF A POLLUTANT AT THE POINT OF USE THAT IS IMPORTANT, NOT MERELY ITS PRESENCE

The foregoing observation is not particularly profound, but it is a useful one to make because there is a strong tendency for investigators whose scope of study terminates at the edge-of-pavement to assess the relative significance of the quality characteristics of the runoff data by comparing them with some published criteria value or other. There is nothing fundamentally wrong with this practice, and it may be the only readily available reference frame for providing some perspective. The difficulty, however, lies in the tendency of such comparisons to create impressions of "problems" or serious concerns, which may be unwarranted. Thus there is a related fourth point to be made, namely:

- EDGE-OF-PAVEMENT VALUES ARE USEFUL FOR COMPARING SITES, BUT HAVE LIMITED SIGNIFICANCE FOR ASSESSING THE POTENTIAL FOR

ADVERSE IMPACTS

The absolute magnitude of a particular pollutant in a receiving water can have quite different degrees of significance, depending upon external factors, the water body, and its designated beneficial use. For example, chloride contributions from road de-icing salts may be a legitimate concern where the runoff is to a freshwater stream or lake. It will be of no concern at all where runoff enters a tidal river, an estuary or a coastal water. Perhaps even more to the point is the rather substantial relationship between the toxicity of heavy metals and the total hardness of the receiving water. Figure 43 shows the regional variation of total hardness in surface waters and table 27 illustrates the extent to which water hardness influences the toxicity level of a few heavy metals. Even a cursory review of this information will clearly show that a similar stream concentration resulting from runoff may have a radically different significance in different regions of the country. Thus, we come to a fifth essential point:

- THE SIGNIFICANCE OF A PARTICULAR POLLUTANT CONCENTRATION LEVEL IN A RECEIVING WATER IS INFLUENCED BY EXTERNAL FACTORS.

Table 27. Criteria levels for acute toxicity.

HARDNESS	LEAD	ZINC	NICKEL	COPPER	CADMIUM
50	74	180	1090	12	1.5
100	172	320	1800	22	3.0
300	660	800	4250	62	9.6

Notes: Total Hardness in mg/l; Heavy Metal concentrations in µg/l; EPA Criteria for Aquatic Life protection.

7.3.2 Beneficial Use and Applicable Criteria

There are numerous formal published water quality criteria for pollutant concentrations for various designated beneficial uses, e.g., protection of aquatic life, human health. However, limiting values for specific pollutants are different in each case. What is important is to select and apply the appropriate criteria set, and even more important, to understand the assumptions on which they are based.

As an example, consider water quality criteria intended to protect human health. These are derived from projected effects arising from long-term ingestion, given an assumed typical consumption rate, and adjusted downward (often several times during the course of criteria development) to account for uncertainties. The point is that they were derived, and should logically be considered, from human ingestion considerations, and thus apply to water delivered to a consumer after treatment and conveyance to the point of use. Inasmuch as all surface water supplies are treated before distribution, direct comparison of what were intended to represent end-of-tap water quality criteria, to edge-of-pavement highway runoff characteristics is inappropriate. At most, one should consider the pollutant concentrations attributable to highway runoff in the stream at the intake of a potable water supply treatment plant. This avoids speculation about possible variations in removal efficiencies of different treatment plants. Even here, however,

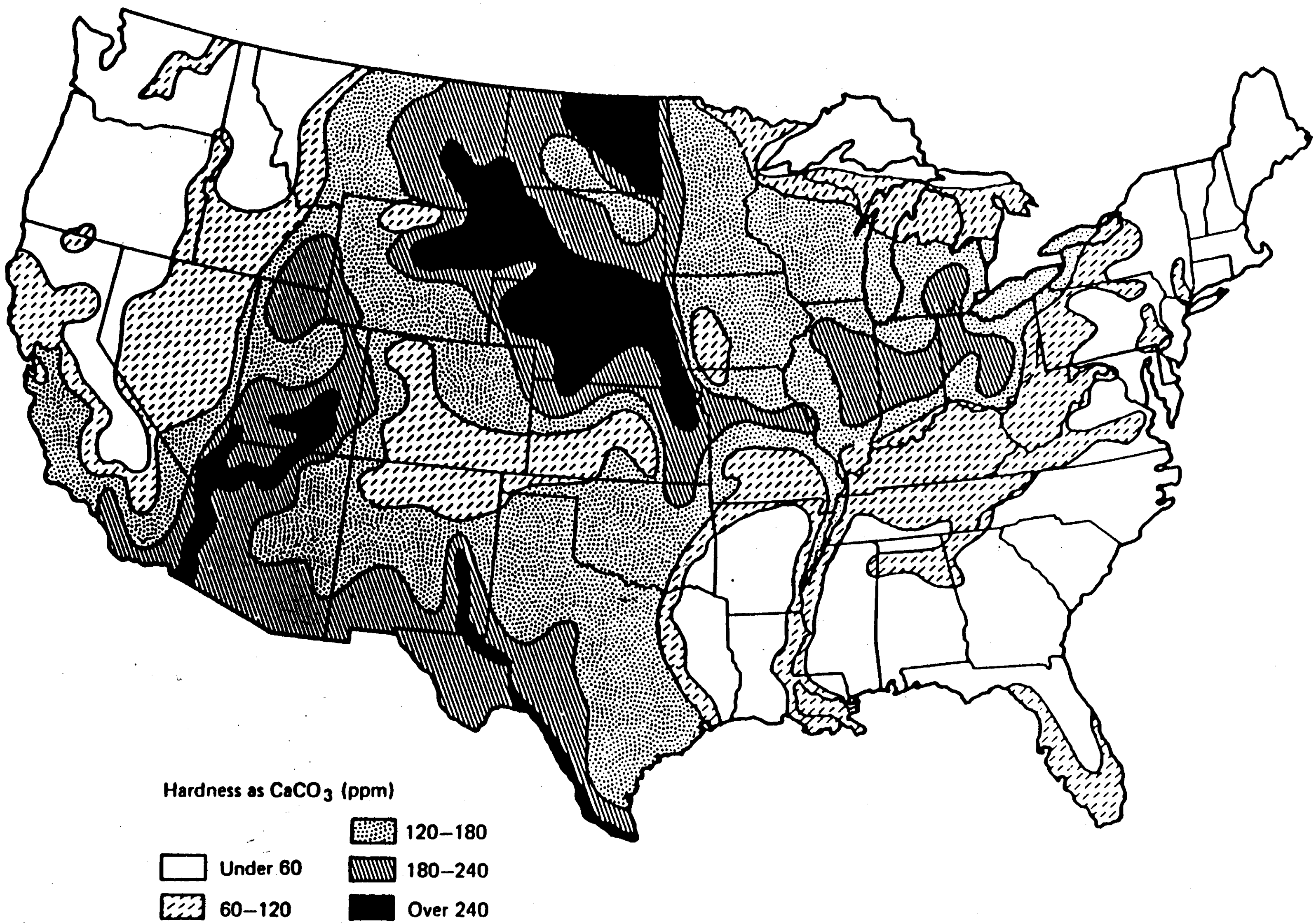


Figure 43. Total hardness levels of surface waters.

one must properly take into account the intermittent nature of pollutant concentrations arising from highway runoff. Stormwater runoff can only occur when there is rainfall, and in most of the United States runoff episodes take place less than 10 percent of the time. In order to be applied in the same context in which they were determined, health effects data would need to be adjusted for this to properly reflect intermittent rather than continuous exposure. As a pragmatic matter, it is doubtful that there is a single stream which serves as a drinking water source in this country and, at the same time, is small enough to have any appreciable impacts due to highway runoff.

In December of 1986 a brochure was distributed jointly by the American Waterworks Association (AWWA) and the Association of State Drinking Water Administrators (ASDWA) in the form of an advisory on lead. This is significant because lead is perhaps the pollutant most strongly associated with highway runoff. The brochure was intended to assist the public in reducing their possible exposure to lead in drinking water. It points out that the presence of lead in tap water is rarely due to the occurrence of lead in the source waters of a community's water supply because it is easily removed by conventional treatment processes. One of the most significant human health concerns addressed by this brochure is the dissolution of lead from plumbing systems.

The more likely designated use which is subject to a possible threat by highway stormwater runoff is the protection of aquatic life. This is because there are (or should be) desirable aquatic life forms in streams of all sizes, even small streams that might be susceptible to highway runoff in certain instances. Here again, however, the water quality criteria are based on continuous rather than intermittent exposure, and adjustments should be made to reflect the time varying nature of highway runoff.

7.3.3 Spatial and Temporal Variations

In order to determine whether or not stormwater runoff from highways can be expected to create, or significantly contribute to, a water quality problem, one must properly account for the spatial and temporal variations that are inherent in nonpoint source discharges.

The temporal aspects relate to the fact that with highway runoff we are dealing with transient, short duration exposures that occur intermittently, and are attempting a comparison with criteria values that are often based on continuous exposure. An extension of a procedure used by the NURP (17) program to relate these different temporal scales is used in the procedures described later for assessing the problem potential of a highway site.

The spatial aspects relate to the reductions in concentration that most pollutants experience during transport from the discharge site to more distant locations in the receiving water system. For many situations it will be most appropriate to evaluate significance at locations in the immediate vicinity of the discharge. As discussed later, there will be circumstances for which spatial effects should be considered in any assessment of problem potential.

7.3.4 Ambient Water Quality

As used here, ambient water quality refers to pollutant concentration levels present in a water body due to sources other than highways. These may include either defined sources such as urban or agricultural runoff and point source discharges, or it may relate to upstream sources that are undefined and commonly referred to as "background."

Practical considerations argue for a realistic assessment of the comparative influence of all sources in question. If non-highway contributions are proportionately large, and are either uncontrollable or not controllable to a sufficient extent to have a significant influence on the water body, then anything one might do to control highway runoff may be insignificant in what it accomplishes.

Such relationships must be addressed with care. There will be cases where several different sources contribute partially to a problem, whose solution would require action by all. When the other source contributions are subject to control and action is planned, then there will be sound reason to consider control of highway runoff, even though it may not be a dominant component of the total. Such situations must be distinguished from those in which technically achievable reductions in highway loads would have no real effect.

7.3.5 Receiving Water Type

Regardless of the presence of pollutants in highway runoff, or even the magnitude of the loads discharged, the potential for causing water quality problems is influenced to a major degree by the characteristics of the water body that receives the runoff. The type of water body (stream, lake, estuary, coastal) and an appropriate expression of size relative to the discharge have a major influence. Secondary (but important) characteristics include distance from the discharge point to the sensitive part of the water body, the background quality exclusive of any influences from highway runoff, and the relative contribution of specific pollutants from other sources.

Lakes respond differently to pollutant loads than do streams. The transport processes that are dominant in determining pollutant fate are significantly different in the two types of water body. As a result, lakes tend to respond to cumulative pollutant mass loads delivered over an extended period, and are usually analyzed on an annual or seasonal basis. In contrast, streams respond on an individual event scale. In streams, storm runoff produces a contaminated pulse of water that moves downstream, and hence, is well removed from the discharge location at the time that the next storm discharge occurs. Estuaries exhibit transport patterns that are intermediate to the above two; there is a combination of mixing and advective transport, and residence times for pollutants become more significant than in rivers, though normally less than in lakes.

The key point is that different analysis and evaluation procedures must be applied depending on the water body type. In addition, desired beneficial uses tend to be different, depending on the water body type, and hence the specific pollutants of most concern. Each of the principal water body types is discussed briefly in this section, though most of the attention is directed to streams. Streams will be, by far, the type of water body most often exposed to the direct effects of highway stormwater runoff, and the type that is potentially most sensitive to such discharges. There will be some exceptions, but in most cases highway runoff loads to estuaries and lakes will be relatively insignificant, given the relative size and diluting volumes of these water bodies, and the magnitude of the pollutant loads they also receive from other sources.

7.4 STREAMS

Figure 44 schematically illustrates the behavior of a runoff pulse entering a stream. This case is typical of a highway crossing a stream with the runoff from the highway segment draining directly to the stream. The initial concentration of a pollutant in the stream pulse is related to the mass load contributed by the storm event and the amount of dilution provided by the stream flow. The length of the slug of runoff-contaminated water is influenced by the duration of the runoff event, and perhaps more importantly, by the velocity of the stream flow. For example, consider a runoff event with a duration of 1 hour. If it discharges into a stream flowing at 1 mi/hr, the slug will extend over a distance of 1 mile when the event ends. At a stream flow rate of 10 mi/hr, clearly the contaminated stretch will cover 10 miles, though the resulting concentration would be considerably lower than in the former case.

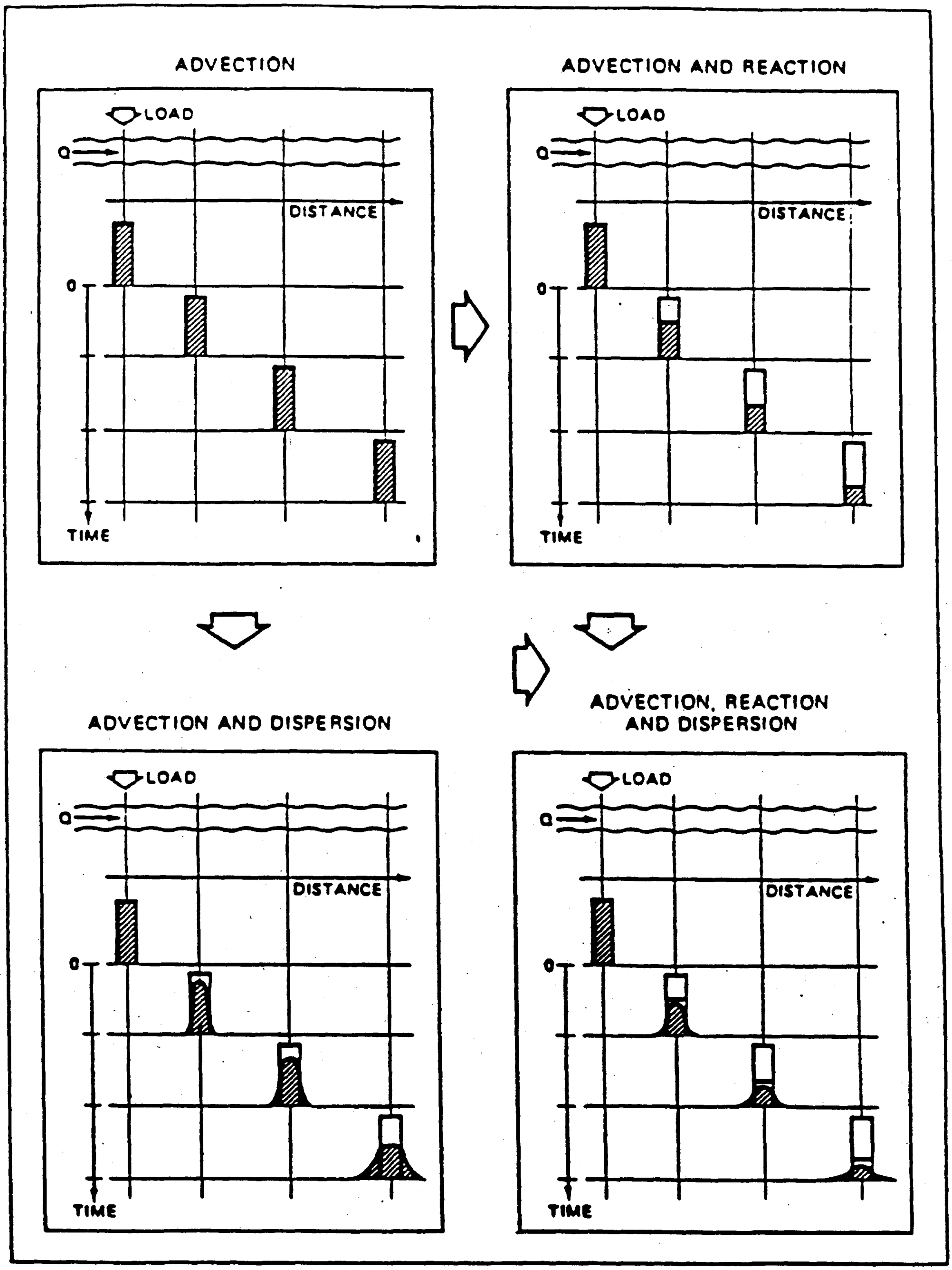


Figure 44. Transport mechanisms for pollutant discharges to streams.

As a pulse moves downstream, dispersion causes the leading and trailing edges to mix with stream water that was initially uncontaminated by the runoff event. The result is a spreading of the pulse and progressive reduction of the maximum concentration. For pollutants subject to reaction and decay (e.g., settling, oxidation, biological action) the concentration in the pulse decreases as the pulse moves downstream, at a rate determined by the decay rate for the pollutant in question.

The overall water quality impact pattern produced in a stream by stormwater runoff from a highway site is one of a series of pulses, each of a different magnitude and spread, spaced at intervals along the length of the stream in accordance with the varying intervals between storm events. From analysis of a large number of rainfall records, for much of the country storm durations average about 6 hours, and intervals between storms average 3 to 4 days.

For virtually all pollutants then, the stream segment receiving maximum exposure to the pollutants in runoff is that in the immediate vicinity of the discharge. Locations further downstream are exposed to lower concentrations due to dispersion and decay, and also as a result of dilution by fresh inflows (not considered in the schematic pattern shown in figure 44).

Accordingly, an analysis that focuses on the stream segment in the immediate vicinity of the initial mixing of runoff and stream flow will be addressing the most severely impacted stream reach. If no significant adverse impact is projected there, one should not expect problems in reaches further downstream. Further, it is useful to recognize that a marginal problem projected for this segment should not be assumed to apply to the entire stream. Normally, even where a problem condition is produced by runoff, it will apply to some fraction of the total stream length. An additional level of analysis may be appropriate, in special cases, to define the expected spatial extent of the objectionable conditions.

Stream biota at a particular stream location are therefore exposed to a variable sequence of episodes with different pollutant concentrations and different durations of exposure, separated by much longer intervals during which they are not in contact with pollutants from storm runoff. A probabilistic analysis is available and can be used to define the characteristics of these intermittent and variable patterns of stream concentration. The theoretical basis was described by DiToro [58], and a practical description of its use is provided in several different EPA publications [17,18]. The way this statistical analysis procedure (discussed earlier in Section 5.0) operates is illustrated schematically by figure 45. The statistical parameters of the stream and runoff flows and concentrations are first determined and then used in a relatively simple computation to directly compute the probability distribution of the instream concentrations produced by the stormwater runoff. Results may be summarized in graphical form as illustrated by figure 46, either as a probability distribution or in terms of the average return period of specific stream concentrations. The influence of uncertainty in inputs or the projected effect of controls can be shown as an aid to review and decision making.

A basis for estimating the mean and coefficient of variation of the concentrations of a pollutant in runoff has been addressed in earlier sections of this volume. There is no sound basis for making initial estimates of background (upstream) concentrations of a pollutant. Where it is desired to specifically include this effect in an analysis, it would be necessary that an appropriate record exist and that the user analyze it to determine the desired statistical parameters. An alternate approach is useful. Upstream concentrations are assigned a value of zero, so that the analysis results reflect only the effect of highway runoff.

Regional differences in storm intensity patterns were illustrated earlier (table 21). A more

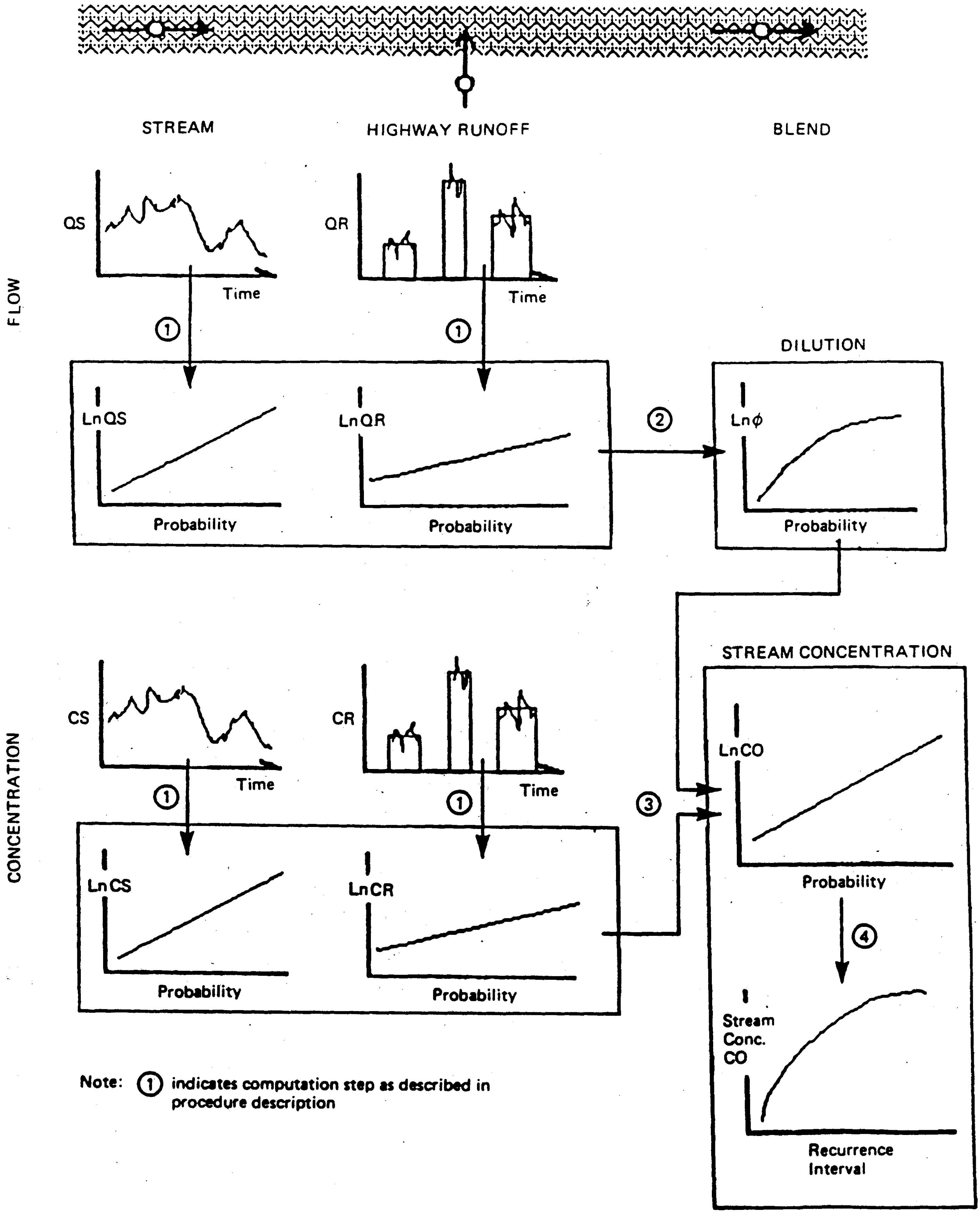
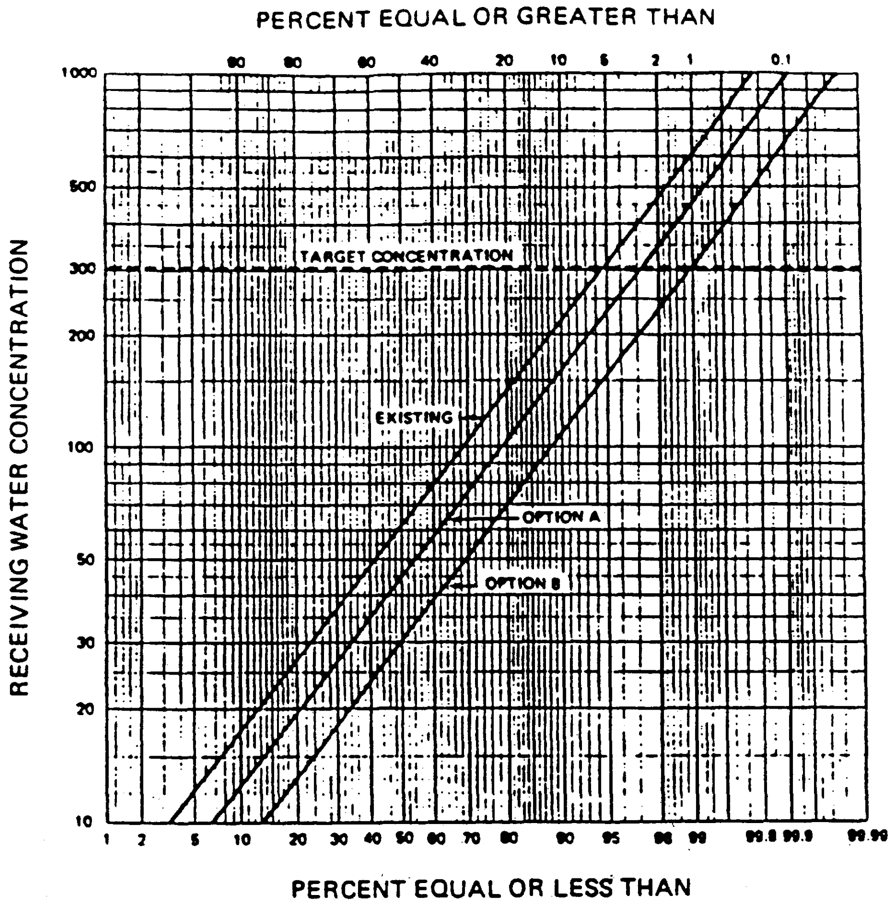


Figure 45. Schematic outline of probabilistic analysis method.



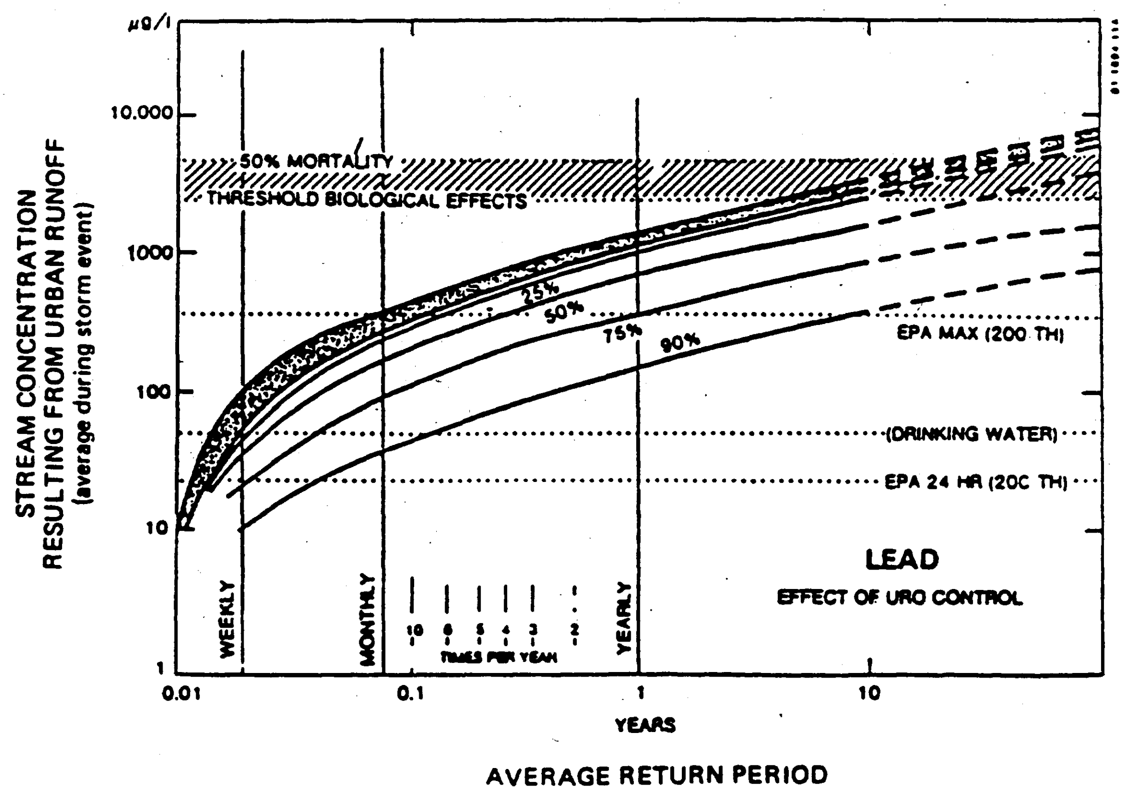


Figure 46. Probability of occurrence of stream concentrations.

extensive summary is provided in section 2.2 of the Design Procedures document, and further refinement can be obtained by the analysis of a local rain gage record using the SYNOP computer program, another product of this study. Combined with the area and percentage of impervious surface of the highway catchment, the rainfall statistics provide the desired estimate of the mean and coefficient of variation of runoff flows. The stream flows that dilute the runoff loads vary from day to day, and have characteristic annual average values (cfs/sq mi) in different regions of the country. Figure 47 provides a basis for initial estimates of mean stream flows. The absolute magnitude of the average flow at a stream location receiving highway runoff will be determined by the unit flow characteristic of the area, and the size of the upstream drainage area that contributes flow to the stream. USGS publications provide information on annual average flow for specific gages for refining local estimates.

The remaining input, the coefficient of variation of daily stream flows, could be developed from an appropriate analysis of the flow record, but this type of analysis is not normally performed. A basis for estimating the coefficient of variation of daily stream flows is provided by figure 48, which was developed from the analysis of a sample of stream flow records in different areas of the country. It shows the relationship between coefficient of variation and the ratio of the 7Q10 (the lowest 7 day average flow with a 10 year recurrence interval) to the average stream flow. Both of these values are routinely determined and reported.

The ultimate use of this procedure for specific project evaluations would be to conduct analyses using site-specific values of the statistical parameters for flows and concentrations. A step-by-step description of the procedure for conducting a specific site analysis is provided in the Design Procedures document produced under this study. The probabilistic analysis procedure is applied here, using typical ranges of values for the input parameters, in a general screening analysis to provide an overview of the potential for untreated highway stormwater runoff to create water quality problems.

The mean stream flow (MQS) and the mean runoff flow (MQR) are direct inputs to the stream impact analysis, and the analysis can be generalized by using the flow ratio (MQS / MQR). The coefficients of variation of the inputs can be assigned representative values for the screening analysis, as follows. The data analysis results reported in section 3.6 indicate that runoff concentrations can be assigned a CV of 0.75. An examination of the rainfall statistics presented in the Design Procedures document indicates a CV of 1.3 to be a good general approximation for rainfall intensity, and hence runoff flow rates. The CV of stream flows has a wider range than the foregoing, but based on figure 48, can be assigned a reasonably representative value of 1.5.

The final input required is the site median concentration of a pollutant in the highway runoff. As summarized in section 3.5, this will vary with the specific pollutant, and with site conditions. The effect however can be generalized by assigning the site median concentration a value of 1. In this case, all stream concentrations that are computed by the stream analysis procedure, can be interpreted as multiples (or fractions) of the site median concentration.

The remaining point to address for the screening analysis is the particular stream concentration to portray among all those that populate the distribution of stream concentrations produced by runoff. We elected to use the concentration computed to occur on an average of once in 3 years, because the acute toxic criteria specify this recurrence interval.

Figure 49 depicts the results of this overview screening analysis. The horizontal axis reflects increasing flow ratios, i.e., highway runoff entering increasingly larger streams. The vertical axis shows the concentration produced in the stream during a storm event once every 3 years, expressed

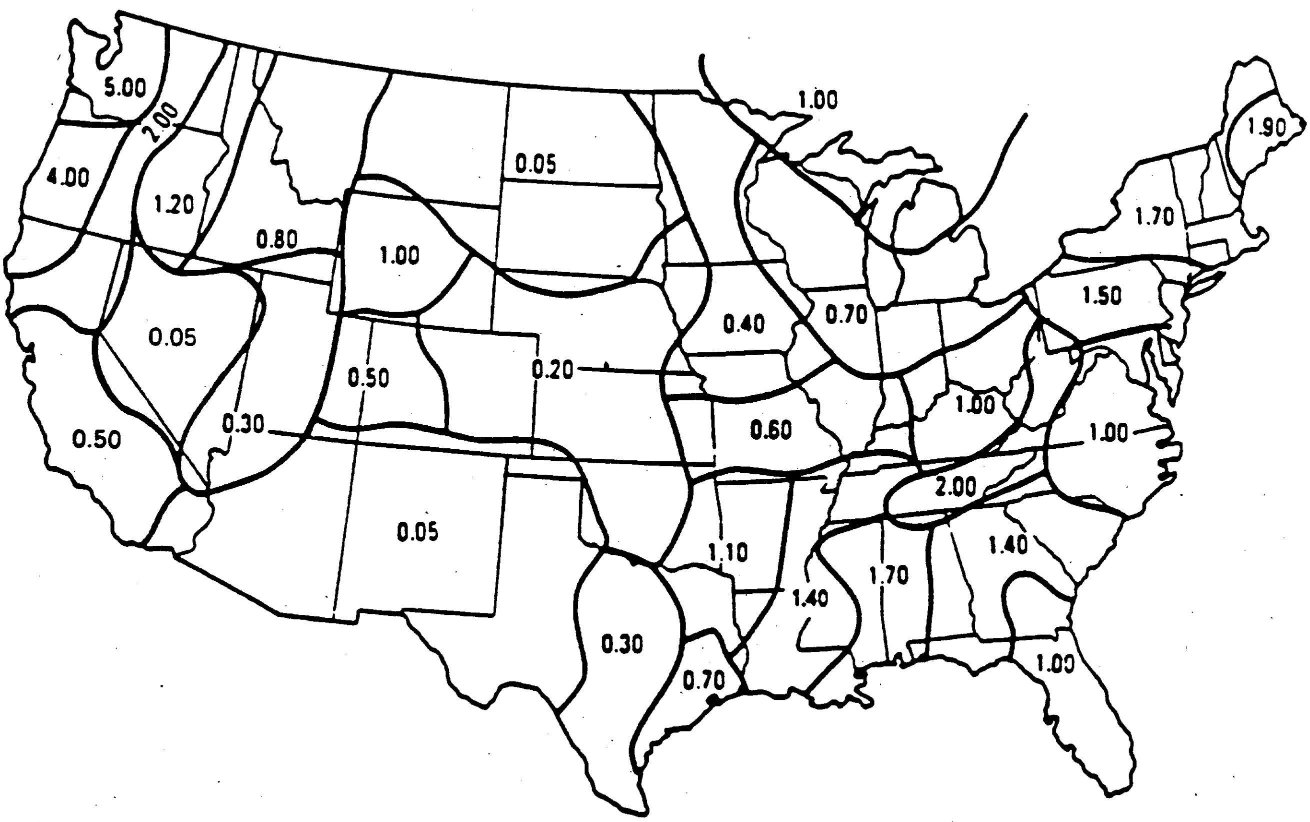


Figure 47. Regional estimates of annual average streamflow ($ft^3/s/mi^2$).

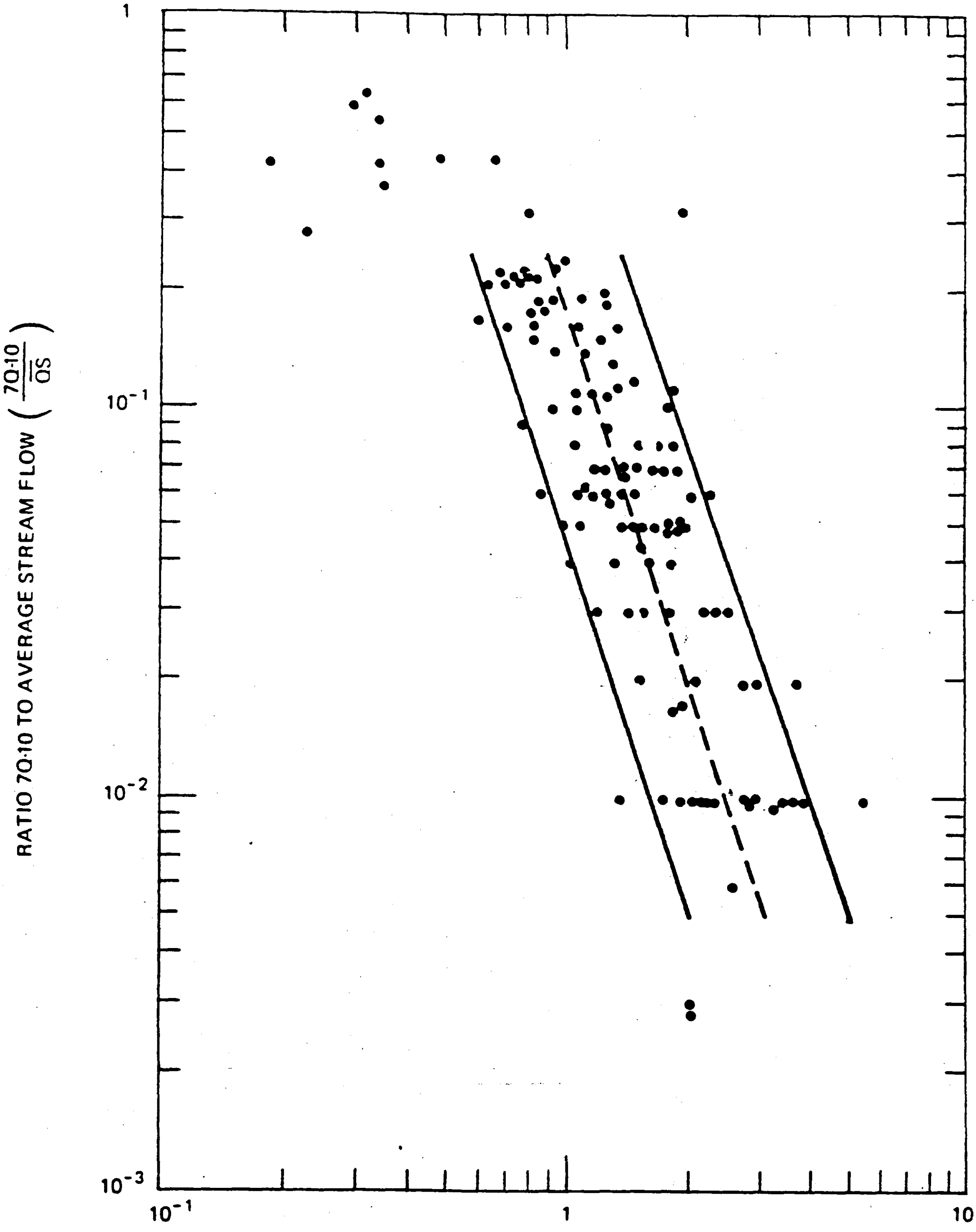


Figure 48. Guide for estimating coefficient of variation of daily streamflows.

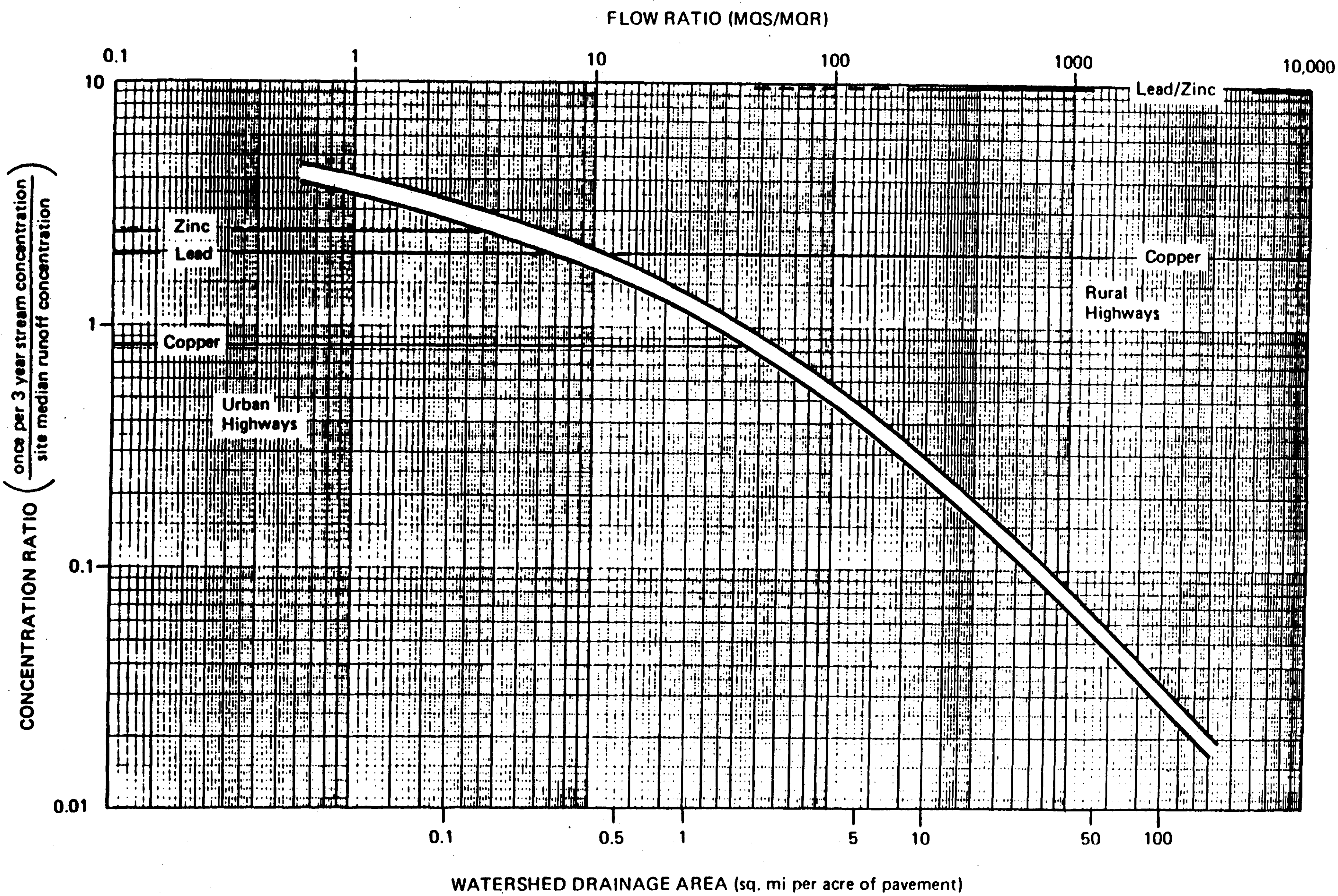


Figure 49. Screening analysis of stream impacts.

as a ratio of the site median concentration in runoff. The width of the band that is plotted accounts for regional differences in the average number of storms per year, ranging from 80 to 120.

Two additional items of information are plotted on this figure to enhance its utility in providing an overview of the conditions under which highway runoff could have potential to create problem conditions. The first is a translation of the flow ratio into an approximate relationship between the highway drainage area, and that of the watershed that contributes to the stream. The other approximates the concentration ratios that will produce criteria violations.

Even with the substantial differences in both rainfall and streamflow in different parts of the country, the dominant influence on the stream concentrations produced by runoff (and hence problem potential), will be the Drainage Area Ratio (DAR). This is defined as the ratio of the stream drainage area (which determines stream flow), to the paved highway drainage area (which determines runoff flow and hence pollutant load). This ratio can be determined readily for any site-specific situation, and so is a useful basis for structuring a screening analysis. The DAR is important because it determines what the ratio of the stream and runoff flows will be.

Since area rainfall has an influence on streamflow as well as runoff flow, an estimate of the approximate flow ratio can be developed from the following relationship based only on the drainage area ratio.

$$MQS / MQR = K * DAR \tag{31}$$

where:

DAR = ratio of total watershed area upstream of highway to paved area of highway
K = a constant that varies regionally, as discussed below

Based on the typical rainfall statistics for the zones depicted in figure 41, the constant in equation 31 will have a value of about K = 0.04 in parts of the country that are east of the 90th meridian. It will have a value of K = 0.12 in the Pacific northwest, and about K= 0.01 in the southwest. For the remaining areas it may be estimated at about K = 0.025.

Note that the important relationship in figure 49 is the flow ratio. The foregoing approximation of the relationship between flow ratio and DAR is provided simply to assist the user in relating the results to the more readily estimated drainage area relationship.

The criteria levels superimposed on the concentration ratio vertical axis will vary somewhat (up or down) depending on the total hardness of the receiving water, and on the fraction of the pollutant's total concentration that is soluble. For the screening analysis results shown by figure 49, a total hardness of 100 mg/l was used. Lead was assumed to have a soluble fraction of 10 percent, and copper and zinc of 40 percent. Urban highways are shown on the left, and rural highways, with lower site medians for all pollutants are shown on the right.

The screening results suggest that urban streams with watersheds more than a few square miles per acre of highway pavement (or rural streams more than 0.5 sq mi per acre) are unlikely to experience violations of acute toxic criteria from highway stormwater runoff. The foregoing crude screening analysis is presented to provide a general perspective. The basis for a more detailed analysis and instructions for applying it to a specific site are provided by the Design Procedures document and by the interactive microcomputer program that are other products of this study.

7.5 LAKES

The most common water quality problem caused by pollutant discharges to lakes is an accelerated rate of eutrophication due to elevated nutrient levels resulting from pollutant loads.

The Vollenweider model (67,68) provides a widely accepted and useful screening tool for examining the relationship between a load source and the expected trophic level of a lake. The model formulation is usually expressed as follows:

$$P = \frac{W'}{H/t + V_s} \tag{32}$$

where:

P = average concentration of P in lake ($gm/m^3 = mg/l$)
W' = annual unit mass loading (grams per sq meter per year)
H = average depth of lake (meters)
t = hydraulic detention (years)
V_s = net P settling velocity (meters per year)

For the stormwater runoff applications addressed by this document, the basic model can be transposed to employ terms and dimensional parameters that are more convenient for highway situations. The settling velocity is usually estimated at 5 meters per year for small lakes. The hydraulic detention time is a function of the lake volume (surface area and depth) and the average total inflow. Accordingly, the model formulation can be transposed to the following format.

$$P = \frac{(ANMASS * 112)}{(MQS * 221) + (ALAK * 5)} \tag{33}$$

where:

ANMASS = annual highway mass loading (lbs per year)
ALAK = surface area of lake (acres)
MQS = average total lake inflow rate (cu ft per second, CFS)
P = average lake concentration (micrograms/liter)

For a site-specific analysis, this model is employed in the step-by-step analysis procedure that is presented in the Design Procedures document and in the interactive microcomputer program.

An overview of the potential influence of highway stormwater runoff is developed here by simplifying the above equation, using approximate relationships between drainage area and runoff or stream flow. The drainage area ratio (DAR) is used to generalize on the differences that will occur at individual sites. This area relationship is the ratio between the total watershed drainage area for the lake, and the paved surface area of the highway. A lower bound for this ratio can be established at about 1 by assuming a six or eight lane highway completely encircling a very small lake (1 acre). In most cases, the DAR will be orders of magnitude higher than this. Figure 50 shows the projected annual average lake concentration (micrograms per liter of P) using the runoff concentrations for the median urban and nonurban highway sites. The approximate relationship

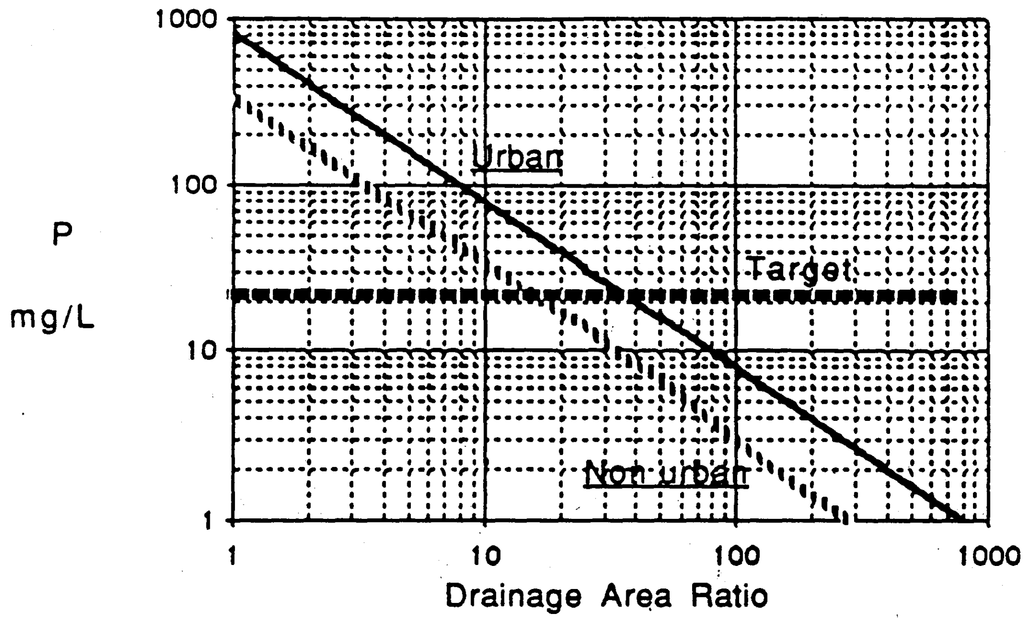


Figure 50. Screening analysis of lake impacts.

between highway runoff and eutrophication potential is seen to be a function of the drainage area ratio.

An average total phosphorus concentration of 20 micrograms per liter is overplotted on figure 50, to provide a point of reference. This was the concentration level indicated by a study of lakes in the north temperate zone that was considered to provide an approximate delineation for the existence of undesirable eutrophication conditions. Inspection of the plot indicates that highway runoff discharges to lakes are not likely to be significant when the DAR is greater than about 70 for urban highways, or greater than about 30 for rural highways. The projected impact is about one half or less than the reference lake concentration under these conditions. In other terms, whenever the total watershed area is appreciably greater than 0.1 square mile per acre of paved highway surface area, the problem potential will tend to be small.

However, while this simplification provides a useful order-of-magnitude sense of problem potential, the user should be aware that the reference value shown is not a formal criterion and that local conditions and/or policies may dictate the use of either higher or lower target concentrations. For example, higher concentrations are frequently applied for lakes in the southern tier of states, or for some lakes in developed areas in more northerly locations. In contrast, where a lake is considered to be in relatively pristine condition, substantially lower target concentrations may be assigned. For a site-specific lake impact analysis, locally applicable criteria should be obtained from the relevant State environmental agency.

7.6 ESTUARIES

Simple screening techniques are available, but are only appropriate to apply for very "simple" estuarine situations. There are very few of these. On the other hand, virtually all estuaries and tidal rivers will be quite large relative to highway runoff areas, and their water quality can be expected to be dominated by other sources. For the rare case where a problem attributable to highway runoff is believed to exist, an appropriate site-specific analysis will be required.

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