U.S. Department of the Interior
U.S. Geological Survey

Prepared in cooperation with the
FEDERAL HIGHWAY ADMINISTRATION

Data Quality Objectives and Criteria for Basic Information, Acceptable Uncertainty, and Quality-Assurance and Quality-Control Documentation

Open-File Report 98-394

A Contribution to the
NATIONAL HIGHWAY RUNOFF DATA AND METHODOLOGY SYNTHESIS

U.S. Department of Transportation

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U.S. Department of the Interior
U.S. Geological Survey

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By GREGORY E. GRANATO, U.S. Geological Survey; FRED G. BANK, and PATRICIA A. CAZENAS, Federal Highway Administration

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Marlborough, Massachusetts
1998

U.S. DEPARTMENT OF THE INTERIOR
BRUCE BABBITT, *Secretary*

U.S. GEOLOGICAL SURVEY
Thomas J. Casadevall, *Acting Director*

For additional information write to:

Chief, Massachusetts-Rhode Island District
U.S. Geological Survey
Water Resources Division
28 Lord Road, Suite 280
Marlborough, MA 01752

Copies of this report can be purchased from:

U.S. Geological Survey
Branch of Information Services
Box 25286, Building 810
Denver, CO 80225-0286

PREFACE

Knowledge of the characteristics of highway runoff (concentrations and loads of constituents and the physical and chemical processes which produce this runoff) is important for decision makers, planners, and highway engineers to assess and mitigate possible adverse-impacts of highway runoff on the Nation's receiving waters. In October, 1996, the Federal Highway Administration and the U.S. Geological Survey began the National Highway Runoff Data and Methodology Synthesis to provide a catalog of the pertinent information available; to define the necessary documentation to determine if data are valid (useful for intended purposes), current, and technically supportable; and to evaluate available sources in terms of current and foreseeable information needs. This paper is one contribution to the National Highway Runoff Data and Methodology Synthesis and is being made available as a U.S. Geological Survey Open-File Report pending its inclusion in a volume or series to be published by the Federal Highway Administration. More information about this project is available on the World Wide Web at http://mass1.er.usgs.gov/fhwa/runwater.htm

Fred G. Bank
Team Leader
Natural and Cultural Resources Team
Office of Environment and Planning
Federal Highway Administration

Patricia A. Cazenas
Highway Engineer
Natural and Cultural Resources Team
Office of Environment and Planning
Federal Highway Administration

Gregory E. Granato
Hydrologist
U.S. Geological Survey

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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yards	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
NOTE: Volumes greater than 1000 l shall be shown in m^3.				
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5(F-32)/9 or (F-32)/1.8	Celcius temperature	°C
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.71	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact)		
°C	Celcius temperature	1.8C + 32	Fahrenheit temperature	°F
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

* SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380.

(Revised September 1993)

Data Quality Objectives and Criteria for Basic Information, Acceptable Uncertainty, and Quality-Assurance and Quality-Control Documentation

By Gregory E. Granato, U.S. Geological Survey; Fred G. Bank, *and*
Patricia A. Cazenas, Federal Highway Administration

Abstract

The Federal Highway Administration and State transportation agencies have the responsibility of determining and minimizing the effects of highway runoff on water quality; therefore, they have been conducting an extensive program of water-quality monitoring and research during the last 25 years. The objectives and monitoring goals of highway runoff studies have been diverse, because the highway community must address many different questions about the characteristics and impacts of highway runoff. The Federal Highway Administration must establish that available data and procedures that are used to assess and predict pollutant loadings and impacts from highway stormwater runoff are valid, current, and technically supportable.

This report examines criteria for evaluating water-quality data and resultant interpretations. The criteria used to determine if data are valid (useful for intended purposes), current, and technically supportable are derived from published materials from the Federal Highway Administration, the U.S. Environmental Protection Agency, the Intergovernmental Task Force on Monitoring Water Quality, the U.S. Geological Survey and from technical experts throughout the U.S. Geological Survey.

Water-quality data that are documented to be meaningful, representative, complete, precise, accurate, comparable, and admissible as legal evidence will meet the scientific, engineering, and regulatory needs of highway agencies. Documentation of basic information, such as compatible monitoring objectives and program design features; metadata (when, where, and how data were collected as well as who collected and analyzed the data); ancillary information (explanatory variables and study-site characteristics); and legal requirements are needed to evaluate data. Documentation of sufficient quality-assurance and quality-control information to establish the quality and uncertainty in the data and interpretations also are needed to determine the comparability and utility of data sets for intended uses. The fact that a program's data may not meet screening criteria for a national synthesis does not mean that the data are not useful for meeting that program's objectives or that they could not be used for water-quality studies with different objectives.

INTRODUCTION

The Federal Highway Administration (FHWA) and State transportation agencies (STAs) are responsible for determining and minimizing the effects of highway runoff on the quality of receiving waters while planning, designing, building, operating, and maintaining the Nation's highway infrastructure. This responsibility is established by Federal and State legislation, including the National Environmental Policy Act, the Clean Water Act, the Safe Drinking Water Act, the Coastal Zone Management Act, and other legislation, as well as derivative rules, regulations, executive orders, and policies (FHWA, 1986; Young and others, 1996). Federal and State environmental agencies are increasing efforts to quantify and regulate sources of nonpoint-source pollution through mandatory monitoring programs and to establish best management practices (BMPs) to minimize the impact of these sources (FHWA, 1986; Young and others, 1996). As part of this effort, the FHWA has tried to supply valid, current, and defensible legal and technical information relating to the quality of highway runoff. In this report, the term "information" refers to the documentation of the characteristics of the study, the study site, and processes used to collect, analyze, interpret and validate the data collected. The term "data" refers to documented measurements made in the field, or to results of laboratory analysis of samples collected in the study.

The FHWA, in conjunction with many STAs, has conducted an extensive program of water-quality monitoring and research during the last 25 years (Smith and Lord, 1990). The objectives and monitoring goals of highway runoff have been diverse. Data from different highway runoff studies have been combined to

- Characterize various physical properties and chemical constituents in highway runoff;
- Determine pollutant loads for constituents in highway runoff;
- Assess the effects of highway stormwater discharges on receiving waters;
- Identify the sources and mechanisms that determine the quantity of pollutants in highway runoff;
- Develop information for the design and operation of BMPs;
- Respond to regulatory monitoring requirements and litigation; and
- Predict the impacts of highway runoff on surface- and ground-water quality for aquatic life, human consumption, and recreational and industrial uses.

Diverse study objectives and monitoring goals impose different data and information requirements. As study objectives and monitoring goals increase in complexity, the cost and data requirements increase and the level of acceptable uncertainty decreases. Preliminary monitoring at a single site may require only a few samples. However, complex scientific investigations designed to characterize physical and chemical processes, or to develop design or predictive methods may require thousands of samples over an extended period of time (Sonnen, 1983). To date, information and water-quality data from relatively few highway-runoff monitoring studies (fig. 1) have been available to support planning, design, construction, operation, and maintenance decisions for the Nation's highway infrastructure.

Problem

The FHWA must verify that available data and procedures used to support decisions concerning highway runoff are valid (useful for intended purposes), current, and technically supportable. The validity of historical data can be difficult to determine if documentation is not sufficient to substantiate the quality of the data. Also, continuing changes in sources of highway-runoff pollutants add increasing uncertainty as to the current validity and utility of historical data sources. Such changes include the disappearance of leaded fuels (Young and others, 1996); the development and use of new and potentially problematic fuel additives, such as Methyl*tert*-butyl ether (MTBE) (Delzer and others, 1996); and changes in materials used for automobiles (Helmers, 1996) and highway construction, such as pulverized rubber tires in pavement mixtures (Young and others, 1996).

To demonstrate that water-quality data are valid and technically supportable, sufficient documentation must be available to prove that the data are meaningful, representative, complete, precise, accurate, comparable, repeatable, and admissible as legal evidence (Alm and Messner, 1984; FHWA, 1986; ITFM, 1995a, 1995b; U.S. Environmental Protection Agency, 1997). These terms have operational definitions that are used to determine data-evaluation criteria for this investigation. Although the concepts intertwine, each is a distinctive part of the evaluation process. For data to be meaningful, they must be collected as part of a study designed to examine a typical highway site largely free from the influence of a unique contributing source. For example, the data set collected for the Washington State Department of Transportation during the eruption of Mount St. Helens may be representative, complete, precise, accurate, comparable, and admissible as legal evidence, but it can not be considered meaningful in characterizing typical highway-runoff quality (Driscoll and others, 1990b). A data set that is representative accurately and precisely characterizes a population, a process, and parameter variations at a study site. A data set that is complete contains enough representative information to characterize the uncertainties in the data and resultant interpreted values. For example, a data set may completely define water-quality characteristics for one storm, but a one-storm data set would not characterize differences from storm to storm, season to season, or year to year. To be considered complete,

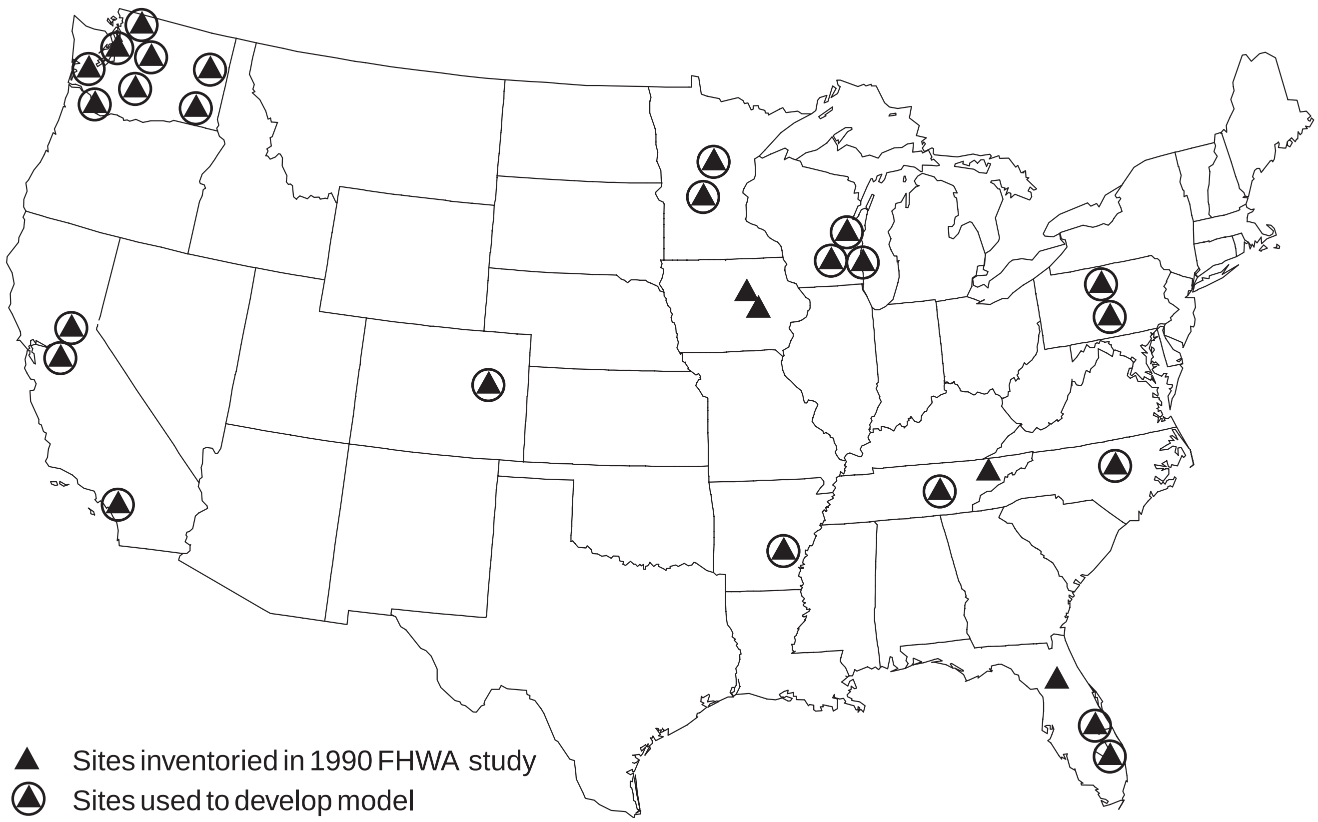

Figure 1. Locations of highway-runoff study sites inventoried during the 1990 study and sites used by the FHWA to develop the water-quality prediction model (modified from Driscoll and others, 1990, Volume III).

a data set from a monitoring study should characterize seasonality over more than 1 year because annual highway-runoff solute loads have been shown to vary from approximately 50 percent to 200 percent of the median from year to year over a 5-year period (Granato, 1996). Precision implies a high degree of repeatability for samples obtained under similar conditions. Accuracy implies a lack of bias (no systematic errors). Data that are comparable are taken from the same matrix, such as the water column, suspended solids, sediment, or biota by using documented sampling and analysis methods demonstrated to produce results with similar and acceptable levels of bias and variability. Data sets that are admissible as legal evidence must contain enough information to withstand any reasonable challenge to their quality and veracity.

The quality and quantity of environmental data required to support a decision can vary greatly depending on the nature and scope of the problem and the regulatory environment. However, a national synthesis requires robust data-evaluation criteria to ensure adequate representation of the different characteristics and natural settings of U.S. highways and maximum utility of data sets for scientific, engineering, and regulatory needs of highway agencies. The U.S. Environmental Protection Agency (USEPA) and the Intergovernmental Task Force on Monitoring Water Quality (ITFM) have established criteria for water-quality data to be included in national data bases (USEPA, 1994, 1996; ITFM, 1995a, 1995b). Review of data within the context of currently accepted environmental data-quality specifications and objectives for a national synthesis is necessary to establish the accuracy of available information. A well-defined data set is important because decision makers increasingly bear personal as well as institutional responsibility for the veracity of environmental monitoring information that is collected to meet regulatory purposes (Young and others, 1996).

Purpose and Scope

The purpose of this report is to evaluate data-quality criteria that are used to examine a sampling of the available highway-runoff data sets that were collected during the last 25 years. This report outlines the data quality objectives process, describes basic information requirements, assesses acceptable uncertainty, and provides an overview of necessary quality-assurance and quality-control information. These criteria are needed to demonstrate that existing information is valid, current, and technically supportable for current and future uses. The criteria were derived from published materials from the FHWA, USEPA, ITFM, and U.S. Geological Survey (USGS). Input from technical subject-matter experts throughout the USGS also were used to determine the evaluation criteria.

The choice of criteria for this national synthesis reflects the potential difficulties involved in combining data from diverse programs to develop a data base that covers broad geographical areas and catalogs consistent, technically sound water-quality data. The fact that a program's data may not meet these screening criteria does not mean that these data are not useful for meeting that program's objectives or that they could not be used for water-quality studies with objectives different from those stated herein. Some data sets may be disqualified because the required information for a particular study may not be sufficiently documented in available reports. A detailed investigation of each study would require on-site inspection, extensive interviews with program personnel, and a detailed examination of original records. Even if the appropriate people and original records were available, this type of effort would go far beyond the scope of this national synthesis.

DATA QUALITY OBJECTIVES

The data quality objectives (DQOs) process is designed to help weigh the costs of data acquisition against the consequences of a decision error caused by inadequate input data. The DQOs process also is intended to help weigh the costs and benefits of local short-term monitoring requirements against regional and national long-term information needs. Standards for quality assurance and quality control (QA/QC), comparability, and documentation must be higher for a national synthesis than for a local monitoring program to distinguish between real intersite differences and sampling artifacts. Strict national standards may add to monitoring costs on a case-by-case basis, but experience indicates that monitoring activities need to be improved and integrated to meet the full range of local, regional, and national information needs more effectively and economically (ITFM, 1995a).

The validity of data is, in some ways, a relative term. Data that are adequate for one purpose may be totally inadequate for another (Keith and others, 1983; USEPA, 1994). DQOs are used to define the degree to which experimental uncertainty in a data set must be controlled to achieve an acceptable level of confidence in a decision based on the data (USEPA, 1986, 1994, 1996; ITFM, 1995b). The concept of DQOs is meaningful only in relation to intended uses and risks of decision error. The quality of data that is required is dependent upon the problem at hand and local regulatory restrictions that can change with time. When problems pertaining to highway-runoff quality are evaluated, the DQO process can be used to determine the level of acceptable uncertainty and the resultant QA/QC needed to determine what data are appropriate for program objectives (USEPA, 1986, 1994). Once a problem is identified, the decision risks are evaluated, and resultant DQOs are defined, these criteria can be used to evaluate different program designs and (or) data sets (USEPA, 1994). DQOs also provide a standard for comparison for use in evaluating and combining different data sets for quantitative analysis (USEPA, 1996).

In the DQO process, decision errors are characterized as Type I or Type II errors. A Type I error occurs when a determination is made, on the basis of available data, that problems exist when they do not really exist. A Type II error occurs when real problems exist but the determination is made, on the basis of available data, that no problems exist. Substantially overestimating concentrations, loads, and the impacts of highway runoff pollutants—a Type I error—could intensify and lengthen regulatory processes, lead to changes in highway alignments, and force design changes and the adoption of additional BMPs. Therefore, a Type I error may increase costs for planning, design, construction, and maintenance of the Nation's highways. Substantially underestimating concentrations, loads, and the impacts of highway runoff pollutants—a Type II error—also can cause problems, incur high corrective costs, and negatively affect public perceptions about the veracity of environmental information provided by transportation agencies. Discovery of large prediction errors during the planning, design, and construction phases of a highway could increase costs. Type II errors discovered while monitoring runoff from a highway once it is in operation could result in regulatory actions, fines, and costs associated with additional BMPs.

The DQO process also applies to the interpretation of field data. The interpretive process, whether conceptual, statistical, or deterministic, is often the best means to synthesize available data into a form that will help determine the cause and effect relations that are used to support decisions. The financial and legal risks to decision makers and agencies for Type I or Type II errors will drive the selection of acceptable uncertainty levels for interpretive methods (USEPA, 1986, 1994). The interpretive process (including necessary simplifications and assumptions) propagates uncertainties generated in the data collection process. Once DQOs are established, however, the characteristics of the interpretive process can be used to determine the type, amount, and allowable uncertainty of data that are needed to support decisions (USEPA, 1994).

Information requirements for determining highway-runoff quality are diverse and vary from region to region, from state to state, and from situation to situation. Therefore, it is incumbent upon State, regional, and Federal decision makers and regulators to determine the DQOs necessary to address each issue. A single quantitative set of DQOs might either be too restrictive and disqualify a data set otherwise appropriate for a given use, or too vague and preclude useful predictive interpretations. Therefore, this study will evaluate a sample of available information to determine if existing reports sufficiently document the basic information, acceptable uncertainty, and QA/QC necessary to meet various DQOs that may be established by decisionmakers and regulators to evaluate a particular runoff issue.

BASIC INFORMATION REQUIREMENTS

To establish data quality and to ensure the usefulness of available water-quality information, basic information needed to evaluate the validity of the data and the methods of data collection and processing must be documented. For a national synthesis, data are useful only if collected and analyzed in a relatively consistent manner, because differences in methods commonly overshadow real variations caused by differences in the explanatory variables (ITFM, 1995a). The ITFM established metadata standards to describe the content, quality, and other characteristics that are needed to determine how useful a data set is for any particular application (ITFM, 1995a, 1995b). Basic data requirements include information about the monitoring objectives, sampling design, methods for collecting and handling samples, field and laboratory measurements, and data qualifiers.

In a review of water-quality data collected by Federal, State, and local water-quality monitoring entities, Hren and others (1987) defined five characteristics necessary to establish that data are useful. To be useful, data must be: (1) representative of the system under study; (2) available for public use as original data; (3) collected from a readily located sampling site (to assess data comparability and to interpret results of geographic/climatological variations); (4) associated with sufficient quality assurance (QA) information (to indicate the validity, reliability, and compatibility of data from different sources); and (5) available in useful computer files (to increase reliable compilation and manipulation of large volumes of data). These criteria were developed to screen data from diverse programs for inclusion in a database that could provide consistent, technically sound water-quality data representing broad geographic areas through time (Hren and others, 1987). A national synthesis of surface-water pesticide data concluded that quantitative synthesis may not be feasible when each study has unique objectives, sampling schedules, sampling and analysis methods, target analytes, detection limits, data presentation, and complete data sets that are not available in open literature (Larson and others, 1997).

Monitoring Objectives and Program Design

Study objectives and monitoring goals define where samples are collected, the frequency of collection, the timing and duration of sample collection, matrixes sampled, methods used, and properties and constituents that are analyzed (Hren and others, 1987; Larson and others, 1997). These characteristics can affect the applicability and availability of data for broad-scale studies. Data quality objectives determined by study objectives and monitoring goals define the maximum allowable errors consistent with the level of confidence in decisions made with data collected (USEPA, 1994). For example, in an analysis of urban-runoff monitoring requirements, Sonnen (1983) calculated that as few as 24 samples with about 6 analytes might be sufficient to provide information for BMP design equations at one site; whereas, 54,000 samples with about 100 analytes might be needed to determine physical and chemical processes and the environmental mechanisms that control concentrations of various stormwater constituents in a region. The purpose of many data-collection programs is to monitor problem sites; thus, data sets assembled from these programs are biased (Norris and others, 1990). Therefore, the study objectives and monitoring goals of a data-collection program may determine if results can be combined into a national synthesis without substantial qualifications on decisions made by using the assembled database.

Metadata Standards

Metadata standards established by the ITFM are designed to aid in the determination of data comparability among different monitoring programs. The ITFM defines comparability as the characteristics that allow data from multiple sources to be of such definable quality that the data can be used to address program objectives other than those for which the data were collected (ITFM, 1995b). To determine comparability, potential data users must be able to determine when, where, and how data were collected, as well as who collected and analyzed the data. The ITFM established the following minimum set of qualifiers to be documented with the sampling and analytical data:

- Parameter, property, constituent, or identifier evaluated;
- Sample matrix (the water column, suspended solids, sediment, atmospheric deposition, or biota);
- Methods for collection, handling, analysis, and interpretation;
- Type of data measured (concentration, population variable, or ratio);
- Location (latitude and longitude) of sampling point;
- Date and time of day sample was collected;
- Data collection and analyzing entities (who actually made the measurements);
- Data source (whose monitoring program); and
- Indication of data quality (including precision, bias, detection limits, and a defined QA/QC system).

Documentation of these basic criteria were evaluated and deemed essential in several reports written to examine the utility of data for regional or national water-quality assessment (U.S. General Accounting Office, 1981; Childress and others, 1987; Hren and others, 1987; Norris and others, 1990; Larson and others, 1997).

Ancillary Information

Ancillary information is also needed to evaluate available data for a national synthesis. Ancillary information about the characteristics of a study area may provide explanatory variables that can be used to standardize data to a common basis for comparison, or to account for some of the variability in the data (Norris and others, 1990). For example, flow data are needed for surface-water quality assessments because concentrations of many constituents are affected by changes in flow (Norris and others, 1990). In a study using a compiled database of approximately 2,800 storms measured at urban monitoring stations in metropolitan areas of 24 states, Driver and Tasker (1990) found that physical and climatic information, such as impervious area, land use, rainfall characteristics, and mean minimum January temperatures, were useful in determining loads and concentrations of stormwater constituents. Other characteristics, such as local geology, soil properties, and surrounding land and water use, also have been shown to be important characteristics for data evaluation. For example, Gupta and others (1981) indicated that a large percentage of highway runoff constituents are inorganic and are derived from local geologic materials.

Ancillary information also has proven useful in past evaluations of highway runoff pollution. Gupta and others (1981) determined that the concentrations and loads of constituents in highway runoff were affected by

- Highway design features;
- Traffic characteristics (speed, volume, braking, acceleration);

- Climatic conditions (amount, intensity, and form of precipitation);
- Maintenance policies (sweeping, mowing, repairing, deicing, and so forth);
- Surrounding land use (industrial, commercial, residential, or rural);
- Percentage of impervious area within the total drainage area;
- Type of pavement material;
- Average age of automobiles in the study area;
- Application of littering and vehicle emission laws;
- Use of additives in vehicular operation;
- Types of soils and vegetation along the highway right-of-way; and
- Local and regional atmospheric deposition.

Subsequent studies indicate that these characteristics, as well as the hardness of local waters, drainage system characteristics, and the implementation of BMPs influence the constituents in and effects of highway runoff (FHWA, 1986; Driscoll and others, 1990a; Young and others, 1996).

Legal Requirements

The FHWA and the STAs conduct most water-quality sampling for legal and scientific objectives. Data may be technically valid but not admissible in court. Consequently, sampling programs must be designed to produce legally admissible data (FHWA, 1986). In the regulatory and legal arena, the costs and penalties for submitting data and supporting information that are not deemed to be valid can be high for the responsible individuals and organizations (Mallan and others, 1993; Klodowski, 1996).

Data that are presented as legal evidence must meet three tests of admissibility; they must be shown to be (1) relevant (the data support a claim made in the case), (2) material (the claim addresses an issue in the case), and (3) competent (the data are valid, current and technically supportable). Relevance and materiality are highly case-specific, but competence can be controlled by using and documenting proper data-collection methods. Data sets that are admissible as legal evidence must contain enough information to withstand any reasonable challenge to their quality and veracity. To demonstrate competence, agencies must prove by documentation that data-collection methods are accepted by the scientific community and were performed properly, and that data were collected, verified, and interpreted by qualified personnel. For analytical data, documentation of the quality-control process and quality-assurance measurements should substantiate competence (Klodowski, 1996). The USEPA and FHWA require chain-of-custody information for authentication of water-quality samples to be admissible as legal evidence (FHWA, 1986).

The legal requirements for providing interpretive results are increasing as are the requirements for producing field and laboratory data (Haan and others, 1990). Defensible interpretations are increasingly dependent on the availability of information that documents the uncertainty and QA/QC practices that are used to develop, test, and verify interpretive models (Haan and others, 1990; Heijde, 1990; Water Science and Technology Board, 1990). For model results to be admissible in a technical or legal setting, it must be demonstrated that

- Underlying data are valid, unbiased, complete, and original or properly documented from a reliable source;
- The underlying theory of the model and modeling assumptions are correct;
- The computer programs properly implement the theory; and
- The programming and data processing were done accurately with sufficient safeguards against error.

Estimates of the uncertainty, the predictive accuracy, and the risks of an incorrect analysis are the determining factors when models and resultant interpretations are held to a legal standard of "truth" (Haan and others, 1990).

ACCEPTABLE UNCERTAINTY

Uncertainty is a measure of the errors and losses of information inherent in environmental studies that prevent the characterization of exact properties of the underlying distribution of that information (Ward and Loftis, 1983). The total uncertainty is the sum of uncertainty caused by natural variability, measurement errors, and interpretive generalizations. Environmental data collection always involves some error as an inherent characteristic of the hydrologic environment; sampling design; land-use history of the study area; and methods used for sample collection, sample analysis, and data interpretation (USEPA, 1986, 1994; Childress and others, 1987; Brown and others, 1991; Clark and Whitfield, 1993).

Rigorous uncertainty assessments are needed to determine if data are sufficiently valid and technically supportable, because the usefulness of water-quality data is inversely related to the amount of uncertainty in the data (Montgomery and Sanders, 1985). The acceptable uncertainty of data and interpretations for a given problem must be evaluated in terms of the regulatory objectives, the decisions to be made by using the data, and the possible consequences of making incorrect decisions (USEPA, 1986, 1994). The total uncertainty increases when data from different studies are combined because differences in analytical laboratories, methods, and the characteristics of pollutant sources through time are incorporated into the resultant data set. To support decisions, the level of total uncertainty from random and systematic error introduced into the different sampling processes must be less than the natural variability caused by differences from site to site and study to study.

Historically, inconsistent performance within and between analytical laboratories has been a constant and substantial source of uncertainty (U.S. General Accounting Office, 1981). Use of validated methods, reference laboratories, and experienced personnel does not ensure reliable analytical results (Keith and others, 1983). Participation in an interlaboratory comparison program is one component of good laboratory QA/QC practices. Results from a laboratory implementing good QA/QC practices should be more reliable than results from an uncontrolled analytical program.

Results of interlaboratory comparisons indicate that analytical uncertainties in data sets are larger than published values for the accuracy of standard methods. Different interlaboratory comparisons have documented consistent problems with accuracy, repeatability, and performance through time in the population of participating laboratories throughout the period of highway runoff research (General Accounting Office, 1981; Polvi and others, 1985; Farrar and Long, 1997). One study of analytical laboratories used for National Pollutant Discharge Elimination System (NPDES) compliance monitoring revealed that there was only a 32- to 42-percent chance that any given laboratory would measure all constituents within acceptable limits (Polvi and others, 1985).

An indication of analytical uncertainty in available data sets may be derived from examination of statistics for analytical results of natural-matrix reference samples from the USGS interlaboratory evaluation program (Farrar and Long, 1997). Interlaboratory statistics—for example the most probable value (MPV) of chromium concentrations and the estimated error of laboratory results—from the USGS program from 1989 through 1997 are shown in figure 2. The range of the MPV concentrations for these samples is within the ranges of measured concentrations for most metals reported as constituents in highway runoff (Smith and Lord, 1990). In the concentration ranges presented, percent accuracy increases with increasing concentration. The uncertainty for the "best" laboratories (those in the top 5 percent of the performance rating in the USGS interlaboratory evaluation program) ranged from plus

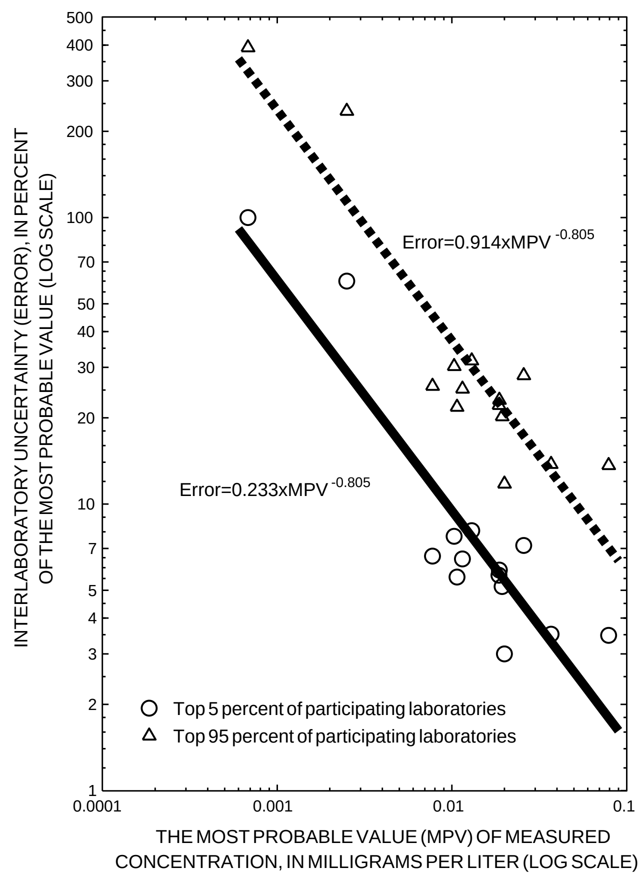

Figure 2. The analytical uncertainty of reported results from laboratories in the USGS interlaboratory evaluation program for the most probable value of chromium concentrations in natural-water matrix samples that were tested from 1989 through 1997.

or minus 100 to 3 percent of the MPV as concentration increased, but “most” laboratories (in the top 95 percent) ranged from plus or minus 400 to 12 percent of the MPV (fig. 2). The uncertainty range for the “best” laboratories probably indicates the magnitude of error expected for the analytical methods used. However, the uncertainty range for “most” laboratories indicates the effects of inadequate quality control in addition to expected method error. The range of uncertainty for “most” laboratories in these interlaboratory studies is probably a conservative estimate of the uncertainties caused by combining data from different sources because it does not include outliers (the laboratories rated in the bottom 5 percent of the USGS interlaboratory evaluation program), or laboratories not participating in QA/QC programs. Combining analytical data from laboratories that have inadequate or undocumented QA/QC programs may introduce an unacceptable level of uncertainty.

Differences between methods and materials that are used for water-quality sampling and analysis in different studies (or changes within a single study over time) also are a substantial source of uncertainty that can impede aggregation of data from available sources (ITFM, 1995b). The uncertainty introduced by different methods can greatly overshadow real differences in constituent concentrations (Horowitz and others, 1994). Combining data from studies that were designed to collect concentrations of dissolved constituents (in filtered water) with data from studies that were designed to collect total concentrations (in water and suspended sediments) may obscure meaningful interpretations because the concentrations of metals and other contaminants in suspended sediments can be orders of magnitude higher than their concentrations in the dissolved fraction (Chapman and others, 1982; Horowitz, 1991).

Each step in the methods used to collect, process, and analyze water-quality samples can potentially change measured concentrations. Contamination that is introduced during sampling and analysis may substantially increase measured concentrations (Horowitz and others, 1992, 1994). Methods and materials that were designed to minimize contaminants that are introduced by the sampling process were shown to systematically decrease measured dissolved metal concentrations by up to an order of magnitude in an experiment using concurrent, side-by-side comparisons (Taylor and Shiller, 1995).

Alternatively, methods and materials that are used in the sample-collection, handling, and analysis process may artificially reduce measured concentrations by removing constituents from solution. For example, figure 3 demostrates that filter diameter, pore size, and the amount of water filtered can control measured constituent concentrations of dissolved constituents in filtered samples (Horowitz and others, 1992). The concentration of suspended sediment in the stream associated with the samples shown in figure 3 was relatively low [about 11 milligrams per liter (mg/L)] in relation to the range of suspended sediment concentrations (about 4 to 1,160 mg/L) reported for highway runoff (Smith and Lord, 1990). Therefore, a thorough understanding of the sampling and analysis methods that are used for each source is important if data from different sources are combined.

Unknown or variable detection limits are also a substantial source of uncertainty when combining available data (Larson and others, 1997). Statistical methods (Helsel and Cohn, 1988; Helsel, 1990) can be used to extrapolate data below detection limits, but not without introducing additional uncertainty. A comparison of results from Phase I (Gupta and others, 1981) and Phase II (Kobriger and Geinopolos, 1984) of FHWA water-quality studies along Interstate-81 (I-81) near Harrisburg, Pennsylvania, provides insight to possible sources of uncertainty. These two studies are presented because the laboratory that analyzed the samples, sample collection and processing methods, historical rainfall statistics, climatic conditions, and other geographic characteristics were similar for both studies.

The median, mean, and range of event mean concentrations (EMCs) of chromium measured along I-81 are plotted against the reported annual average daily traffic volume (ADT) in figure 4. The boxes indicate the measured range of the EMC populations with respect to the estimated range of ADT measurements, assuming an error bar of plus or minus 10 percent for ADT. The median and mean runoff volumes for monitored rain storms was 0.47 and 0.2 inch (per unit area), respectively, for Phase I, and 0.16 and 0.04 inch, respectively, for Phase II (Driscoll and others, 1990b). Despite the fact that Phase II had more than twice the traffic and about one-third the dilution, the minimum EMCs measured during Phase II were about 50 percent of the minimum EMCs measured during Phase I. Higher minimum chromium

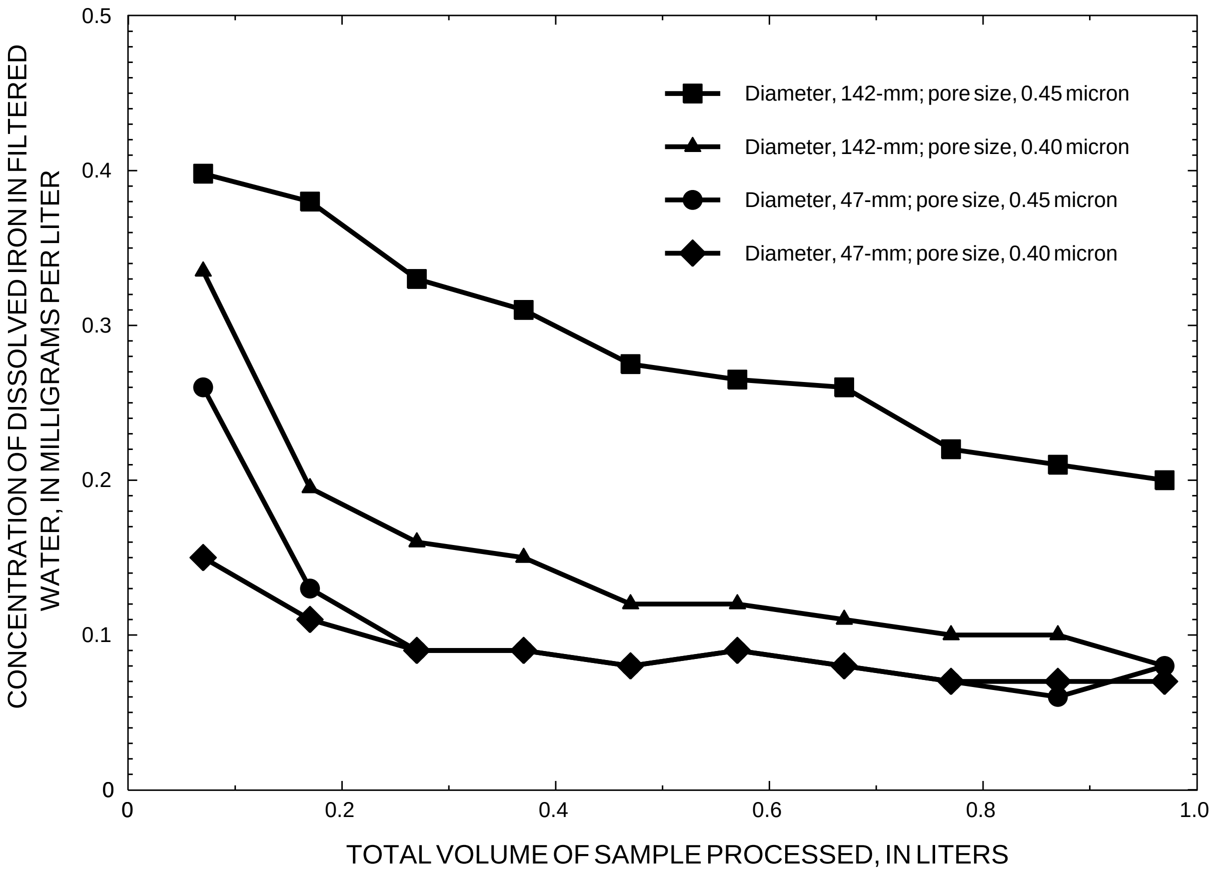

Figure 3. Effect of filter diameter and pore size and total volume of water processed, on measured concentrations of dissolved iron (from Horowitz and others, 1992).

EMCs detected during the Phase I study may be an artifact of a lower laboratory detection limit in effect for samples analyzed during Phase II, contamination by field sample collection and processing during Phase I, or a background source of contaminants that did not influence EMCs during Phase II. The large differences in runoff volume statistics for these two studies conducted along I-81 in Pennsylvania raise questions about the comparability of data and also indicate that uncertainty may arise from inadequate characterization of the natural variability in the amount and type of precipitation and runoff conditions at any given study site. In any case, these artifacts change population statistics of the combined data base and increase the uncertainty of predicted concentrations and loads from a model constructed by using the two data sets.

The uncertainty in model results is the sum of the uncertainty in the input data as well as the uncertainty incorporated by the modeling process (Young, 1983; Haan and others, 1990). Uncertainty in data from sampling programs that are used to characterize spatial and temporal water-quality processes will translate to uncertainties in model results (Montgomery and Sanders, 1985). The effects of large uncertainties in data that are used to construct or calibrate a model are popularly termed "garbage in, garbage out" (Haan and others, 1990). The modeling process can introduce uncertainty through interpretive errors, data-entry errors, and selection of the wrong model (Montgomery and Sanders, 1985). Proven success in one situation does not reduce the uncertainty in the application of a model to a new situation or to a different site because the true effect of one input condition can often be compensated by errors in values for other input conditions (Water Science and Technology Board, 1990).

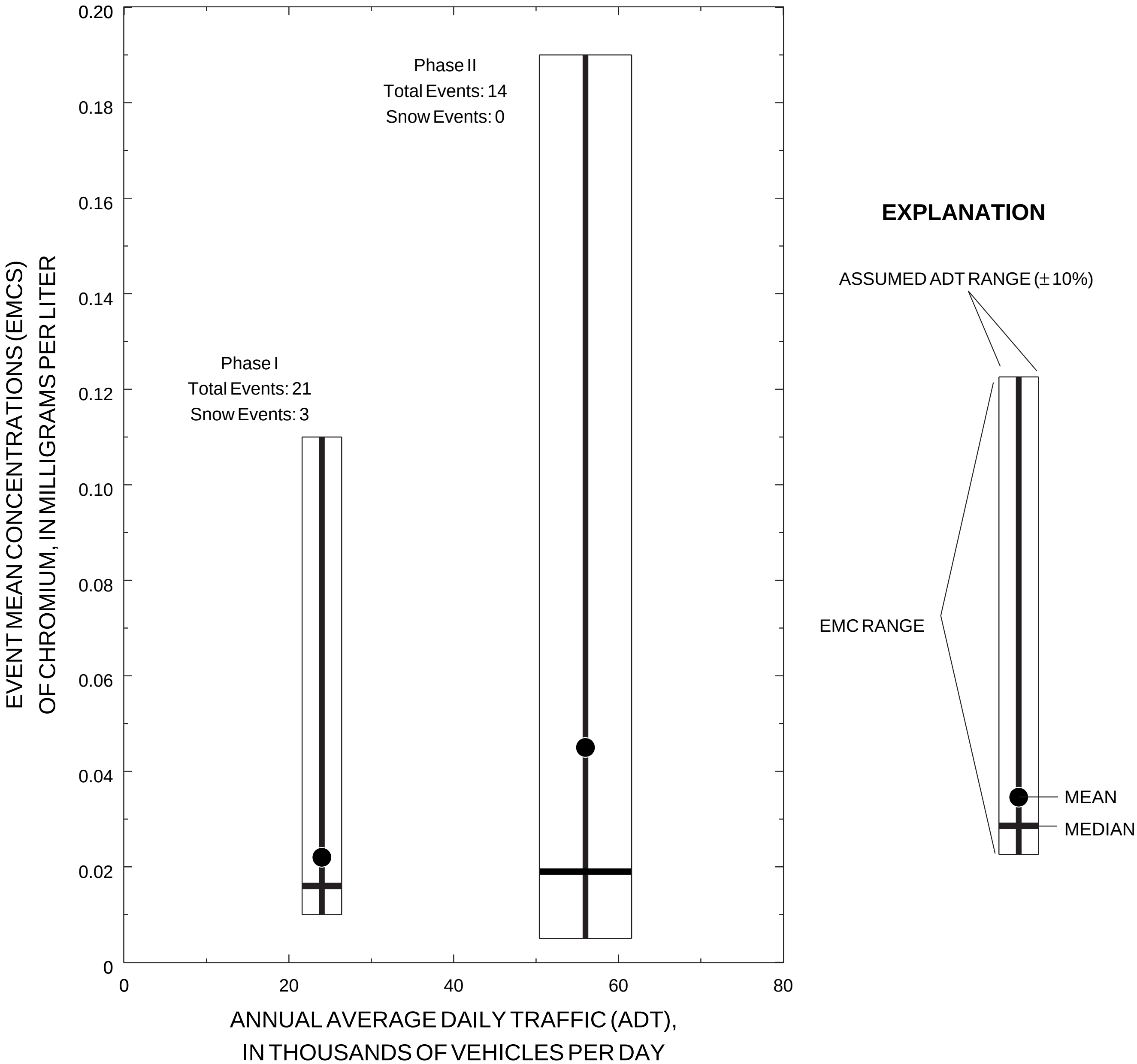

Figure 4. The median, mean, and range of event mean concentrations (EMC) of chromium and the average daily traffic (ADT) volume, with an assumed uncertainty of 10 percent, measured along I-81 in Pennsylvania during phase I (1976-1977) and phase II (1980-1981) of the FHWA water-quality studies (data from Driscoll and others, 1990, Volume III).

Model uncertainties can be assessed by applying the model to data or to sites that were not used in the formulation of the model. When models are applied to data from sites or studies that were not used to create the model, the differences in site characteristics, data-collection methods, and source changes will be reflected in the measured uncertainty of model results. For example, an urban-runoff-quality model created by using data collected from about 100 storm events at 81 sites characterizing different land uses in 12 urban areas was shown to have an uncertainty of plus or minus an order of magnitude when tested against data from different watersheds in the same region (Marsalek and Schroeter, 1988). For another regional urban-runoff model (Driver and Tasker, 1990), statistical analysis indicated that the model could be used to estimate EMCs and loads of contaminants with an uncertainty of plus or minus 56 to 334 percent.

However, when the Driver and Tasker (1990) model was applied to data collected in urban watersheds in Tennessee, large prediction errors (up to about 806,000 percent for lead) indicated that changes in pollutant sources, differences in site characteristics, and changes in data-collection methods limit the accuracy of the existing model without adjustments for these factors (Hoos and Patel, 1996).

Uncertainties in the input data sets caused by differences in field or laboratory methods and reporting limits between studies may obscure evidence for physical or chemical relations that can be used to frame predictive models. When data from different studies were combined (Driscoll and others, 1990b), quantitative relations between pollutant concentrations and traffic volume were weak. For example, if differences in the minimum EMCs indicated in figure 4 are an artifact of methods used, this may be a factor precluding formulation of a useful model for minimum EMCs based on ADT and the physical characteristics of the study sites. Results of studies using internally consistent methods (Shaheen and Boyd, 1975; Kobriger and others, 1981; Racin and others, 1982; Kerri and others, 1985), however, indicate relatively strong correlations between traffic volume estimators and measured pollutant concentrations and loads (Young and others, 1996).

Weak correlations between traffic volume and the magnitude of measured highway-runoff pollutants may reflect large uncertainties in historical traffic volume data estimators. ADT measurement and calculation methods have been standardized only recently and have not been consistent through time or from place to place (Wilkinson, 1994). Although ADT estimates from permanent counting stations are considered 95 percent accurate, estimates from 24- to 48-hour counts (typical for many sites) may deviate from actual ADT values by more than 100 percent if affected by special conditions such as inclement weather, seasonality, or a special event (Anthony Esteve, Office of Highway Information Management, FHWA, written commun., 1997).

The most recent predictive water-quality model developed by the FHWA (Driscoll and others, 1990a) used local and regional environmental characteristics correlated with the median of EMCs at each site to predict the environmental impact of highway runoff. While the use of EMC values is a practical approach for formulation of national regression equations, information is lost when populations of average values are combined (Schaeffer and Janardan, 1978). EMCs can be calculated from discrete measurements of concentration and flow (Driscoll and others, 1990a), but temporal variations within storms cannot be determined from EMC data. Although model predictions based on EMCs will tend toward the center of input parameter populations, data for individual sites or individual storms may deviate considerably from the normal range. Figure 4 indicates that individual EMCs at a given site can vary as much as an order of magnitude. Consequently, instantaneous concentrations may vary from the normal range by more than an order of magnitude. Providing model results without indicating that results are based upon central parameter values, and without indicating the uncertainty in the results, may be perceived as misleading (Haan and others, 1990).

Even when data distributions follow expected patterns, uncertainty in the data may preclude quantitative modeling. A cause- and-effect relation may be inferred logically, but problems with data may alter or obscure the true quantitative relation. For example, a relation between ADT and the maximum concentrations and therefore loads of constituents in runoff at a site is suggested by the data presented in figure 4, but this relation can be distinguished from variability caused by differences in sampling programs only if there is enough QA/QC to substantiate that results are otherwise comparable.

A documented uncertainty analysis is an important tool to assess the comparability of data and resultant interpretations. Organizations collecting data commonly use methods that are not comparable to obtain and interpret data. Also, continuing changes in the science and technology of environmental monitoring increase uncertainty in the comparability of data (ITFM, 1995a, 1995b). If, however, sufficient QA/QC information is collected, documented, and available, the uncertainty can be determined quantitatively. If this information is not available, a subjective determination of the uncertainty and resulting validity associated with existing environmental data must be derived (USEPA, 1986, 1994).

QUALITY ASSURANCE AND QUALITY CONTROL

Quality assurance and quality control (QA/QC) programs are used to detect and control errors and to maintain and document the reliability and uncertainty of results. Historically, QA/QC programs have been recognized as an essential component of laboratory analysis, but the usefulness of data for decision-making is affected by many external factors (Brown and others, 1991). QA/QC requirements to document that data from laboratory and field sampling activities are valid, current, and technically supportable have been increasing over the last two decades.

Data are no better than the weakest link in the data-collection processes. Without sufficient QA/QC, the effectiveness of validated methods, reference laboratories, and experienced personnel cannot be established conclusively (Keith and others, 1983). QA/QC programs must evaluate all aspects of a data-collection effort, including program design; sample collection, transport, and storage; chain of custody control; sample analysis; documentation; and data reporting (FHWA, 1986; Childress and others, 1987; Clark and Whitfield, 1993). The USEPA specified the application of quality assurance to all steps within environmental data-collection efforts as early as 1984, and suggested such practices as early as 1979 (Alm and Messner, 1984; Childress and others, 1987). QA/QC practices are required by many Federal agencies involved in water quality and have been encouraged in courses, meetings and publications supported by most professional water-quality organizations because documentation of QA/QC information has been deemed essential to ensure that data are reliable and legally defensible (Childress and others, 1987).

The FHWA recognizes the importance of QA/QC activities to demonstrate that data are valid, current, and technically supportable (FHWA, 1986). The FHWA has long encouraged the collection and publication of QA/QC information with highway runoff monitoring data, including

- A quality-assurance plan documenting methodologies and operating procedures, and specifying the accuracy and precision of field and laboratory methods, as well as specifying method detection limits;
- Interoffice quality-assurance reviews as specified in the QA/QC plan to examine and approve (1) site selection, (2) project documentation, (3) procedures and records for calibration and maintenance of instrumentation and equipment, (4) sample collection handling and preservation methods, and (5) availability of properly trained personnel;
- Appointment of a quality-assurance coordinator to ensure that QA/QC activities are actually being done and documented, and to review and approve final data before release;
- Selection, documentation, and adherence to proven methods;
- Selection of laboratories based on their ability to conduct the required analysis at a given detection limit, comply with accreditation requirements, and adhere to published QA/QC procedures;
- Sufficient personnel training and performance evaluation; and
- Sufficient analytical quality control to demonstrate that measured values represent actual environmental conditions within specified limits of accuracy, precision, completeness, and comparability between studies (FHWA, 1986).

The need for extensive QA/QC documentation is greatest when data from different studies are combined. Cause-and-effect relations may be indicated within a study as long as field and laboratory methods are consistent and control sites are used. When absolute values from individual studies are to be combined, however, the standards of data quality must be higher because differences in methods that were used to collect and analyze water-quality samples may obscure cause-and-effect relations (Childress and others, 1987; Hren and others, 1987). A synthesis of available data cannot be truly quantitative without adequate quality-assurance programs that quantify the precision, accuracy, and integrity of published data (Childress and others, 1987; ITFM, 1995b).

The ITFM has recently defined strict guidelines for the collection, analysis, and documentation of water-quality information. The issues involved in achieving data comparability are consistent with operating in a well-defined quality system for physical, chemical and biological measures in the field and in the laboratory (ITFM, 1995a, 1995b). The ITFM requires that sample-collection procedures and analysis methods need to be fully described, validated, and conducted by competent personnel. To document that data-collection information is internally reliable and comparable to results from other groups, performance needs to be evaluated against a reference (ITFM, 1995b). The USEPA recommends the use of quality-assurance plans within the scope of a data quality objectives process to document all activities needed to ensure that the data-collection program will produce the type and quality of data that will be sufficient to support decisions made using data collected (USEPA, 1986, 1994).

A QA/QC program to document and control data reduction, evaluation, and modeling as part of the interpretive process is as important as traditional QA/QC programs for data collection and analysis (Brown and others, 1991). When QA/QC issues in data interpretation activities are actively integrated into the QA/QC for data-collection activities, the feedback often results in better data and models for the intended purposes (Clark and Whitfield, 1993). Rigorous QA/QC procedures are required at all stages of a modeling effort (Heijde, 1990). Interpretive errors arise from natural heterogeneity, measurement errors, and structural differences between the real world and the methods used for predictions; therefore, QA/QC programs must be designed to quantify these sources of uncertainty. However, QA/QC practices and sufficient peer reviews are not generally widespread in the application of many modeling efforts (Water Science and Technology Board, 1990).

A successful modeling process requires substantial QA/QC efforts with scientific and technical reviews at each stage of the process (Water Science and Technology Board, 1990). The QA/QC procedures for model development include verification of the structure and coding, model validation, record keeping, and software documentation. The QA/QC procedures for model application include selection and verification of input data, and documentation of the data-analysis procedures and modeling methodology. Documenting a calibration and sensitivity analysis—determining how input parameters control model output—is important to indicate how uncertainty in input values will affect uncertainty in calculated results. QA/QC procedures for a model also include a post audit to quantify how well the model works for the same system later in time, or for a different system with slightly different input parameters (Water Science and Technology Board, 1990).

SUMMARY

Transportation agencies face many different issues concerning the characteristics and effects of highway runoff. The FHWA and State transportation agencies need to determine what information is available and whether this information is valid (useful for intended purposes), current, and technically supportable. The types and urgency of various environmental concerns and regulatory issues vary among the States and regions of the Nation. These technical and regulatory complexities make it difficult to establish a uniform set of data quality objectives. It is important, however, to establish criteria that may be used in the data evaluation process.

Basic information requirements, information about the uncertainty of data sets, and documentation of quality-assurance and quality-control practices will indicate the potential utility of available water-quality information for any given purpose. Basic data requirements include information about the monitoring objectives, sample design, data qualifiers, and methods for sample collection, sample handling, and field and laboratory measurements. Study objectives and monitoring goals determine where samples are collected, the frequency of collection, the timing and duration of sample collection, the matrixes sampled, the methods used, and the properties and constituents that are analyzed. Ancillary information on characteristics of a study area often provides explanatory variables needed to standardize data to a common basis for comparison or to account for some of the variability in the data. Uncertainty analysis provides important information for the design and evaluation of data-collection programs. This examination of potential errors and losses of information inherent in environmental studies can be used to quantify and minimize risks associated with decision errors. Quality-assurance and quality-control activities throughout the sample collection, processing, analysis, and interpretive process establish that data are valid, current, and technically supportable by defining and controlling uncertainty and errors in the data collected. The fact that a program's data may not meet these screening criteria does not mean that the data are not useful for meeting that program's objectives or that they could not be used for water-quality studies with objectives different from those required for a national synthesis.

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District Chief,
Massachusetts—Rhode Island District
U.S. Geological Survey
Water Resources Division
28 Lord Rd., Suite 280
Marlborough, MA 01752