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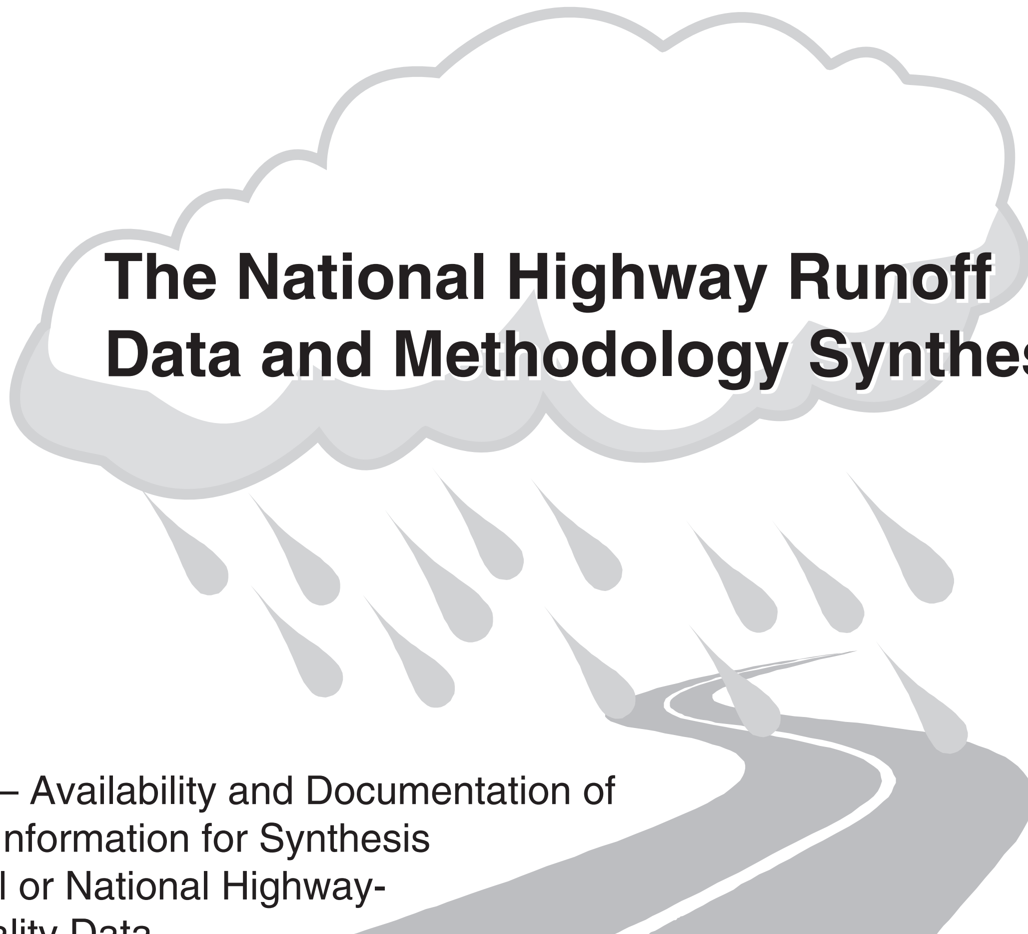

The National Highway Runoff Data and Methodology Synthesis

Volume III – Availability and Documentation of Published Information for Synthesis of Regional or National Highway-Runoff Quality Data

Office of Natural Environment
400 7th Street, SW
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NOTICE

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16. Abstract

Knowledge of the characteristics of highway runoff (concentrations and loads of constituents and the physical and chemical processes that produce this runoff) is important for decisionmakers, planners, and highway engineers to assess and mitigate possible adverse impacts of highway runoff on the Nation's receiving waters. 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 report describes the NDAMS report-review process, summarizes results of this metadata review process, and provides an interpretation of these results. The evaluation of available literature includes reviews of 252 reports, including 34 literature review or summary reports and 218 detailed reports. Evaluation of many individual documentation elements indicates that the available literature does not properly document research to a degree that would establish that existing data are valid, comparable, or technically defensible for regional or national synthesis. Furthermore, when individual metadata requirements are combined, the proportion of available reports that meet these multiple criteria quickly decreases to the point where regional or national synthesis is not possible. This paper is one volume in a three volume series. The titles of these volumes are:

FHWA-EP-03-054 Volume I--Technical Issues for Monitoring Highway Runoff and Urban Stormwater

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FHWA-EP-03-056 Volume III--Availability and documentation of published information for synthesis of regional or national highway-runoff quality data

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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 decisionmakers, 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. More information about this project is available on the World Wide Web at http://ma.water.usgs.gov/fhwa/

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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

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

CONTENTS

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TABLES

National Highway Runoff Water-Quality Data and Methodology Synthesis, Volume III—Availability and Documentation of Published Information for Synthesis of Regional or National Highway-Runoff Quality Data

By Gregory E. Granato

Abstract

This report describes the National Highway Runoff Data and Methodology Synthesis (NDAMS) report-review process, summarizes results of this metadata review process, and provides an interpretation of these results. The evaluation of available literature includes reviews of 252 reports, including 34 literature review or summary reports and 218 detailed reports. These reviews represent a sample of about 10 percent of all reports in the NDAMS bibliographic database and more than 50 percent of the reports in the database designated as highway-runoff reports. Generally, reports were selected in reverse chronological order for review from among the population of highway-runoff reports. The metadata reviews indicate that much of the available data are not sufficiently documented for inclusion in a technically defensible regional or national data set. Results of the metadata review process indicate that few reports document the information and data necessary to establish the quality or representativeness of research results for purposes of regional or national synthesis. Even fewer reports meet documentation criteria when multiple criteria are applied. Furthermore, research indicates that technical issues involved with the collection, processing, and analysis of suspended sediments, trace elements, and organic compounds raise doubts about the veracity of many data sets. Efforts to coordinate environmental-research projects should include an electronic system to facilitate information exchange that incorporates consistent sampling protocols, national data-documentation standards, and a technical audit process designed to ensure that data meet documentation and data-quality requirements. Such a system is necessary to produce data that meet local, regional and national information needs.

Introduction

The Federal Highway Administration (FHWA) and State transportation agencies have the responsibility of determining and minimizing the effects of highway runoff on water quality while planning, designing, building, operating, and maintaining the Nation's highway infrastructure. Federal and State environmental agencies are increasing efforts to quantify and regulate sources of nonpoint-source pollution (FHWA, 1986; Young and others, 1996). These efforts include mandatory monitoring programs such as the National Pollutant Discharge Elimination System (NPDES), which may be applied to stormwater outfalls when the U.S. Environmental Protection Agency (USEPA) or a State Environmental Protection Agency determines that the stormwater discharge contributes to perceived water-quality problems in receiving waters (USEPA, 1992; Sieber, 1994; 1995; Young and others, 1996). Increasingly, regulatory agencies are using the estimated characteristics of the different nonpoint sources in a given watershed to determine and apply a total maximum daily load (TMDL) for receiving waters (Shoemaker and others, 1997). In many cases, highway agencies are required to implement best management practices (BMPs) to minimize the potential effect of highways as a nonpoint source of runoff constituents (Shoemaker and others, 2000).

Transportation agencies have been conducting an extensive program of water-quality monitoring and research during the last 30 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 (Granato and others, 1998). Data from different highway runoff studies have been combined to characterize runoff quantity, quality, and processes; develop information for the design, implementation and assessment of BMPs; develop information for regulatory or legal needs; and to assess and predict the potential for environmental effects from runoff. These diverse study objectives and monitoring goals impose different data and information requirements (table 1).

As study objectives and monitoring goals increase in complexity, the cost and data requirements increase and the level of acceptable uncertainty decreases (Sonnen, 1983; Granato and others, 1998). Data-quality objectives (DQOs) depend on the intended uses for the data collected. DQOs for runoff studies include qualitative assessments, quantitative studies, and predictive studies (table 1). Qualitative assessments, such as reconnaissance studies, provide order-of-magnitude estimates of runoff quality and (or) associated environmental effects. Quantitative studies provide more exact and defensible information that can be used to compare populations of data from different sites on the basis of site-specific characteristics. Predictive studies produce data and information for development of quantitative predictive equations for estimation of the quality of runoff and associated effects at unmonitored sites, with an associated assessment of the uncertainty in the predictions.

The type, quantity, and quality of necessary information depends on study goals and objectives. Local information needs may necessitate a qualitative or quantitative assessment of runoff quality or may require a predictive model to assess conditions at unmonitored sites. The primary objective of a regional or national synthesis of runoff quality, however, is to quantitatively predict runoff quality and the potential for adverse effects in the environment at unmonitored sites across the country on the basis of readily obtainable site-specific information and data (Granato and others, 1998; Tasker and Granato, 2000).

The information needs and regulatory requirements that face transportation decisionmakers necessitate an evaluation of the available highway-runoff research results with respect to the DQOs for a regional or national synthesis of information and data (Granato and others, 1998). The DQOs process is designed to help weigh the costs of data acquisition against the consequences of a decision error caused by inadequate data. In order to distinguish between real intersite differences and sampling artifacts, 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 (table 1). Comprehensive 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 [Intergovernmental Task Force on Monitoring Water Quality (ITFM), 1995a]. It is incumbent upon decisionmakers and regulators to determine the DQOs necessary to address each issue, but some basic aspects of data documentation (such as methods and QA/QC documentation) are considered necessary for all valid current and technically defensible highway runoff studies (Granato and others 1998; Jones, 1999).

Table 1. Monitoring goals and information needed to meet data-quality objectives for qualitative, quantitative, or predictive assessment in highway-runoff research efforts

[**Information necessary to assess data on the basis of data-quality objectives:** Data-quality objectives, 1, qualitative research needs; 2, quantitative research needs; 3, predictive research needs. Documentation criteria, E, essential; N, not applicable; O, optional; R, recommended. **QA,/QC:** quality assurance and quality control. BMP, best management practices]

Monitoring goal	Information necessary to assess data on the basis of data-quality objectives																																			
	Focus									Matrix									Explanatory variables												Data quality					
	Atmospheric deposition			Highway runoff			Receiving water			Water quality			Sediment quality			Biological assessment			Site, location information			Temporal information			Precipitation			Flow			Methods documentation			QA/QC		
	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3
Runoff-quality characterization	O	O	E	E	E	E	N	N	R	E	E	E	O	R	E	N	N	O	O	E	E	O	E	E	O	O	E	O	E	E	R	E	E	R	E	E
Runoff loads	O	O	E	E	E	E	N	N	N	E	E	E	O	R	E	N	N	N	R	E	E	R	E	E	O	R	E	R	E	E	R	E	E	R	E	E
Sources and transport of runoff constituents	R	E	E	E	E	E	N	N	R	E	E	E	R	E	E	O	R	E	R	E	E	R	E	E	R	E	E	R	E	E	E	E	E	E	E	E
Fate of runoff constituents	N	N	O	E	E	E	E	E	E	E	E	E	E	E	E	O	R	E	R	E	E	R	E	E	R	E	E	R	E	E	R	E	E	R	E	E
Design and operation of BMPs	N	N	O	E	E	E	E	E	E	E	E	E	E	E	E	O	R	R	R	E	E	R	E	E	R	E	E	R	E	E	R	E	E	R	E	E
Regulatory and legal monitoring requirements	N	R	E	E	E	E	E	E	E	E	E	E	E	E	E	O	R	R	R	E	E	R	E	E	R	E	E	R	E	E	R	E	E	R	E	E
Potential effect of runoff on:																																				
Aquatic life	N	N	O	R	E	E	R	E	E	E	E	E	R	E	E	R	E	E	R	E	E	R	E	E	R	R	E	R	E	E	R	E	E	R	E	E
Drinking water	O	R	E	O	R	E	E	E	E	E	E	E	O	R	E	N	N	N	O	R	E	O	R	E	O	R	E	O	R	E	O	R	E	R	E	E
Industrial use	O	O	O	O	R	E	E	E	E	E	E	E	N	N	N	N	N	N	O	R	E	O	R	E	O	R	E	O	R	E	O	R	E	R	E	E
Recreational use	O	R	E	O	R	E	E	E	E	E	E	E	O	R	E	O	R	E	O	R	E	O	R	E	O	R	E	O	R	E	O	R	E	R	E	E

A single quantitative set of DQOs, however, might either be too restrictive and disqualify a data set that otherwise would be appropriate for a given use, or too vague and preclude useful predictive interpretations. In order to address these concerns, the U.S. Geological Survey (USGS), in cooperation with the FHWA, evaluated a sample of available information to determine if existing reports sufficiently document the basic information, explanatory variables, and data-quality indexes necessary to meet various DQOs that may be applicable to different runoff issues.

The FHWA must establish that the available data and procedures used to assess and predict concentrations and loads of highway-runoff constituents and the potential for adverse effects of these constituents in receiving waters are valid (useful for intended purposes), current, and technically supportable. 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; USEPA, 1992; 1997). The nature and scope of the problem and the regulatory environment determine the quality and quantity of environmental data required to support a decision. A national synthesis, however, requires robust data-evaluation criteria to ensure maximum utility of data sets for scientific, engineering, and regulatory needs of highway agencies. Robust data-evaluation criteria are also necessary to ensure adequate representation of different highway characteristics, land-use features, and natural settings at sites across the United States (Granato and others, 1998).

Purpose and Scope

This report describes the NDAMS report review process, summarizes its results, and provides an interpretation of these results. The study approach, including the report review process, is described in summary. Results of the metadata review process are described in terms of the population of reviewed reports. This report will concentrate on the population of reviewed reports rather than individual reports because the NDAMS is an assessment of all available data rather than a critique of the work of individual programs. The review information is interpreted in terms of the DQOs and research needs for a regional or national synthesis of runoff-quality data. The fact that the documentation and data for an individual program may not meet criteria for a regional or 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.

This report is part of a three-volume series, which completely documents the criteria, methods, and results of the NDAMS review-process, and the interpretation thereof. In this report (Volume III), the need for information and data will be identified but not explained because detailed technical explanations are provided in the expert chapters in Volume I of the series. These expert chapters are detailed syntheses of technical issues pertinent to the study of highway-runoff quality and the potential for effects on receiving waters and ecosystems. Volume I represents a synthesis of work published by many researchers in the scientific and engineering communities whose contributions are recognized in the subject-specific expert chapters. Volume II of this series and a report by Dionne and others (1999)—which is included on the accompanying CD-ROM—document the report review process. The complete results of the NDAMS metadata review process (for the entire population of reviewed reports as well as the individual reviews for each of the 252 reviewed reports) are documented in the database FHWA2001.mdb on the CD-ROM accompanying Volume II of this series.

Acknowledgments

A large number of professionals in the USGS, the FHWA, State Departments of Transportation, and the USEPA contributed to the study and therefore to the interpretive results documented in this report. More specifically, the author would like to thank the subject-matter experts who developed the criteria for assessment of the available highway runoff information and documented these criteria in the expert chapters included in Volume I of this series. The author would also like to thank the document reviewers for this report (Volume III), who provided input and information that substantially improved the report. Report reviewers for Volume III include Patricia Cazenas, Highway Engineer, FHWA, Washington, D.C.; Abdelmoez Abdalla, Environmental Protection Specialist, FHWA, Lansing, Mich.; Howard Jongedyk, Highway Research Engineer, FHWA, Alexandria, Va.; Mary Ashman, Technical

Editor, USGS, Northborough, Mass.; Leslie DeSimone, Massachusetts Rhode Island Water-Quality Specialist, USGS, Northborough, Mass.; Daniel Hippe, Northeast Region-Water Quality Specialist, USGS, Reston, Va.; and Stephen K. Sorenson, Assistant Chief, Office of Water Quality, USGS, Reston, Va..

APPROACH

During the NDAMS project, the USGS compiled a catalog of relevant literature, developed criteria for evaluation of runoff-quality studies, reviewed a sample of the available literature, and interpreted the results of this review process. Uniform criteria for evaluation of runoff-quality studies were necessary to establish data quality. A catalog of relevant literature was necessary to establish the population of available documents. The review of the literature and subsequent interpretation thereof was necessary to determine if existing information is valid (useful for intended purposes), current, and technically defensible for regional and (or) national synthesis of highway-runoff quality data (Granato and others, 1998; Dionne and others, 1999).

A literature search was conducted to catalog literature relevant to the study of highway runoff. As reports were collected and citations were verified, pertinent information was entered into a bibliographic database (fig. 1). More than 2,600 reports were cataloged in a stratified bibliographic database FHWA2001.mdb during the study. This MS Access database is available on the CD-ROM accompanying Volume II of this series.

The USGS Water Resources and Biological Resources Disciplines combined their input with that from State and Federal environmental and transportation agencies to establish key issues and data-evaluation criteria. Within the USGS, a team of subject-matter experts was assembled to examine technical issues associated with the collection, processing, interpretation, and documentation of data that would be valid, current, comparable, and technically defensible for individual studies and for subsequent regional and (or) national synthesis of highway-runoff data. As a result of these efforts, the USGS produced a series of reports (each concerning one aspect of highway runoff-quality investigations) that document data-evaluation criteria. The criteria for monitoring the quality of runoff are defined in a series of "expert chapters" that include: basic information and data quality (Granato and others, 1998); QA/QC (Jones, 1999); precipitation and runoff flow (Church and others, 1999); the geochemistry of runoff (Bricker, 1999); sediments in runoff (Bent and others, 2001); trace elements in runoff (Breault and Granato, 2000); organic chemicals in runoff (Lopes and Dionne, 1998); the potential ecological

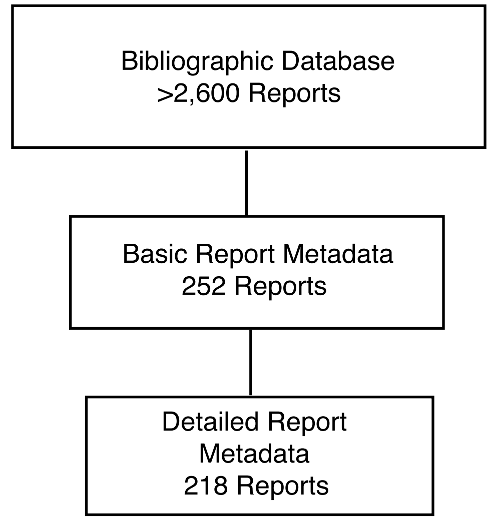

Figure 1. Conceptual diagram of the stratified metadatabase FHWA2001.mdb.

effects of runoff (Buckler and Granato, 1999); monitoring atmospheric deposition (Colman and others, 2001); and statistical techniques for interpreting runoff data (Tasker and Granato, 2000). The reports describing criteria for monitoring the quality of runoff are included as chapters in Volume I of this series, and are included as Adobe Acrobat files on the CD-ROM accompanying Volume II of this series.

The data-evaluation criteria defined by the subject matter experts was incorporated into the design of the NDAMS review sheets (Dionne and others, 1999) and formed the basis for the review process. The NDAMS review sheet is divided into 12 major sections and 14 water-quality constituent group subsections (Dionne and others, 1999). The report describing the NDAMS review sheets is included as an Adobe Acrobat file on the CD-ROM accompanying Volume II of this series. The 12 numbered sections document (1) administrative review information, (2) investigation and report information, (3) temporal information, (4) location information, (5) water-quality monitoring information, (6) sample-handling methods, (7) constituent information, (8) sampling focus and matrix, (9) flow-monitoring methods, (10) field QA/QC, (11) laboratory QA/QC, and (12) uncertainty and error analysis.

The evaluation of available literature included reviews, which totaled 252 reports, including metadata from more than 34 literature review or summary reports, and more than 218 detailed reports. These reviews represent a sample of about 10 percent of the reports in the stratified metadatabase and more than 50 percent of the reports in the bibliographic database with "highway" as a primary subject. Generally, reports were selected for review from among the population of highway-runoff reports in reverse chronological order in an effort to characterize information collected since the last FHWA synthesis in 1990.

Results of the review process were entered as standardized metadata tables within the bibliographic database to facilitate use for current and future stormwater runoff investigations. The database-design-document report (Granato and Tessler, 2001) is included as an Adobe Acrobat file on the CD-ROM accompanying Volume II of this series. The final design of the NDAMS project database was determined when the review process was about 75 percent complete. The experience and knowledge of the reviewers was used to translate the results of the review process using the NDAMS review sheets into standard responses that would lead to consistent and objective interpretations of available data in published reports. Whenever possible, narrative descriptions in the review sheets were condensed into yes-no questions (or yes-no variants that would include responses for "not applicable" or "unknown" where appropriate), standard multiple-choice questions, or extendable lists of appropriate responses. Information in the review sheets was converted to database inputs by means of standard lists. These lists (domain tables in the database) ensured that the data could be repeatably entered, and that information recorded in the database could be aggregated and classified for interpretation (Granato and Tessler, 2001). For example, the reviews included a search for information about the sampling materials (such as equipment, bottles, and preservatives), but examination of review results indicated that this information was not typically available, or was not described in a consistent manner among the reviewed reports. Therefore, the question about sampling materials was simplified to a "yes" or "no" response. Also, some information from the review forms was omitted when its inclusion in the database would not add meaningful information. For example, although it is recognized that trained and professional sampling teams are necessary to consistently collect reliable stormwater-quality data, it proved impossible to quantify this measure of data quality in an objective review of a published report, and therefore, comments about the sampling team were omitted from the database.

Pertinent information about the 252 reports that were reviewed was recorded as "basic report metadata" in the metadatabase. Basic report information (an overview of the report contents), which comprises the classes of chemical constituents sampled, the sampling matrixes, and the hydrologic and physical focus of each investigation, was recorded in the "basic report metadata" component of the database (fig. 1). Published literature reviews and summary reports were included in the evaluation of available information in this level of the stratified metadatabase because they are often a valuable source of general information; they provide references to sources of detailed information and perspectives on the potential use of original data in regional or national synthesis efforts. Detailed information on water-quality investigations was not recorded for the 34 literature reviews and summary reports, because these reports generally do not provide enough detail about the data-collection programs that they summarize to permit evaluation of the quality of information in the original interpretive studies.

Reports that document details of the runoff-quality investigations received a full data-quality evaluation. Metadata from more than 218 detailed reports were documented in all three levels of the stratified metadatabase (fig. 1). Detailed report metadata included documentation methods, temporal information, site location and characteristics, sample collection and processing methods, water-quality constituents of concern, flow-monitoring methods, QA/QC methods, and uncertainty analyses. Metadata were recorded on the appropriate review sheet when subject information was clearly documented in the report being reviewed.

The NDAMS project metadata review process and the associated report-review QA/QC program is documented by Dionne and others (1999) and Granato and others (2003; Volume II). The QA/QC program for the review process included the use of training, standard protocols, standard forms, supervisory and group evaluations of completed reviews, duplicate and replicate reviews, and other mechanisms to ensure that the metadata defining each report were collected and documented in a complete and consistent manner. The design of the report-review metadatabase and the report-review metadata-entry QA/QC process complemented the QA/QC program for the review process because the data-entry technician and the person who checked the data-entry results each examined the review for obvious errors and inconsistencies. A glossary of relevant terms, a copy of the report-review sheets, and report-review instructions are documented in detail within three appendixes in the review-methods report (Dionne and others, 1999). In addition, rules for metadata entry are included in the database user's manual on the CD-ROM accompanying Volume II of this series. Therefore, the reviews are repeatable and these methods can be used by transportation research organizations to catalog new reports as they are published.

RESULTS OF THE METADATA-REVIEW PROCESS

Results of the metadata-review process form the basis for evaluation of existing highway-runoff research data in terms of the information needs for regional or national synthesis efforts. Documentation of general information and metadata, runoff-quality constituents, explanatory variables, and data-quality information all are necessary for integration of a valid, current, comparable, and technically defensible data set. The metadata review process documented the availability of this information in individual research reports. The information and metadata generated by the NDAMS review process, however, are considered in terms of the population of available data.

General Information and Metadata

General information and metadata including basic report information, the physical focus, the hydrologic focus, and the sampling matrixes are necessary to evaluate the runoff data in the available literature. Basic report information provides an overview that characterizes each report, the organization(s) involved in the research, and the information available in each report. The physical focus indicates the type of study sites documented in each report. The hydrologic focus indicates the type of hydrologic sampling efforts documented in each report. The sampling matrix indicates the types of samples that were collected in the investigation(s) documented in each report. All this information describes the population of reviewed reports and provides a context from which the more detailed reviews may be evaluated.

Basic Report Information

The basic report information provides generalized metadata about the population of reviewed reports. This metadata includes the sponsoring agency, the dates of publication, the areal extent of the study described in the report, the type of data presented, the presentation format, and several data-quality indices, which indicate the suitability of the report to meet highway-runoff research-information needs. The basic report information also indicates whether or not more detailed information about measures of flow, concentrations and loads of runoff constituents, QA/QC practices, and other subjects are included in the more detailed reviews.

Knowledge of the organizations that conducted and sponsored the research may be useful to facilitate further research, indicate objectivity of the parties involved, and indicate the quality of information provided (Dionne and others, 1999). About 29, 10, and 4 percent of the 252 reviewed reports document the sponsor as State DOTs, the FHWA or other DOTs, respectively (fig. 2). About 29 percent document the sponsor as some other government agency and about 27 percent of all reviewed reports do not identify the sponsor.

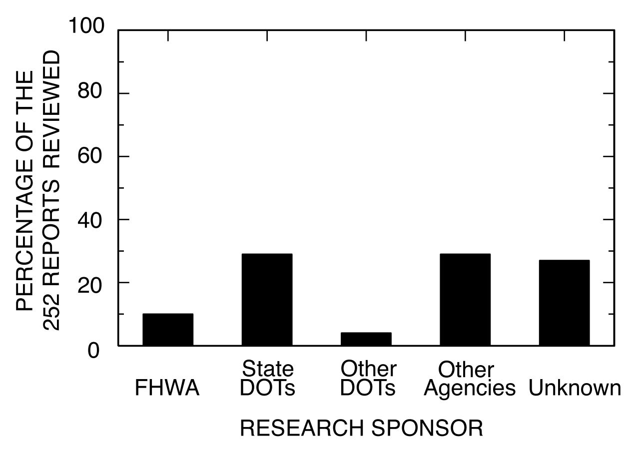

Figure 2. Proportion of the 252 reviewed reports that document the research sponsor.

Reports in the bibliographic database have publication dates that span the period 1905 through 2000, but more than 90 percent were published during or after 1979, and about 55 percent of these reports were published during or after 1990. The population of publication dates for the reviewed reports is not substantially different from the general population of cataloged reports or the population of reports with highway runoff as the primary emphasis (fig. 3). About 94 percent of the reviewed reports were published during or after 1979, and about 46 percent were published during or after 1990. Many recent highway-runoff reports have been manuals (such as the Washington State DOT Highway Runoff Manual, 1995), modeling studies (Such as Driscoll and others, 1990a,b), and reviews (such as Young and others, 1996), which are based upon older data collected by the State DOTs and the FHWA. Therefore, these older studies were included in the review process to fully characterize information and data currently being used in the decision-making process.

The geographic extent and areal coverage of available studies is also indicated by the population characteristics of the 252 reports that were reviewed. In comparison to the interpretive data necessary for a national synthesis (Tasker and Granato, 2000), most reports focused on a small number of study sites. About 46, 27, 13, 10 and 4 percent of all reviewed reports include data from <3, 3–5, 6–10, 11–20, and >20 sites, respectively. About 61, 17, 6, 5, 10, and >1 percent of these studies have a point, local, watershed, regional, national, or international focus, respectively. Therefore, the majority of reports document point or local studies with a small number of study sites. Local studies,

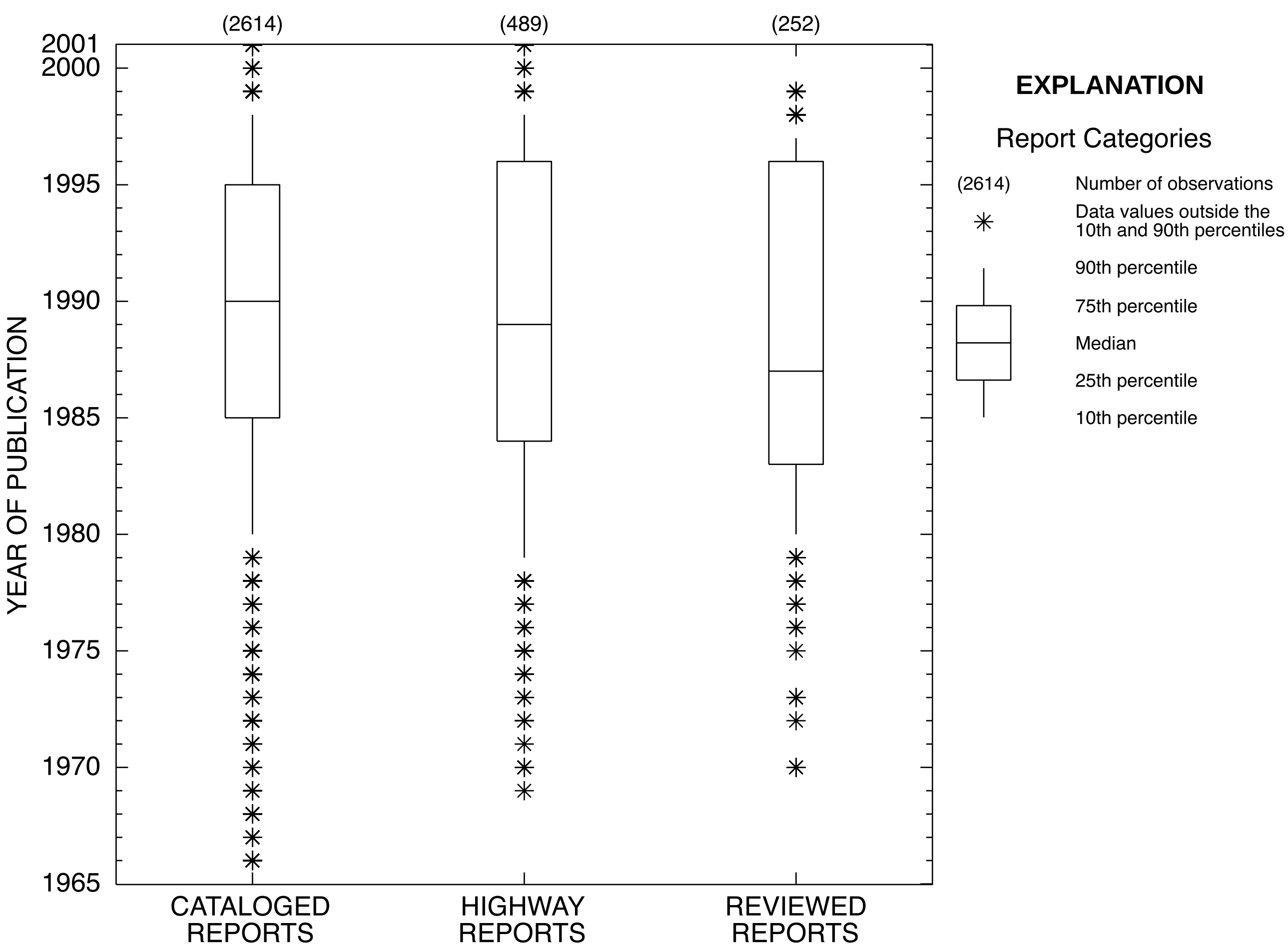

Figure 3. Distribution of the years of publication for all cataloged reports, all cataloged reports with a highway classification, and all reviewed reports (modified from Granato and others, 2003).

however, do not usually collect data that is suitable for the data quality objectives of a regional or national synthesis (Norris and others, 1990).

Information about constituent concentrations is important for characterizing the quality of runoff, but it is necessary to have information about loads to assess the potential effect of runoff on receiving waters (Buckler and Granato, 1999). About 88 percent of the reviewed reports document measured concentrations, about 3 percent document calculated or estimated concentrations, and about 9 percent do not document any concentrations. Information about loads, however, is not as readily available. About 28 percent of reports document calculated or estimated storm loads, about 17 percent document calculated or estimated annual loads, and 55 percent do not document any loads.

The type of available information is also a prime consideration for evaluation of existing data. Summary statistics and graphic presentation formats are good for understanding any given data set (Tasker and Granato, 2000), but individual measurements in a table format are necessary for assembling a national data set for current and future synthesis efforts. About 64 percent of the reviewed reports document some or all of the individual measurements. About 53 percent provide summary statistics, and about 23 percent provide individual measurements and summary statistics (fig. 4*A*). About 81 percent of the reviewed reports provide individual data or summary statistics in tabular format, about 63 percent provide values in graphic format and about 52 percent provide data in both graphic and tabular formats (fig. 4*B*).

Data-quality indices include technical (peer) review, an analysis or indication of the uncertainty in measured values, QA/QC documentation, and the availability of original data (Granato and others, 1998, Jones, 1999, Tasker and Granato, 2000). About 80 percent of the reviewed reports are assumed to have had technical review because of report-review documentation or the publication outlet-such as peer reviewed journals or Federal government reports (Dionne and others, 1999). About 11 percent indicate the uncertainty of study results and about 8 percent include a more formal uncertainty analysis. About 33 percent of the reviewed reports have some QA/QC documentation, although (in the basic report information) this documentation may consist of a simple statement that indicates the use of some QA/QC measure without further details (Dionne and others, 1999). About 59 percent of the reviewed reports provide detailed documentation of original data and about 24 percent include both detailed documentation of original data and some QA/QC documentation (fig. 4*C*).

Availability of reliable runoff-quality data in an electronic format is necessary to facilitate future use of the data collected (Tasker and Granato, 2000). The need for central databases and electronic data standards has been recognized by the ITFM (1995a,b), the Transportation Research Board, (1997), and other government agencies. Availability of electronic data in itself, however, does not convey the usefulness of this data. For electronic data to be useful, QA/QC requirements for collecting, archiving, and handling project data must be met, because it is not a trivial effort to ensure that the electronic records accurately and completely represent the original field and laboratory data collected during the study (Jones, 1999). About 12 percent of the reviewed reports indicate that original data are available in an electronic format. In comparison, only about 5 percent of the 252 reviewed reports indicate the documentation of QA/QC measures and the availability of electronic data (fig. 4*D*).

Physical Focus

The physical focus, which was recorded for each of the 252 reports, indicates what types of site (or sites) were documented as being sampled in a given report (Dionne and others, 1999). Each report reviewed, therefore, may have one or more physical focuses. The population of highway runoff studies includes a wide variety of environmental settings. Reports include monitoring efforts at a highway (74 percent), coastal environment (1 percent of reports), lake or pond (12 percent), stream or river (26 percent), wetland (5 percent), BMP (17 percent), urban separate sewer (18 percent), or urban combined sewer (4 percent) sites. The Venn diagrams displayed in figure 5 indicate that many of these reports also include highway-runoff monitoring within these diverse monitoring environments. Only about 1 percent of the reviewed reports do not provide sufficient information to identify the physical focus.

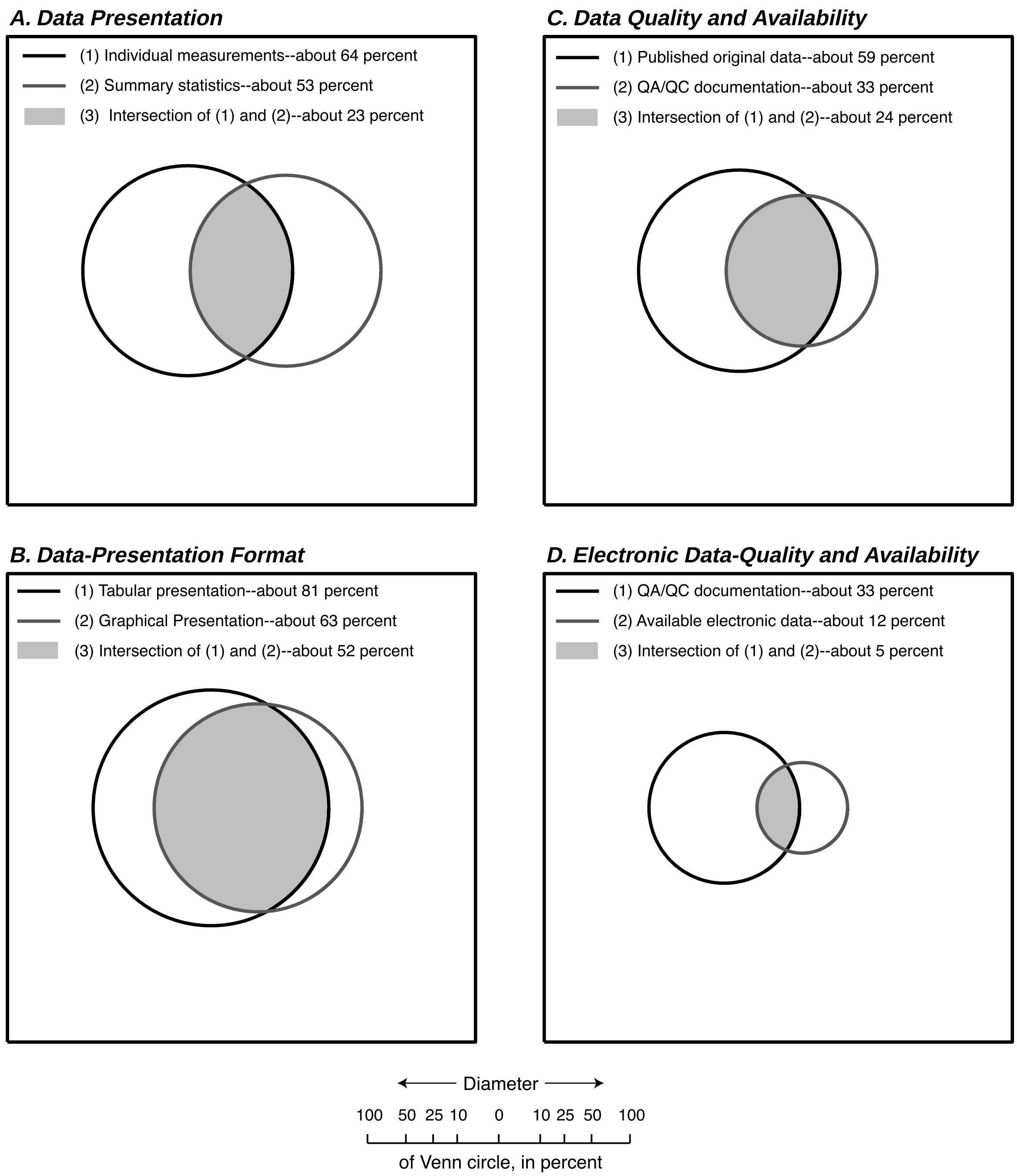

Figure 4. Percentages of the 252 reports reviewed that document the: (*A*) data presentation, (*B*) the data presentation format, (*C*) the availability and quality of original data, and (*D*) the quality and availability of original data in an electronic format.

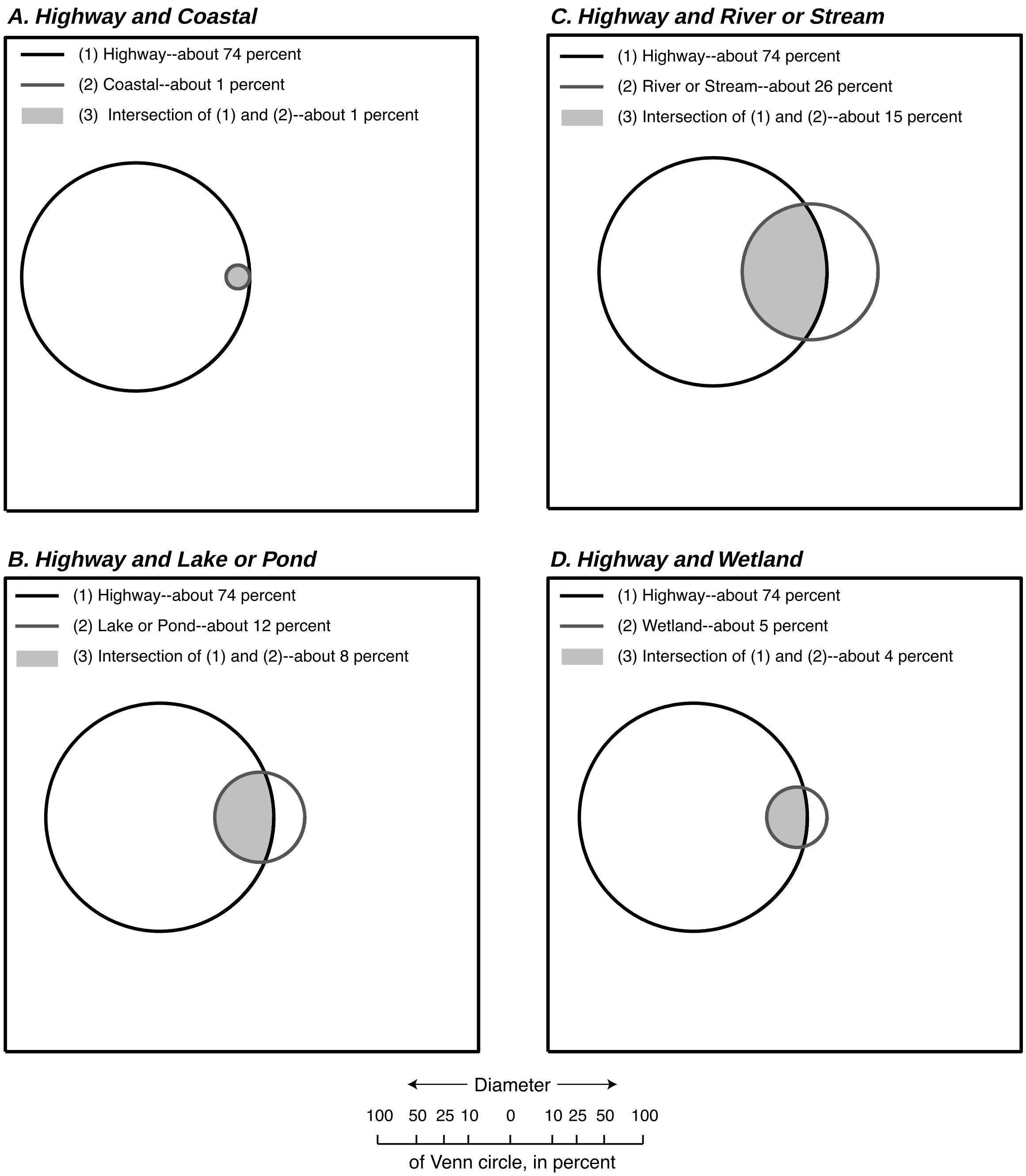

Figure 5. Percentages of the 252 reports reviewed that document the physical focus including: (*A*) highway and coastal sites, (*B*) highway and lake or pond sites, (*C*) highway and river or stream sites (*D*) highway and wetland sites, (*E*) highway and BMP evaluation sites, (*F*) highway and separate-sewer sites, (*G*) highway and combined- sewer sites, and (H) highway and unknown (unidentified) sites.

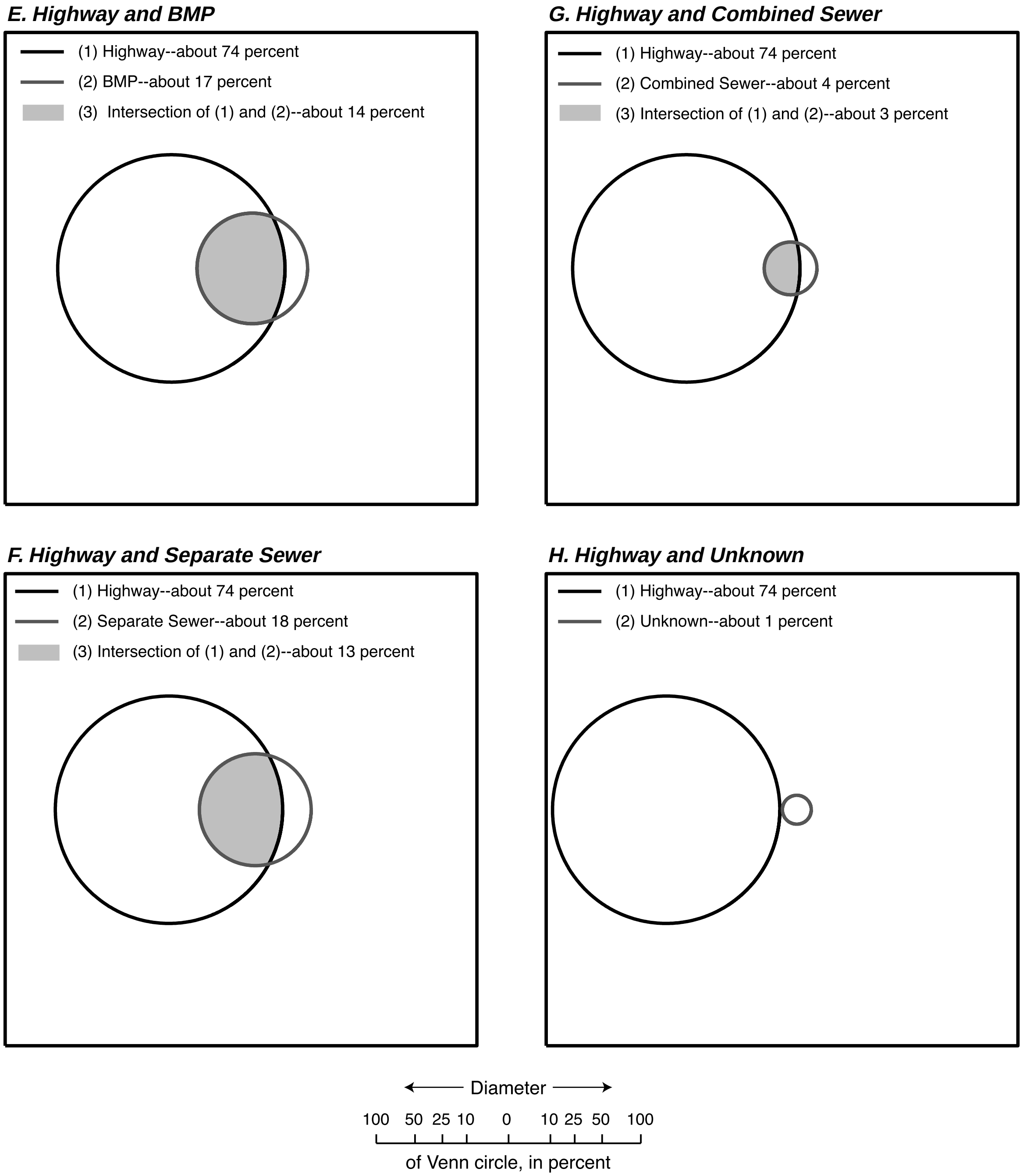

Figure 5. Percentages of the 252 reports reviewed that document the physical focus including: (*A*) highway and coastal sites, (*B*) highway and lake or pond sites, (*C*) highway and river or stream sites (*D*) highway and wetland sites, (*E*) highway and BMP evaluation sites, (*F*) highway and separate-sewer sites, (*G*) highway and combined-sewer sites, and (H) highway and unknown (unidentified) sites—*Continued*.

Hydrologic Focus

The hydrologic focus, which was recorded for each of the 252 reports, indicates the type of monitoring study and includes the four major components of the hydrologic cycle (atmospheric deposition, surface water, the unsaturated zone and ground water). Each study reviewed may have one or more hydrologic focuses (Dionne and others, 1999). About 84, 32, 7, and 4 percent of reports include monitoring efforts to characterize the quality of surface water, atmospheric deposition, ground water or the unsaturated zone, respectively. The Venn diagrams displayed in figure 6 indicate that many reports document monitoring of surface water as well as other components of the hydrologic cycle.

Sampling Matrix

The sampling matrix, which was recorded for each of the 252 reports, indicates the type of samples that were documented as being collected and analyzed in a given report (Dionne and others, 1999). Each of the reviewed reports may have one or more sampling matrixes, which include water, sediment, biota, air or gas emissions, and other (Dionne and others, 1999). Determination of the sampling matrix has important implications for the interpretation of data for trace elements (Breault and Granato, 2000) and for organic chemicals (Lopes and Dionne, 1998). Knowledge of the chemical constituents of runoff in different sampling matrixes may also have implications for understanding the potential for adverse biological effects in receiving waters (Buckler and Granato, 1999). About 81, 40, and 19 percent of reviewed reports include monitoring efforts to characterize the quality of water, sediment, or biota, respectively. The Venn diagrams displayed in figure 7 indicate that most reports tend to focus on one matrix and the availability of data from two or more matrixes is limited. For example, only about 8 percent of reports monitored water quality, sediment quality, and biota in receiving waters (fig. 7*D*). Analysis of all three of these matrixes may be necessary for a regional or national synthesis that would characterize runoff quality and the potential effects of runoff on water quality and the ecology of receiving waters (Lopes and Dionne, 1998; Buckler and Granato, 1999; Breault and Granato, 2000).

The water-sampling matrix is documented in more detail in the review of the 218 detailed reports. About 46, 37, 32, 6, and 1 percent of the detailed reports document collection and analysis of samples from the whole water, filtered water (for dissolved constituents), suspended solids, filter residue (which may include suspended solids and colloids) and colloid matrixes, respectively (fig. 8). A more detailed examination of the various water-sampling matrixes is necessary because concentrations of trace elements and organic chemicals are not comparable among water samples collected in these different matrixes (Lopes and Dionne, 1998, Breault and Granato, 2000). Some reports included descriptions of efforts to sample and analyze more than one matrix, often in an attempt to determine partitioning among matrixes. About 20 percent of the detailed reports, however, indicate that water samples were collected, but did not include sufficient documentation to identify the type of water samples (fig. 8).

Sediment matrixes, in particular, are commonly sampled to determine the availability and (or) fate of potential runoff constituents rather than for determining actual runoff quality. Concentrations of trace elements and organic chemicals are not comparable among samples collected in different sediment matrixes (Lopes and Dionne, 1998, Breault and Granato, 2000). About 12, 10, 8, 6, and 1 percent of the detailed 218 reports document sampling and analysis of bottom or bed material, sediment cores, soil, dust, or roadway sweepings, respectively (fig. 9). About 11 percent document sampling and analysis of some other sediment matrix and about 1 percent did not specify the type of sediment matrix that was sampled and analyzed. About 3 percent document sampling and analysis of the larger grain-size fractions (greater than 63 microns) and 5 percent document sampling and analysis of the smaller grain-size fractions (less than 63 microns).

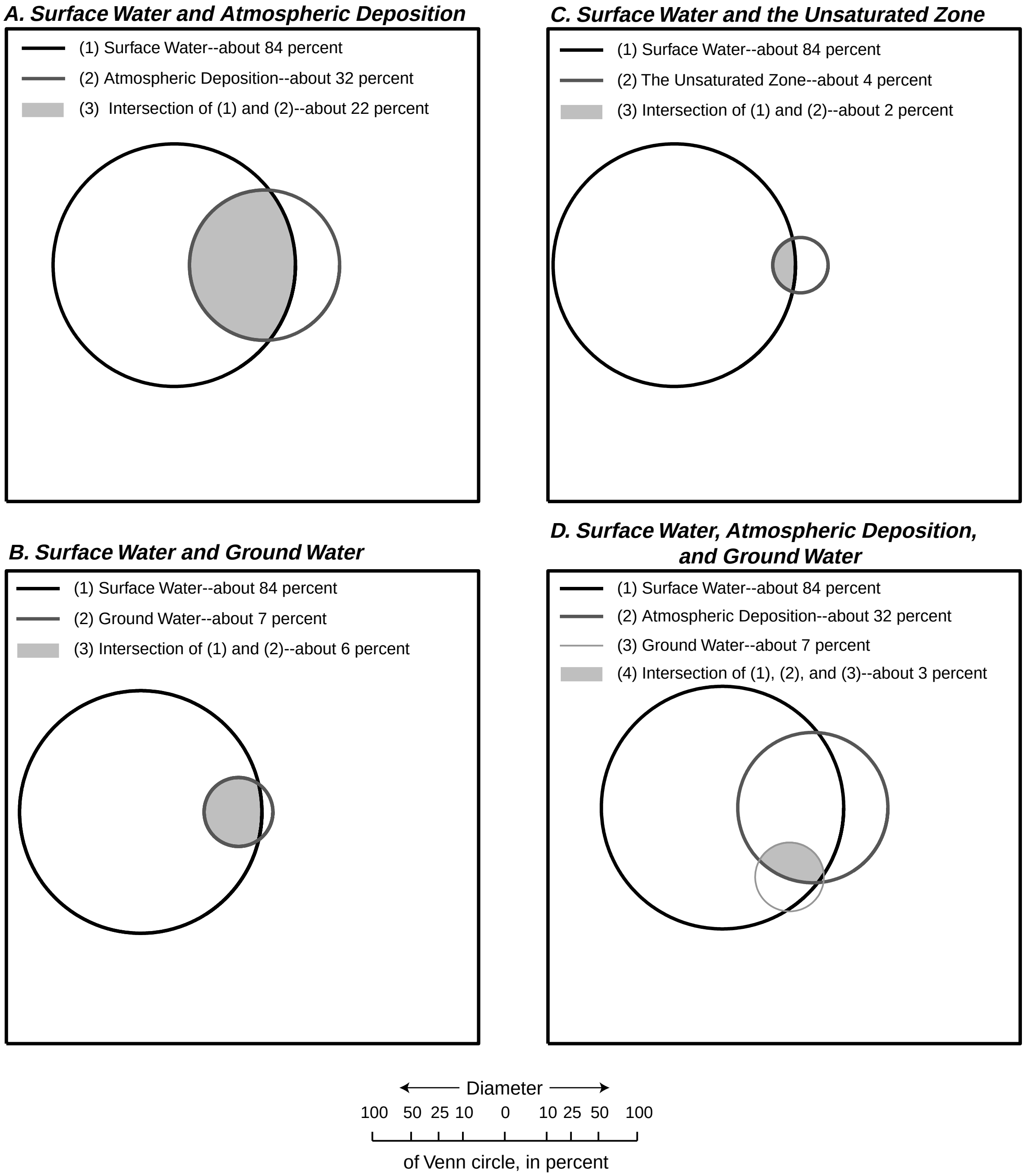

Figure 6. Populations of metadata in terms of the percentages of the 252 reports reviewed that document the hydrologic focus including: (*A*) surface water and atmospheric deposition; (*B*) surface water and ground water; (*C*) surface water and the unsaturated zone; and (*D*) surface water, atmospheric deposition, and ground water.

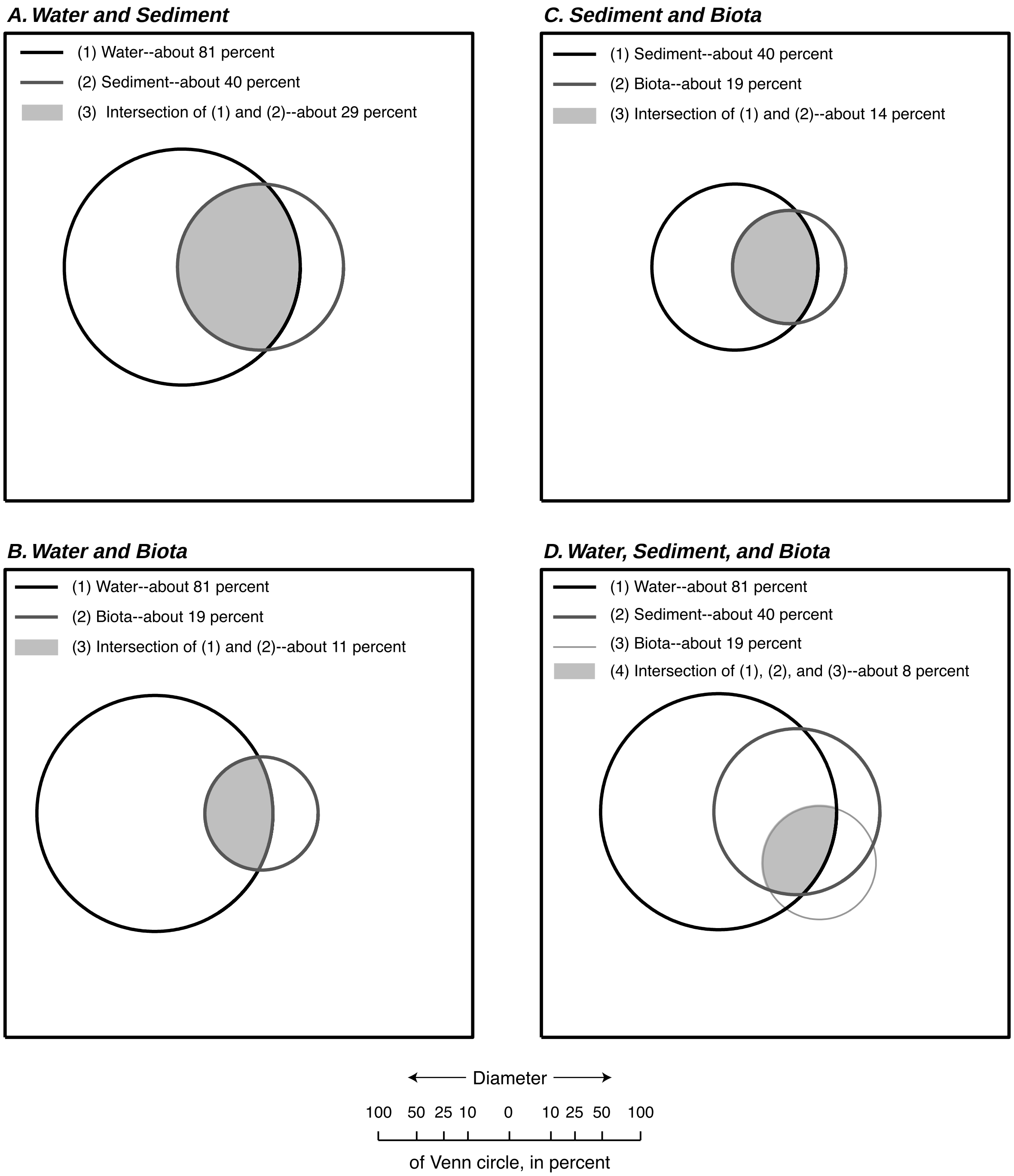

Figure 7. Percentages of the 252 reports reviewed that document the sampling matrix including: (*A*) water and sediment; (*B*) water and biota; (*C*) sediment and biota; and (*D*) water, sediment, and biota.

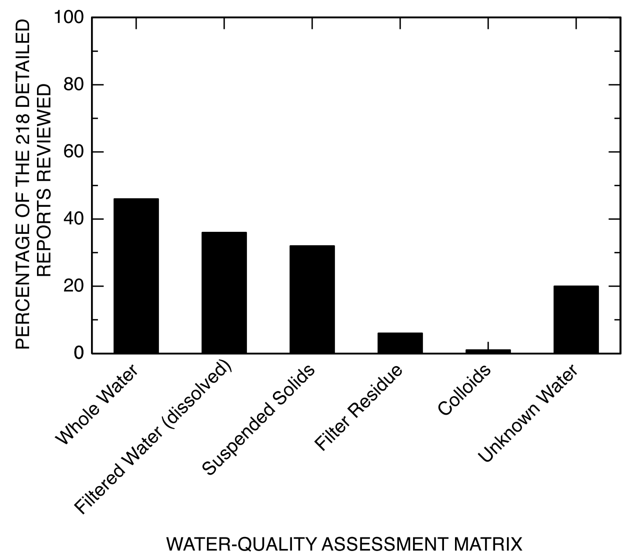

Figure 8. Proportion of the 218 detailed reports that document sampling a water matrix.

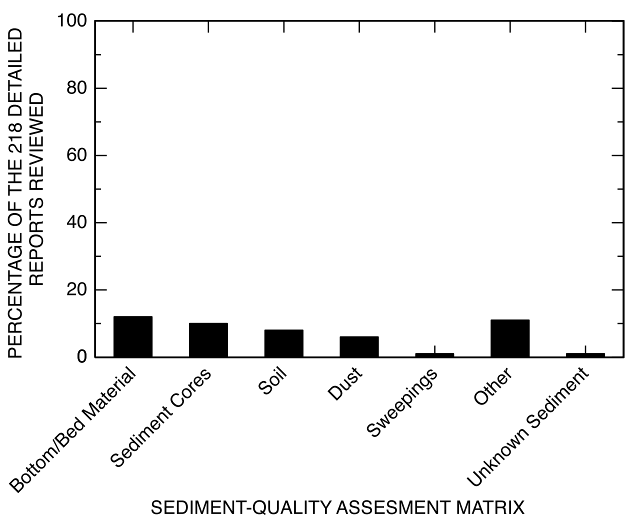

Figure 9. Proportion of the 218 detailed reports that document sampling a sediment matrix.

Runoff-Quality Data

In a regional or national synthesis, it is necessary to systematically classify and interpret runoff-quality data to characterize runoff quality, determine the sources, transport, and fate of runoff constituents, and the potential effects of runoff on the environment. A uniform method to classify runoff-quality properties and constituents is necessary to aggregate comparable data. It is also necessary to define the research objectives that provide meaningful interpretations of runoff-quality data that meet the robust DQOs for a regional or national synthesis.

In the review process, similar types of constituents and properties were organized into 14 categories (table 2) that are operationally defined as constituent classes in a manner that is consistent with the focus of many highway-and urban-runoff studies (Dionne and others, 1999). The NDAMS project produced a computerized, searchable list of all runoff constituents that are categorized by these constituent classes (Granato and others, 2000), which is available on the CD-ROM accompanying Volume II of this series. Each report review may include one or more constituent classes in the basic report metadata designating the type of water-quality properties and constituents documented in each of the 252 reviewed reports. Information for individual water-quality properties and constituents was not recorded for the summary and review reports. Individual information was not recorded because some review papers combine undifferentiated concentrations (that are not truly comparable) into one population and these reports do not commonly include the detailed methods information necessary to evaluate the original data. For example, trace-element concentrations measured in whole-water samples are not directly comparable to concentrations measured in filtered-water samples (Breault and Granato, 2000). Also, a population of constituent concentrations that are analyzed by one laboratory or measurement technique may not have the same population characteristics as a similar set of concentrations measured by a different laboratory or with a different technique (Childress and others, 1987). Reporting information by class of constituents, however, does indicate the availability of data for runoff constituents in the literature.

The percentages of the 34 summary reports, 218 detailed reports, and all 252 reviewed reports that contain information about individual constituent classes are displayed in figure 10. Sediments and solids, trace elements, and industrial-urban organic chemicals that are regulated water-quality constituents (USEPA, 1992) are the focus of a majority of the reviewed reports. Information about other constituents or properties that have been perceived as water-quality problems in runoff, such as nutrients, oxygen demand, and deicers, also is common in summary and detailed reports. Water-quality properties (such as specific conductance and pH) are documented in about 54 percent

Table 2. Characterization, classification, and interpretation of runoff-quality data by operational definition and research objective

[**Operational definition:** Source Dionne and others, 1999. **Research objectives:** E, Ecological (Buckler and Granato, 1999); G, Geochemical (Bricker, 1999); O, Organics (Lopes and Dionne, 1998); S, Sediment (Bent and others 2001); T, Trace elements (Breault and Granato, 2000)]

Constituent class	Operational definition	Research objectives				
		G	S	T	O	E
Properties	Physicochemical measures that indicate water quality (such as specific conductance, pH, and water temperature) and explanatory variables that are recorded on water-quality sampling field-record sheets (such as air temperature and weather).	X		X		X
Deicers	Major inorganic constituents of road salts, other deicers, and cyanide (which is used as a component of anticaking compounds in road-salts).	X		X		X
Majors	Major inorganic constituents commonly present in natural waters at concentrations exceeding about 1.0 milligrams per liter.	X		X		X
Nutrients	Inorganic nitrogen and phosphorus species commonly measured as constituents in water-quality studies.	X		X		X
Trace elements	Inorganic constituents (including metals) commonly measured in natural waters at concentrations less than about 1.0 milligram per liter.	X		X		X
Sediment and solids	Physical measurements of solids in a hydrologic system that may be incorporated into stormwater runoff (including solids, sediment, and turbidity).	X	X	X	X	X
Oxygen demand	Physicochemical measures of potentially biodegradable compounds in solution.	X		X	X	X
Organics	Carbon-based compounds that are identified as industrial/urban pollutants in runoff investigations.	X		X	X	X
Pesticides	Carbon-based compounds used for control of undesirable species in agriculture, landscaping, and right-of-way maintenance.				X	X
Microbiology	Biological measures of water quality in terms of the number of microorganisms of species commonly used to indicate impaired water quality.			X		X
Eutrophication	Biological measures of the trophic state of a water body receiving runoff.	X				X
Biological assessment	Biological measures of the effects of water-quality constituents on organisms present in the ecosystem at documented monitoring sites.	X		X	X	X
Toxicity assessment	Biological measures of the effect of water-quality constituents on test organisms.			X	X	X
Other	Used to record constituents not readily categorized.					

of detailed reports but in far fewer (about 32 percent) summary reports. A higher proportion of summary reports include information on regulatory measures of water quality, such as pesticides and herbicides, microbiology (bacteria), and toxicity testing, than do the detailed reports. The potential effect of runoff on the ecological health of receiving waters is a primary concern for regulators and decision makers. Measures of the biological effect of runoff on receiving waters (biological parameters and eutrophication), however, are not common in the highway-runoff literature (fig. 10).

The research objectives for a given synthesis (table 2) include all the information necessary for interpreting site conditions in runoff studies. Constituents classes included in the research objectives denote the types of data necessary to determine the sources, transport and fate of constituents of interest. For example (as indicated by the "sediment" column under the research objectives in table 2), suspended sediment data can be collected and interpreted without regard to information provided by monitoring any of the other constituent classes (Bent and others, 2001). Data on

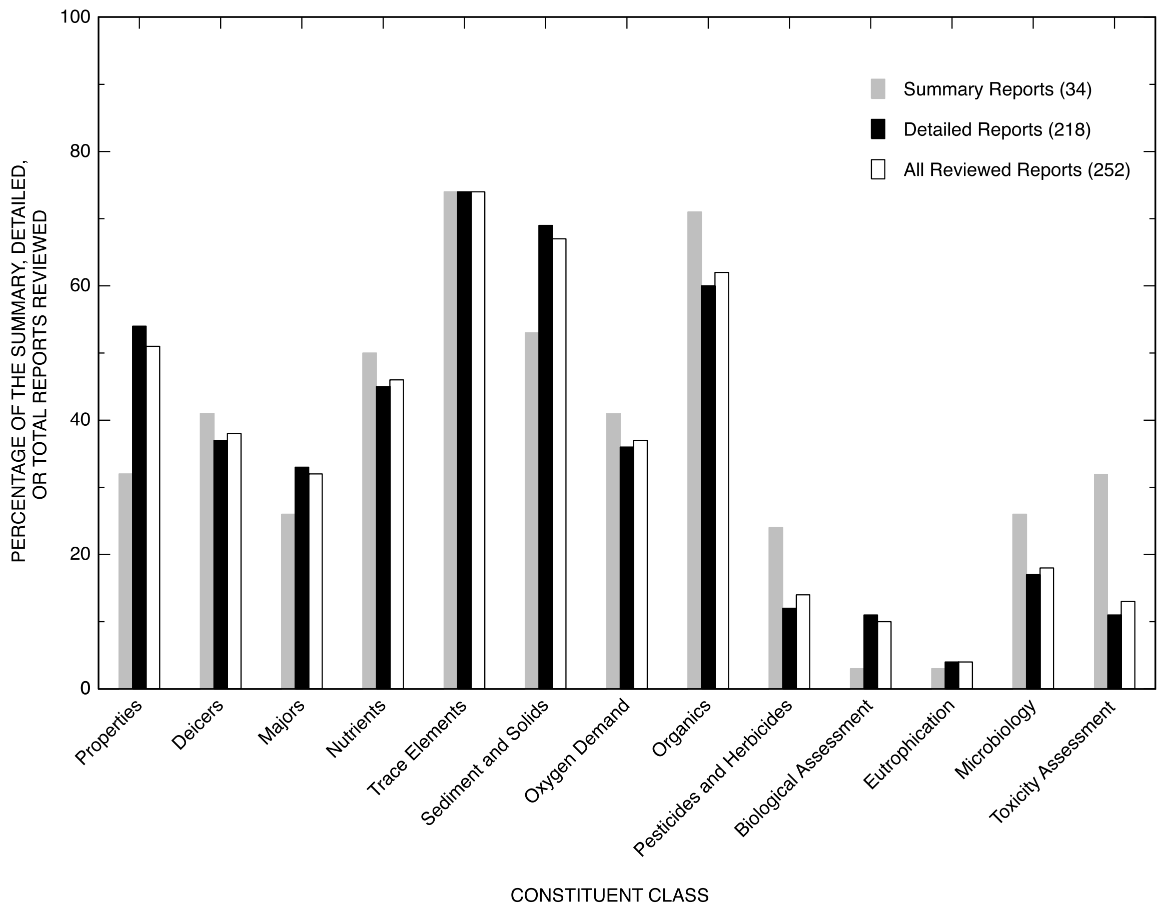

Figure 10. Proportion of the reviewed reports that document analysis of selected constituent classes.

sediment and solids, however, is considered necessary for interpretation of the geochemistry of runoff (Bricker, 1999), trace elements (Breault and Granato, 2000) and organic chemicals (Lopes and Dionne, 1998) in runoff, and the potential biological effects of runoff in receiving waters (Buckler and Granato, 1999). Data on sediment and solids is important for all the research objectives listed in table 2 because sediment can be a contaminant and can accumulate other constituents on the pavement, carry them in runoff, and later release them in receiving waters. Conversely, to meet ecological research objectives, data commonly must be interpreted in concert with information from all the constituent and property classes because of the complex interactions between the local physical, chemical, and biological environment (Buckler and Granato, 1999). Biological processes may also affect interpretation of the local geochemistry and the concentration and (or) speciation of trace elements and organic chemicals in runoff and receiving waters (Lopes and Dionne, 1998; Bricker, 1999; Breault and Granato, 2000). Details about the availability and quality of runoff data, therefore, must be considered in terms of the research objectives and DQO's for regional or national synthesis.

Data-quality issues that are specific to each research objective are discussed individually within the following runoff-quality subsections. As indicated in table 2, however, interpreting runoff quality for a regional or national synthesis may require an integration of interdisciplinary research objectives. General issues such as the need for representative sampling (spatially and temporally), precipitation and flow monitoring, proper water-quality monitoring-methods, proper sample-collection and -handling methods, as well as a defensible QA/QC program, are discussed within the respective subsections of this report.

Geochemistry

To understand the chemistry of the constituents of interest and how they interact with other components in the local geochemical system, it is necessary to make realistic assessments of the quality of runoff and the potential effects of runoff on the environment (Bricker, 1999). Also, the geochemistry of runoff is often a function of the quality and quantity of local atmospheric deposition (Colman and others, 2001). The analyses should provide as complete a chemical characterization of the sample as possible, including water-quality properties and all major constituents as well as the specific constituents of interest, because analysis of one or a few specific contaminants will provide incomplete information and may be misleading in terms of environmental effects. Measurements of water-quality properties and major ions are necessary to calculate the ionic strength of the water and the activities and speciation of both major and trace dissolved constituents. If the analyses are incomplete for the major dissolved constituents (even though these may not be of interest from the regulatory standpoint), it will not be possible to evaluate the behavior (including the solubilities, speciation, complexing, sorption, ion exchange, ion pairing, mobilization, transport and bioavailability) of the contaminant species that determine the potential effect of constituents on the environment (Bricker, 1999).

Water-quality properties may be used to indicate the geochemistry of runoff and receiving waters (Bricker, 1999). The solubility and potential toxicity of trace elements is a function of acidity (measured by pH), the ionic strength (measured by specific conductance), the major-ion chemistry (approximated by alkalinity and (or) hardness), the oxidation-reduction (redox) state (measured by dissolved oxygen and (or) oxidation-reduction potential), the presence of organic ligands (measured by color), and reaction rates (a function of temperature) (Bricker, 1999; Breault and Granato, 2000). The measures of the geochemistry of runoff and receiving waters also are important for interpreting concentrations of semivolatile and volatile organic compounds (Lopes and Dionne, 1998). The most common measurement of water-quality properties documented in the 218 detailed reports reviewed is pH (fig. 11). Other measures are not as common. Many of the water-quality properties are documented in less than 25 percent of the detailed reports that were reviewed.

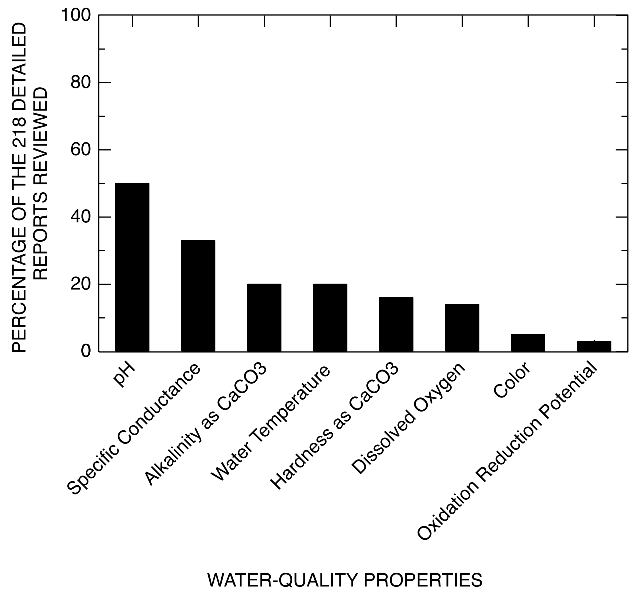

Figure 11. Proportion of the 218 detailed reports that document analysis of selected water-quality properties.

Information about instrument calibration, maintenance, and temperature compensation is necessary to establish that water-quality property records are valid, comparable, and technically defensible (Wilde and Radtke, 1998; Wagner and others, 2000). About 4, 3, and 2 percent of the 218 detailed reports document instrument calibration, maintenance, or temperature compensation, respectively. Explanatory variables, which are recorded on data-collection field sheets, also are important for interpreting field measurements and the water quality of samples collected (Wagner and others, 2000). About 7, 4, 1, and 1 percent of detailed reports document records for the explanatory variables air temperature, weather, barometric pressure, or on-site trash and debris buildup, respectively.

The use of deicing chemicals can have a profound effect on the water-quality and geochemistry of receiving waters (Bricker, 1999). The high salinities associated with the use of deicers affect the chemistry of trace elements in runoff and receiving waters and may affect analytical methods and detection limits (Breault and Granato, 2000). Inorganic deicers are composed of many major and trace elements but primarily contain the major elements chloride, sulfate, sodium, and calcium (Granato, 1996). Documentation of analysis of these major ions, however, is not common in the 218 detailed reports reviewed (fig. 12*A*). This may be because the NDAMS review

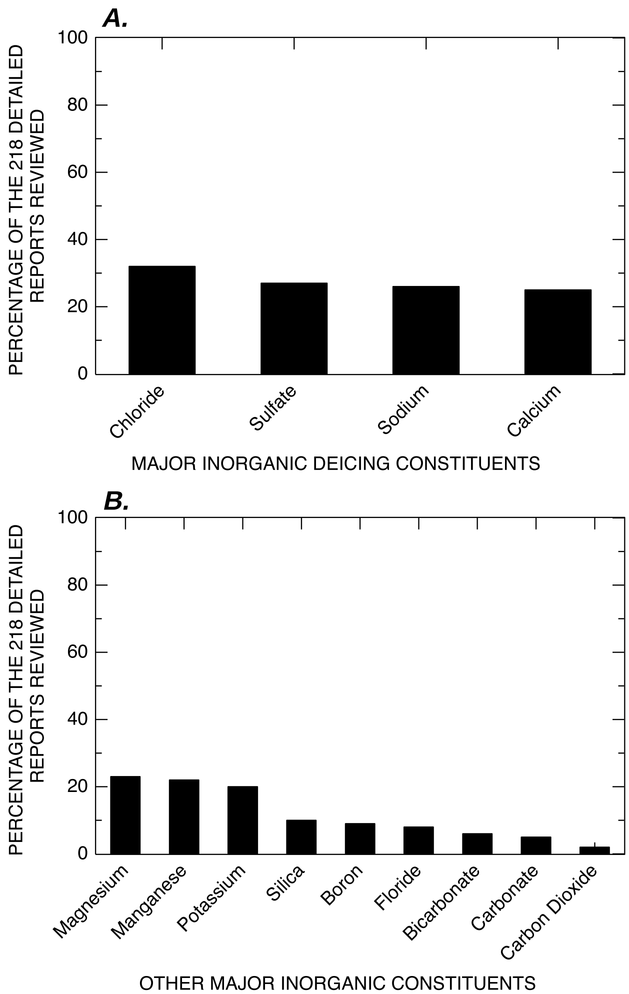

Figure 12. Proportion of the 218 detailed reports that document analysis of major inorganic constituents including (*A*) major constituents in deicers, and (*B*) other major constituents.

process did not focus on "road salt" reports but instead focused on reports that document a complete set of runoff-quality constituents. Information about these major ions, however, is necessary to determine the geochemistry of runoff and to examine the potential for chemical interference in analytical methods used for the analysis of regulated constituents.

The proportion of runoff-quality reports that document the other major inorganic constituents is slightly less than the proportion that document measurement of the major inorganic constituents associated with deicing chemicals (fig. 12*B*). These major inorganic constituents also determine the geochemistry of runoff and may compete with trace elements for ion-exchange sites on sediments, thereby increasing the solubility (and potential for toxicity) of trace elements in runoff and receiving waters (Bricker, 1999).

Nutrients (primarily nitrogen and phosphorus species) are also a primary factor in determining the geochemistry and quality of runoff and receiving waters (Bricker, 1999). Nutrient molecules may directly affect the ionic strength of a solution and the solubility of trace elements (Bricker, 1999; Breault and Granato, 2000). Indirectly, nutrients may stimulate primary production by algae and aquatic macrophytes, which can affect the uptake of runoff constituents and the redox of the solution through photosynthesis, respiration, and decomposition. Documentation of analysis of nutrients, however, is not common in the 218 detailed reports reviewed (fig. 13).

The geochemistry of runoff waters retained in structural BMPs and of receiving waters is affected by chemicals that exert an oxygen demand (Bricker, 1999). For example, the solubility of trace elements in catch basins may be a function of the redox state of water and sediments in the sump (Breault and Granato, 2000). Chemical oxygen demand (COD) is the most commonly documented measure of oxygen demand (fig. 14). This may be because the COD, which is analyzed by means of a chemical rather than a biological method, has fewer pre-analysis handling restrictions or because it is not affected by inhibitory effects of metals on the microorganisms that digest the organic carbon in

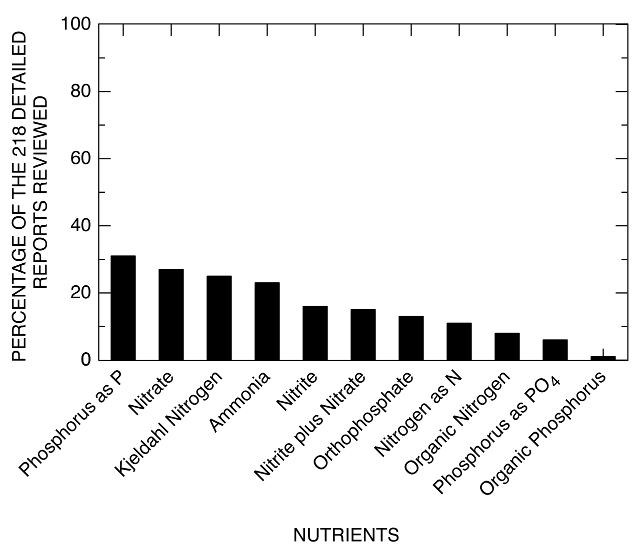

Figure 13. Proportion of the 218 detailed reports that document analysis of selected nutrients.

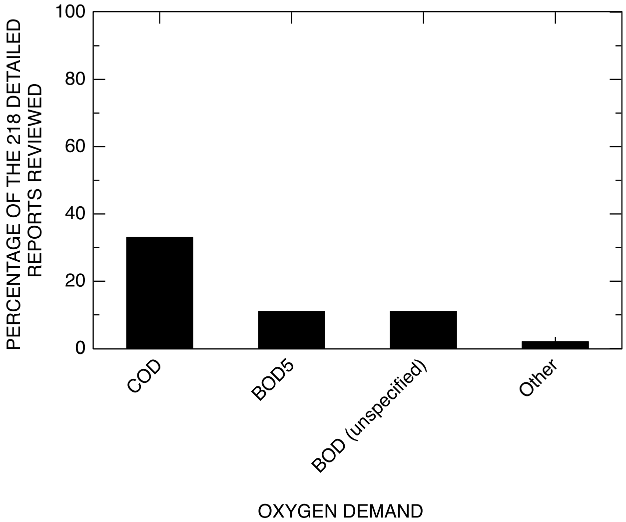

Figure 14. Proportion of the 218 detailed reports that document analysis of selected measures of oxygen demand.

solution (Alley, 1977; Hem, 1992). Use of the 5-day biochemical oxygen demand (BOD) is also documented. A substantial proportion of the reports listing a BOD measurement, however, do not document the BOD test duration (for example a BOD5 is a 5-day BOD test and a BOD20 is a 20-day BOD test), which may have a substantial effect on the measured results. Other methods, including the BOD20 and the ultimate oxygen demand, are documented in about 2 percent of the reviewed reports.

Sediment and Solids

The USEPA (2000d) has identified sediment as the most widespread contaminant of concern in the Nation's waters. Sediment and solids are also vectors for the transport of trace elements and organic chemicals, which can impair the quality of receiving waters and affect aquatic ecology (Lopes and Dionne, 1998; Buckler and Granato, 1999; Breault and Granato, 2000; Bent and others, 2001). Currently, sedimentation is the primary method for control of urban- and highway-runoff quality (Schueler, 1987; Young and others, 1996; Shoemaker and others, 2000). Accurate and representative sediment-concentration data, therefore, is necessary for the assessment and interpretation of the potential effect of runoff on receiving waters (Bent and others, 2001).

Many types of solids concentrations are documented in the 218 reviewed reports (fig. 15). Suspended-sediment concentrations have been expressed as one or more types of "solids" concentrations in the highway- and urban runoff-literature. Many analytical methods are used for measuring sediment and solids concentrations, including filtration, settling, evaporation at different temperatures, and other processes (Guy, 1969; Fishman and Friedman, 1989; Keith and others, 1992; Fishman, 1993; American Public Health Association and others, 1995; American Society for Testing and Material, 2000; Bent and others, 2001). Measurement of volatile solids concentrations commonly entails evaporation or incineration at relatively high temperatures. The total dissolved and volatile dissolved concentrations are not direct measures of sediment concentrations. These concentrations, however, are commonly used to calculate a total or volatile suspended solids concentration from a total solids or total volatile solids measurement, respectively. The "other solids" category in figure 15 includes solids data reported as floatable solids (about 1 percent), settleable solids (about 3 percent) and unspecified residue (about 7 percent of the 218 detailed reports reviewed).

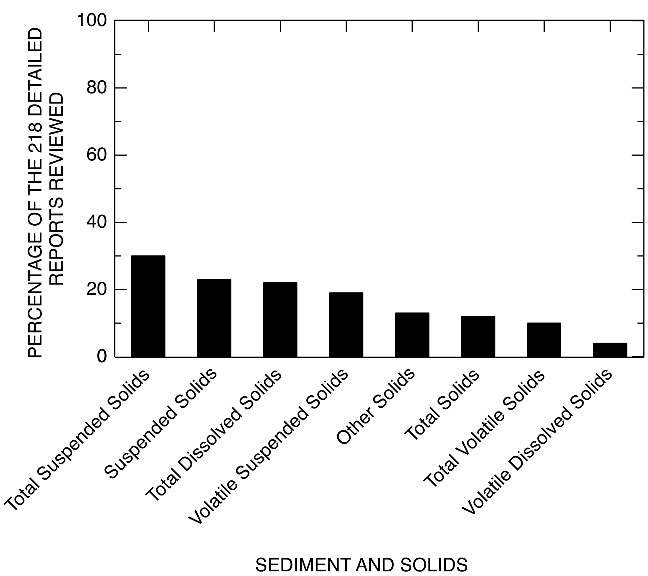

Figure 15. Proportion of the 218 detailed reports that document analysis of selected measures of sediment and other solids.

Turbidity may be a useful surrogate for estimating suspended-sediment concentrations when used in conjunction with an intensive sediment-sampling program (Edwards and Glysson, 1999, Bent and others, 2001). Turbidity is commonly used as a surrogate measurement for real-time analysis of the variability in sediment transport or for estimating sediment concentrations during periods when sediment samples are not available. About 15 percent of the reviewed reports document turbidity measurements.

Information about the grain-size distribution of erodable sediments on the surface and shoulders of roads, in bottom sediments in drainage systems, in BMPs, and in receiving waters, and of suspended sediments in runoff and receiving waters, is important for interpretation of runoff-quality data. Characterization of grain-size distributions will provide valuable information about the sources, transport, fate, and measurement of sediment in runoff reports (Bent and others, 2001). About 9 and 11 percent of detailed reports document grain-size distributions of suspended solids and bottom sediments, respectively.

Many technical issues associated with sediment-sample collection, processing, and analysis must be addressed in order to produce valid, current, and technically defensible sediment data for local, regional, and national information needs (Bent and others, 2001). About 15 percent of the detailed reports document the type of sampler used. Less than one percent, however, document sampler calibration and none of the reviewed reports document the intake-nozzle size (which affects the capture efficiency, grain size distribution and maximum particle size captured by a given sampler; Edwards and Glysson 1999; Bent and others, 2001). It is also considered necessary to compare the automatic sampling methods typically used in runoff studies to isokinetic methods to assess any potential bias in measured concentrations and grain sizes caused by sampler-intake-induced variations in the flow field (Edwards and Glysson, 1999, Bent and others, 2001). Only about one percent of the detailed reports, however, document use of isokinetic methods for sample collection.

Temporal and spatial variability in runoff can be large, because of a combination of factors, including volume and intensity of precipitation, rate of snowmelt, and features of the drainage basin such as drainage area, slope, infiltration capacity, channel roughness, and storage characteristics. About 21 percent of the detailed reports document sampling efforts throughout the entire hydrograph to account for temporal variability. Vertical and horizontal differences in measured sediment concentrations and grain-size distributions may be substantial in the channel cross-section, especially where the water is not well mixed (Edwards and Glysson, 1999, Bent and others, 2001). Despite this fact, only about 6 percent of the detailed reports document the sampling depth and about 1 percent document the flow depth at the time sediment samples were collected. Also, none of the reviewed reports include information relating concentrations in samples from point samplers to concentrations in samples collected by depth- or width-integrated methods.

Use of standard analysis methods by a certified laboratory (a laboratory participating in one or more quality-assurance programs) is critical for use and interpretation of sediment data for a local, regional, or national synthesis (Bent and others, 2001; Gordon and others, 1999). About 14 and 5 percent of the 218 detailed reports document the name of the sediment laboratory and its certification status, respectively. The exact method of analysis, however, is not commonly documented in the reviewed reports. Recent research comparing the analytical methods for determining total suspended solids (TSS; American Public Health Association and others, 1995) and suspended sediment concentration (SSC; (American Society for Testing and Materials, 2000) used thousands of paired samples from surface-water-quality monitoring programs across the United States (Glysson and others, 2000; Gray and others, 2000). This research indicates that the TSS methods do not accurately represent the true concentration of suspended sediment in natural waters because the TSS methods involve subsampling, which may exclude the larger grain-size fractions. Furthermore, the TSS methods are less repeatable in interlaboratory studies than are the SSC methods (Gordon and others, 1999). In response to these findings, the USGS Offices of Water Quality and Surface Water have issued a technical memorandum stating that use of the TSS methods can result in "unacceptably large errors," and that these methods may be "fundamentally unreliable" for analysis of sediment concentrations and calculation of sediment loads (USGS, 2000). Use of the SSC methods, therefore, is considered necessary for determination of suspended-sediment concentrations in surface waters (USGS, 2000).

Theoretically, the potential differences in analytical methods for determining suspended sediment concentrations would be more critical for analysis of highway and urban runoff because the high-energy flows in these systems tend to mobilize the larger grain fractions, which are not represented by the TSS analysis methods. Bent and others (2001) examined this issue by means of paired TSS and SSC data from recent highway-runoff investigations in Massachusetts and Wisconsin. They determined that TSS under represents the true sediment concentration at these sites, and that relations between TSS and SSC concentrations are not transferable from site to site even when grain-size distribution information is available.

Bent and others (2001) also concluded that potential bias in TSS data may have important consequences for the assessment, design, and maintenance of sediment-removal BMPs. They conclude that concentrations of the larger grain size fractions of sediment at the inlet of the BMP structure (before settling) would be underrepresented by the TSS method, which would decrease the estimated capture efficiency of the structure. Bent and others (2001) also observed that differences in grain-size distributions between monitored sites may affect measured TSS concentrations at different sites, which would contribute to the great uncertainties in measured BMP performance among different studies in the literature. Further research, however, may be necessary to quantify the scope of this issue in different highway and urban settings.

Explicit definition of analytical methods used in the analysis of sediment samples, however, is not typical in the reports cataloged in the NDAMS metadata review process. Although the terms (or abbreviations) total suspended solids (TSS), total solids (TS), and suspended solids (SS) may indicate a specific method of analysis, they are commonly used interchangeably in the literature to describe the total concentration of suspended solid-phase material (James, 1999; Gray and others, 2000; Bent and others, 2001). Examination of the population of reviewed reports (fig. 16) indicates that only 2 percent of reports included TSS, TS, and SS concentrations. In comparison, about 52 percent of the 218 detailed reports include analysis of sediment in terms of TSS, TS, or SS concentrations. The term "suspended-sediment concentration (SSC)," however, was not typically used in runoff reports.

Trace Elements

Stormwater runoff may transport substantial loads of trace elements from the land surface to receiving waters. Many trace elements are essential for biological activity and become detrimental only when concentrations in runoff and receiving waters exceed concentrations typical of the natural environment (Breault and Granato, 2000). Trace elements have been a primary focus of most highway- and urban-runoff reports (fig. 10) because some trace elements are regulated for aquatic-life protection. In highway- and urban-runoff reports, the term metal is usually used to describe a trace element that, at low concentrations, may have adverse effects on aquatic biota. Trace elements washed off the highway during rain storms, snow storms, or periods of snow melt may have adverse effects on ecosystems and receiving waters if effective measures are not taken for attenuation of potential contaminants (Buckler and Granato, 1999).

Most reviewed reports include only a few of the trace elements of potential interest to runoff studies (fig. 17). Most of the reviewed reports include analysis of only those trace elements that are the regulated priority-pollutants detected in early highway- and urban-runoff studies (Gupta and others, 1981a; Athayde and others, 1983). About 66, 63, and 56 percent of the 218 detailed reports document sampling and analysis of lead, zinc, and copper, respectively. Cadmium, chromium, and nickel, which were reported as being at or below detection limits in early runoff reports, are documented in fewer reports (about 50, 40, and 39 percent, respectively). These elements were not included in some recent reports, despite the fact that improvements in analytical techniques have lowered detection limits by several orders of magnitude since the early 1970s (Bricker, 1999; Breault and Granato, 2000). Iron, documented in about 42 percent of detailed reports, is present in substantial concentrations, but does not have the same regulatory emphasis as lead, zinc, copper, cadmium, chromium, and nickel.

Fewer than 20 percent of reports document analysis of many of the other trace elements, despite the fact that these trace elements are characteristic of many types of contaminant sources. Analysis of a complete suite of trace elements (for example, all the trace elements indicated in fig. 17) may provide insight into the source, transport, and fate of trace elements and other runoff contaminants (Breault and Granato, 2000). Periodic and routine screening for a complete suite of trace elements in each runoff study may also provide information necessary to assess and address potential problems. Such screening is especially necessary because the chemical composition of highway construction and maintenance materials, automobile

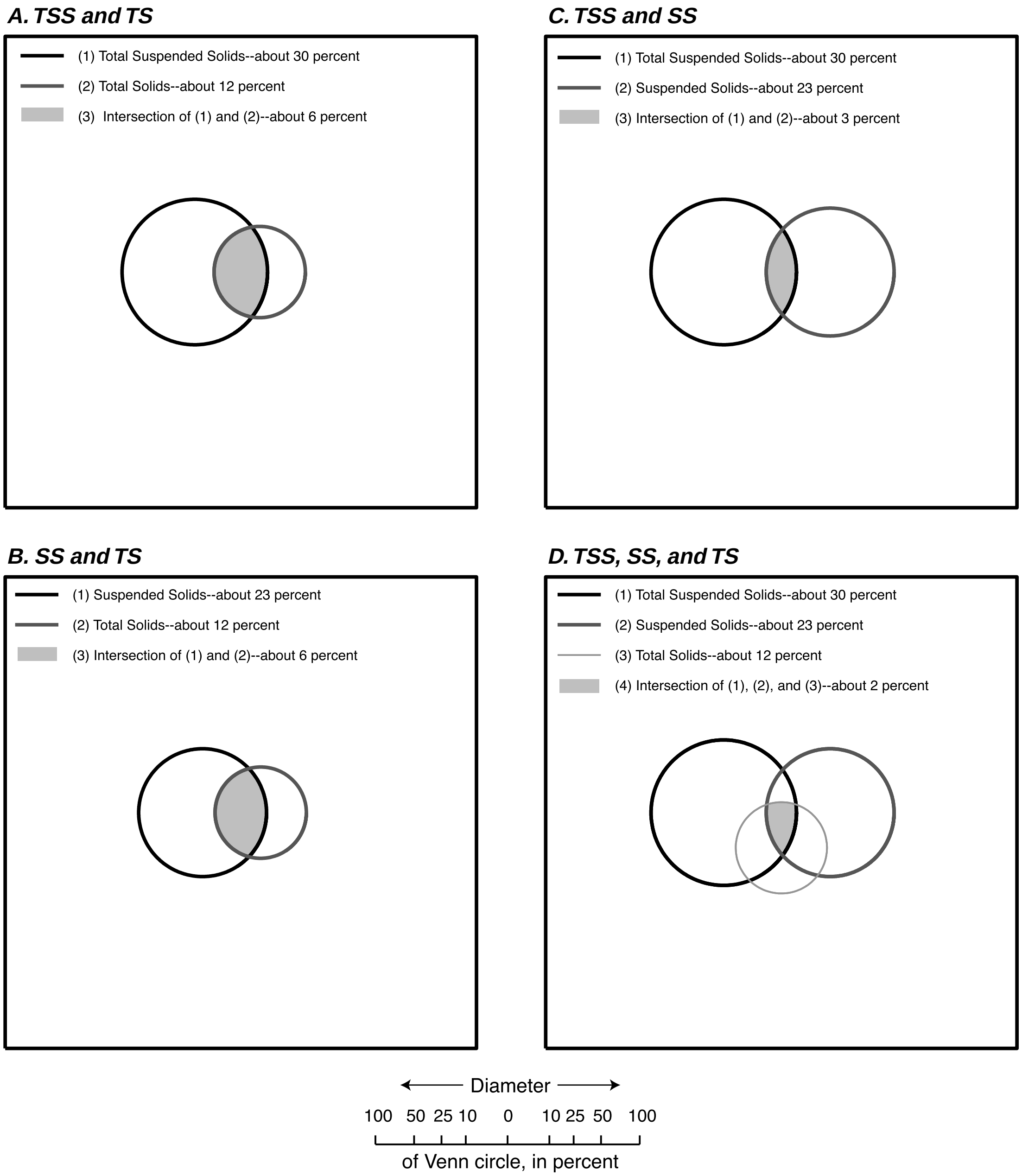

Figure 16. Percentages of the 218 detailed reports reviewed that document analysis of sediment samples including: (*A*) total suspended solids (TSS) and total solids (TS); (*B*) suspended solids (SS) and TS; (*C*) TSS and SS; and (*D*) TSS, SS, and TS methods.

components, and fuels have changed (and continue to change) since the early highway- and urban-runoff studies. These changes have affected the trace-element composition of runoff (Breault and Granato, 2000). For example, titanium and tungsten from studded tires (Bourcier and others, 1980); trace elements from automotive catalysts—including platinum, palladium, rhodium, cerium, lanthanum, neodymium, and zirconium—(Helmers, 1996; Zereini and others, 1997; Tuit and others, 2000); and copper, antimony and tin from asbestos-free brake linings (Armstrong, 1994; Reifenhauser and others, 1995) have been detected in runoff, receiving waters, and biota (Buckler and Granato, 1999; Breault and Granato, 2000).

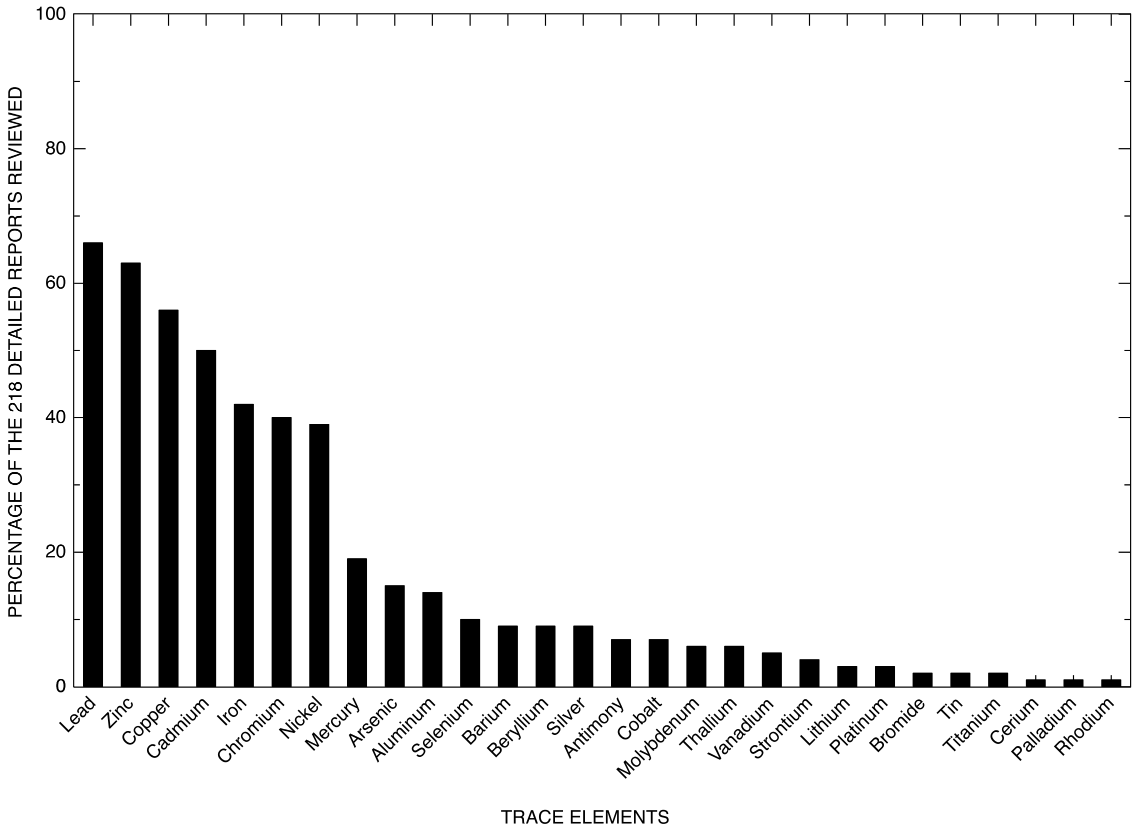

Figure 17. Proportion of the 218 detailed reports that document analysis of selected trace elements.

Many technical issues of concern for monitoring trace elements go beyond the basic considerations necessary for collection of complete and representative runoff samples (Breault and Granato, 2000). Since the 1970s, requirements for documentation of runoff-quality studies have been extended to include study-site characteristics, methods and materials, QA/QC information, and other ancillary information (Granato and others, 1998). During the same period, the accuracy, precision, and detection limits of analytical techniques and instrumentation commonly employed to measure trace elements have improved (Bricker, 1999; Breault and Granato, 2000). In addition, field and laboratory studies have demonstrated that sample-collection, processing, preservation, and analysis methods can substantially affect the measured concentrations of trace constituents. These and other factors have led to profound disagreements within the scientific and regulatory communities about the validity and comparability of existing data, have contributed to the current lack of standardization for trace-element-monitoring methods, and have made it difficult to interpret and assess the quality of historical and current trace-element data. Therefore, trace-element data commonly are considered suspect unless the data-collection agency can provide data-quality information to support the validity of reported results (Breault and Granato, 2000). These data-quality concerns are especially applicable to atmospheric-deposition data sets because of the extremely low concentrations of trace elements measured in atmospheric deposition and the proportionally high potential for sampling bias (Colman and others, 2001).

It is necessary to use methods and materials that do not substantially bias measured trace-element concentrations and to demonstrate the effectiveness of these measures within a documented quality system (Jones, 1999; Breault and Granato, 2000). Trace elements have both natural and anthropogenic sources that may affect the sampling process, including the sample-collection and handling materials used in many trace-element-monitoring studies. About 33 and 17 percent of the detailed reports document the sample-collection and processing materials. About 4 percent of the detailed reports document use of "clean" protocols designed to minimize bias and variability in the sampling process. Trace elements also react with suspended sediments and with sample-collection and processing materials during the time period that is typical for collection, processing and analysis of runoff samples (Breault and Granato, 2000). About 27 percent of the detailed reports document use of preservation methods designed to minimize bias in measured trace element concentrations.

Knowledge of the detection limits of analytical methods for trace elements is necessary, because the relative accuracy and precision of analytical methods decreases as the concentration decreases to the detection limits (Granato and others, 1998; Breault and Granato, 2000). To estimate population statistics and compare data from different sites in a quantitative regional or national synthesis, it is necessary to determine if one or more detection limits exist within a population of measured trace-element data (Tasker and Granato, 2000). About 11 percent of the detailed reports document all the detection limits for the trace elements analyzed. About 8 percent of the detailed reports indicate the detection limits only for those trace elements measured at or below one or more detection limits. About 55 percent of detailed reports document analysis of trace elements but provide no detection-limit information. Among these reports, some indicate that one or more trace elements were determined to be "below detection limits" without quantifying these limits.

Organic Constituents

Runoff from highways and urban areas has long been recognized as a source of organic chemicals that may affect the Nation's water resources (Lopes and Dionne, 1998). Many of these organic chemicals can be classified as either semivolatile organic compounds (SVOCs) or volatile organic compounds (VOCs). SVOCs may be operationally defined as solvent-extractable organic compounds that can be measured by gas chromatography/mass spectrometry (GC/MS) (Furlong and others, 1996). SVOCs typically are hydrophobic and by definition have a moderate tendency to volatilize (Lopes and Dionne, 1998). Examples of SVOCs detected in runoff include phthalates, phenols, and polycyclic aromatic hydrocarbons (PAHs). VOCs may be operationally defined as organic compounds that can be extracted from water by purging with an inert gas, then trapped and determined by GC/MS (Connor and others, 1998). In contrast to SVOCs, VOCs are either hydrophobic or hydrophilic, have a high tendency to volatilize, and distribute preferentially into air because of their volatility. Examples of VOCs detected in runoff include the fuel-related compounds such as benzene, toluene, ethylbenzene, and xylene (BTEX) and chlorinated compounds such as chloroform, PCE, and TCE. Many anthropogenic organic compounds are present in local and regional atmospheric deposition (Colman and others, 2001). Organic compounds are an environmentally significant group of contaminants because they may accumulate in sediment and biological tissue to concentrations that may exert adverse effects including reduced fecundity, endocrine disruption, inhibited or abnormal growth, and mortality (Lopes and Dionne, 1998; Buckler and Granato, 1999). Accurate and representative organic-constituent concentration data, therefore, is necessary to assess and interpret the potential effect of runoff on receiving waters (Lopes and Dionne, 1998).

Organic chemical concentrations in older highway- and urban-runoff studies (for example Gupta and others, 1981a; b) are assessed as dissolved, suspended, and total volatile solids (fig. 15) by means of analytical methods that typically would include VOCs and SVOCs (Fishman and Friedman, 1989; Fishman, 1993; Keith and others, 1992; American Public Health Association and others, 1995). About 30 and 10 percent of the detailed reports document analysis of one or more individual SVOCs or VOCs, respectively (fig. 18). These two categories represent 112 different SVOCs (including 44 PAHs) and 73 VOCs (including 9 fuel-related VOCs). The detailed reports document sampling and analysis for, 93 of the 112 SVOCs and 70 of the 73 VOCs listed in the NDAMS review sheets. The other categories including total organic carbon, oil and grease, hydrocarbons, polychlorinated biphenyls (PCBs), dissolved organic carbon and surfactants are commonly used in the highway- and urban-runoff literature to indicate the total concentration of a suite of organic compounds (fig. 18). Surfactants are commonly identified as methylene-blue active substances (MBASs), which refers to the method of analysis (Keith and others, 1992; American Public Health Association and others, 1995; Burkhardt and others, 1995). Although tires are considered a substantial

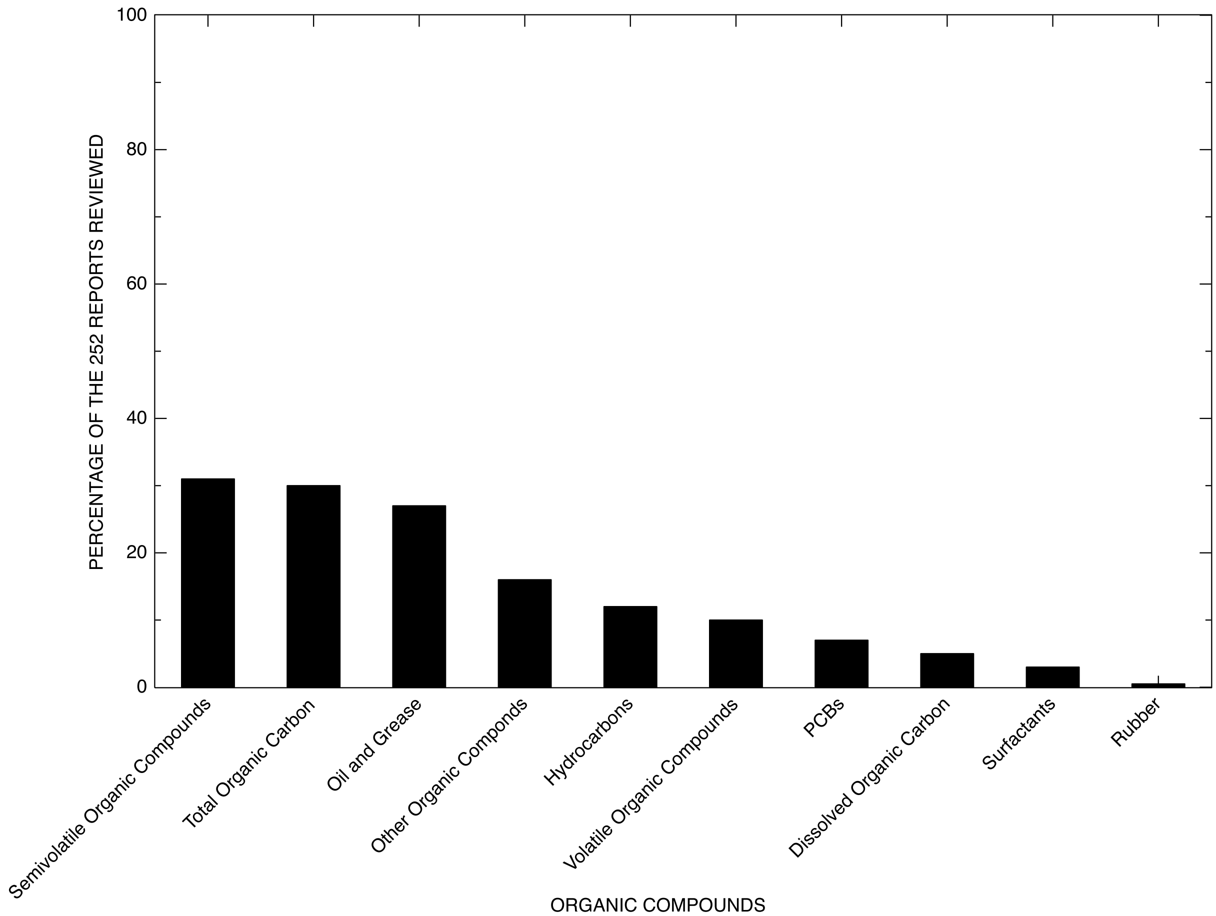

Figure 18. Proportion of the 218 detailed reports that document analysis of selected organic compounds.

source of runoff constituents (Breault and Granato, 2000), less than one percent of the detailed reports document analysis for rubber compounds.

It is necessary to use methods and materials that do not substantially bias measured concentrations of organic constituents and to demonstrate the effectiveness of these measures within a documented quality system (Lopes and Dionne, 1998; Jones, 1999). The materials (such as the water and detergents used to clean field equipment) and the supplies and equipment for collection and handling samples during highway- and urban-runoff studies may volatilize, absorb, or contribute organic compounds. Because the relatively low concentrations of organic chemicals measured in atmospheric deposition create a high probability of sampling bias, proper methods for monitoring atmospheric deposition are critical for defensible results (Colman and others, 2001). Furthermore, equipment, methods, and materials for collection, handling and processing SVOCs may not be appropriate for VOCs (Lopes and Dionne, 1998). About 35 and 25 percent of detailed reports document the sample-collection and -processing materials and the sampler type, respectively. About 12 percent of the detailed reports document protocols such as efforts to preclean the sampler to remove residual organic compounds. About 3 percent document assessment potential volatilization of organic compounds due to sampler location (for example, sampling after an elevated outfall which aerates the stormwater thereby stripping volatile compounds), and about 3 percent document assessment of volatilization of organic compounds due to sampler design (for example, some pumping samplers utilize suction, which can volatilize organic compounds in the sample).

Knowledge of the detection limits of analytical methods used for organic compounds is also necessary for assessment and interpretation of runoff-quality data

(Lopes and Dionne, 1998). For example, the literature review conducted by Lopes and Dionne (1998) identified several cases in which high minimum reporting limits (ranging from 5 to 100 mg/L) result in detection of few SVOCs and VOCs in stormwater. As for trace elements, knowledge of one or more detection limit values within a population of measured organic-compound concentration data is necessary to estimate population statistics and to compare data from different sites in a quantitative regional or national synthesis (Tasker and Granato, 2000). About 5 percent of the detailed reports document all the detection limits for the organic constituents analyzed. About 6 percent document detection limits only for organic constituents measured at or below one or more detection limits. About 49 percent of the detailed reports document analysis of one or more organic compounds but do not provide any detection limit information.

Pesticides are organic compounds that are intentionally applied to private and public properties to control weeds, insects, and other organisms. Pesticides and other agricultural chemicals are commonly detected in industrial, suburban, urban and highway runoff because they are used for landscaping and are applied to rights-of-ways (Wotzka and others, 1994; Voss and others, 1999; Buckler and Granato, 1999). Many of these chemicals are similar to SVOCs because they are hydrophobic (and therefore preferentially partition to sediment and biological tissues) and moderately volatile (Larson and others, 1997). Pesticides are an environmentally significant group of contaminants because pesticides can accumulate in sediment and biological tissue to concentrations that may cause adverse effects including reduced fecundity, endocrine disruption, inhibited or abnormal growth, and mortality (Lopes and Dionne, 1998; Buckler and Granato, 1999; Gilliom, 2000).

Potential concerns about pesticides are discussed in the highway-runoff literature, but these reports conclude that proper management and timing in the application of chemicals to the right-of-way should reduce or eliminate adverse effects (Kobriger and others, 1984; Burch and others, 1985; Kramme and Brosnan, 1985, Kramme and others 1985; Shively and others, 1986). When a specific product is used intentionally for highway-maintenance activities, it is a straightforward process to estimate risks associated with the use of that product. Pesticides not used on the highway right-of-way, however, may serve as a tracer to indicate the potential influence of atmospheric deposition on runoff quality (Colman and others, 2001). Regardless of the actual sources, pesticides and other agricultural products should be given consideration in evaluations of nonpoint-source pollution because they are commonly detected in surface-water runoff and have the potential for adverse effects on the ecology of receiving waters (Buckler and Granato, 1999).

In the NDAMS review process (Dionne and others, 1999), pesticides are classified as insecticides, transformation products, herbicides, or fungicides. Transformation products are compounds created from the incomplete degradation of pesticides. Only about 11, 9, 6 and less than 1 percent of detailed reports document sampling and analysis for insecticides, transformation products, herbicides, or fungicides, respectively (fig. 19). Only 15 of the 59 insecticides, 6 of the 20 transformation products, 11 of the 41 herbicides, and 1 of the 5 fungicides included in the NDAMS review sheets (Dionne and others, 1999) are documented as being investigated in the 218 detailed reports.

Concerns for the collection of valid, current, and technically defensible pesticide data are similar to concerns for sampling other organic compounds. As with other organic compounds, it is necessary to use methods and materials that do not substantially bias measured concentrations of pesticides and to demonstrate the effectiveness of these measures within a documented quality system (Lopes and Dionne, 1998; Jones, 1999). The sample-collection and -handling

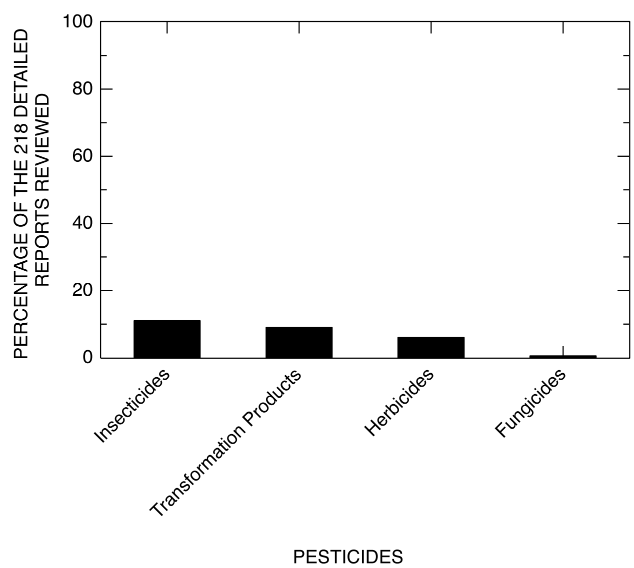

Figure 19. Proportion of the 218 detailed reports that document analysis of selected pesticides.

supplies, equipment, and other materials used in highway- and urban-runoff studies may volatilize, absorb, or contribute pesticides by cross contamination from other sites. About 6 percent of the reviewed reports document measurement of pesticides and the materials used for collection and processing of pesticide samples. About 1 percent document highway-maintenance practices relevant to the interpretation of pesticide-concentration data, and about 1 percent of these reports document use of one or more pesticides on the highway right-of-way.

As for the industrial and urban organic compounds, knowledge of the detection limits for pesticide analysis methods is necessary to determine population statistics and to compare data from different sites in a quantitative regional or national synthesis (Tasker and Granato, 2000). About 5 percent of the detailed reports document all the detection limits for the pesticide constituents analyzed. About 2 percent document the detection limits for constituents measured at or below the stated detection limits. About 6 percent of the detailed reports document analysis of one or more pesticides but do not provide any detection-limit information.

Ecological Assessment

Techniques for ecological assessment of the effects of nonpoint-source pollution have gained increased regulatory and scientific attention in recent years (Davis and others, 1996; Buckler and Granato, 1999). Federal water-quality standards for aquatic-life protection are becoming increasingly stringent, and states have been integrating ecological criteria into the development and enforcement of their water-quality standards. A number of biological assessment techniques are commonly used to provide the information necessary for ecological assessment in highway- and urban-runoff studies (Buckler and Granato, 1999). Biological assessment techniques can increase our understanding of the influence of environmental contaminants on the biological integrity and ecological function of aquatic communities (Davis and others, 1996; Buckler and Granato, 1999).

Many of the contaminants normally associated with runoff from the Nation's highways have the potential for adverse biological effects. The biological effects of runoff constituents depend on their physical and chemical properties, the concentrations of these constituents, the sensitivities of organisms to adverse physical and chemical characteristics of the runoff, and the ability of the system and the individual organism to assimilate a given constituent or a given mixture of constituents (Buckler and Granato, 1999). Biological assessments, in conjunction with analytical chemistry and habitat assessment as multiple lines of evidence, can help provide the cause-and-effect linkages between measures of runoff quality and ecological impairment.

Although the results of bioassays would indicate that highway runoff is not commonly toxic to aquatic biota, constituents from highway runoff and from highway-runoff sediments deposited in receiving waters near the highway are found in the tissues of aquatic biota and may affect the diversity and productivity of biological communities (Buckler and Granato, 1999). More quantitative information, however, is necessary to provide information for regional or national synthesis. Ecological-assessment techniques incorporated in the NDAMS review process (Dionne and others, 1999) include the following categories: biological assessment, toxicity testing, microbiology, and eutrophication (table 2). Few of the detailed or summary reports document analysis of these ecological-assessment techniques (fig. 10).

Many complex site-specific factors affect the ecology of receiving waters and can have profound effects on the response of each ecosystem to a contaminant load. These factors may obscure cause-and-effect relations between measured runoff quality and the ecological response in receiving waters at different sites (Buckler and Granato, 1999). Therefore, information from techniques such as population and community-assessment, chemical analysis of biological tissues, and benthic drift studies may be necessary to measure biological responses to runoff quality.

Population and community surveys provide direct measures of an ecosystem's health because they focus on the structural and functional properties of the biotic components of the ecosystem. These surveys are designed to assess local biodiversity by evaluating the number of individuals and (or) species present at a given site or the type of species present. These assessments can range from evaluations of single indicator species to comprehensive evaluations of the organisms found in an aquatic receiving system. Results of population and community assessments typically require comparison with assessments at virtually pristine sites with similar natural characteristics to indicate whether the ecology of the local water body is affected, and comparison with assessments at similar upstream sites to indicate whether the local land use is affecting biodiversity at the site in question (Buckler and Granato, 1999). About 8 percent of the 218 detailed reports document some type of population or community assessment technique (fig. 20).

Analysis of biological tissues may provide the most direct evidence that runoff constituents are entering the food chain at any given site (Buckler and Granato, 1999). Many trace elements (Breault and Granato, 2000) and organic compounds (Lopes and Dionne, 1998) may be bioaccumulated in aquatic ecosystems. About 6 percent of the 218 detailed reports document use of biological-tissue analysis methods (fig. 20). The comparability, validity, and technical defensibility of these results depend on the types of assessments made and the species included in the population and community assessments and in the biological tissue-analysis programs. About 10 percent of the detailed reports document the species used in the population assessments or the biological tissue analysis, and 7 percent of the detailed reports include population assessment, biological tissue analysis, and species documentation. (An ellipse represents the "species" element in fig. 20 because, by definition, species is not an independent metadata population but is a subset of the population assessed or of the organisms that underwent biological tissue analysis. Therefore, there can be no values for the "species" element that do not also belong to the population assessment or biological-tissue analysis populations).

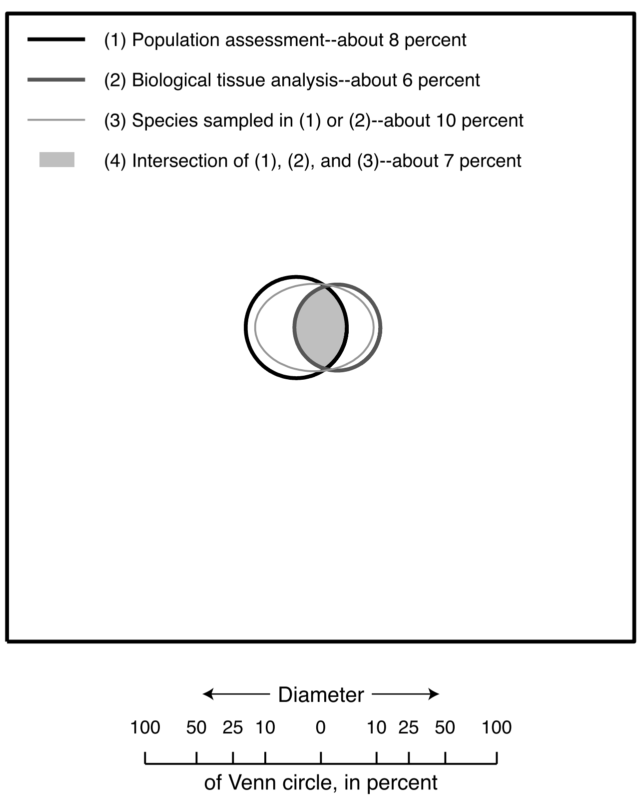

Figure 20. Percentages of the 218 detailed reports reviewed that document biological monitoring methods including population assessment, tissue analysis, and the species sampled for each method.

Fewer than one percent of the detailed reports include assessments of benthic drift. Benthic drift is the process whereby benthic invertebrates leave the bottom material to float downstream in response to elevated contaminant concentrations in the water or bottom sediment (Buckler and Granato, 1999). Benthic-drift studies may be done during runoff events to assess the effect of runoff on biodiversity. Controlled benthic drift studies (experiments in which contaminants are metered into a stream) are also utilized to assess threshold concentrations that produce a measurable biological response. For example, Crowther and Hynes (1977) added sodium chloride to a small reach of a pristine freshwater trout stream and noted that benthic drift of streambed organisms was detected when chloride concentrations exceeded 1,000 milligrams per liter.

A substantial amount of ancillary data is necessary for meaningful use of these biological monitoring techniques (Buckler and Granato, 1999). In a National Water-Quality Assessment (NAWQA) protocol, Fitzpatrick and others (1998) describe site-specific information necessary for use of biological monitoring data in a regional or national synthesis. The categories of information include documentation of site characteristics, water-management features, stream type, the type of geomorphic channel unit and other geomorphic features, bed substrate material, features that determine the amount of available light, habitat features, and a description of aquatic riparian vegetation. Fewer than 5 percent of the detailed reports document any of these features, which are considered necessary for local, regional and national interpretation of biological monitoring data (fig. 21). Fitzpatrick and others (1998) also state that site-specific diagrammatic mapping is necessary for documentation of these habitat features. None of the 218 detailed reports, however, includes diagrammatic mapping as part of the presentation of biological monitoring results.

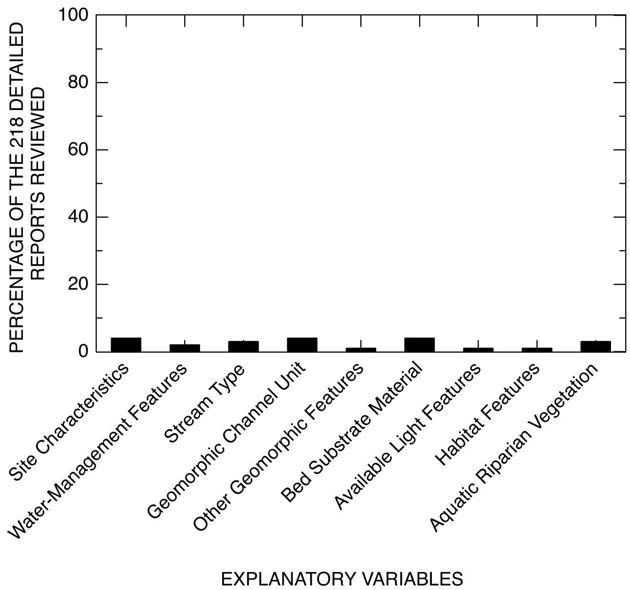

Figure 21. Proportion of the 218 detailed reports that document explanatory site characteristics necessary for interpretation of biological assessment data.

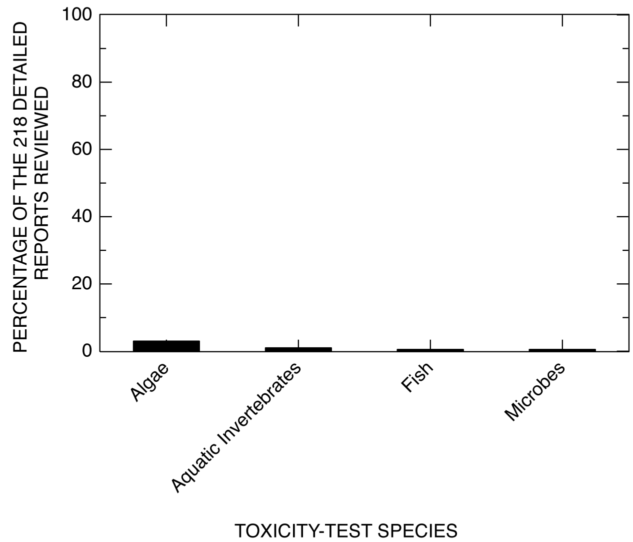

Figure 22. Proportion of the 218 detailed reports that document toxicity testing using selected analysis methods for different groups of test species.

The potential effects of environmental contaminants are commonly evaluated by means of whole-organism or single-species toxicity tests. Toxicity testing has many benefits as a component of a national or regional water-quality assessment, but also has some limitations (Elder, 1990; Buckler and Granato, 1999). Typical responses measured by toxicity tests include mortality, growth, and reproduction. Toxicity-testing procedures have been developed for a wide range of species, including algae, aquatic invertebrates and vertebrates, and more recently, microbes.

Algal assays use standard species (for example, the green alga *Selenastrum capricornutum*) to measure differences in optical density of exposed cultures, oxygen production and (or) carbon-dioxide uptake, cell counts, gravimetric cell-mass determinations, or chlorophyll concentrations between a control sample and the sample being assessed (Buckler and Granato, 1999). About 3 percent of the detailed reports document use of algal assays (fig. 22).

Aquatic invertebrates are commonly used to evaluate environmental contaminants present in runoff, receiving waters, and aquatic sediments (Buckler and Granato, 1999). The survival, growth, and reproductive success of the species in test and control samples are measured to indicate the potential effects of contaminants. About 1 percent of the detailed reports document use of aquatic invertebrate assays (fig. 22).

Toxicity tests on fish commonly focus on exposure of eggs or early life stages to environmental contaminants in water and (or) food or by injected contaminant extracts. Early developmental stages are commonly the most sensitive to chemical stressors and therefore produce measurable responses within timescales feasible for meaningful assessment (Buckler and Granato, 1999). Fewer than one percent of the detailed reports, however, document use of early life-stage toxicity studies with fish (fig. 22).

Microbial assay techniques utilize bioluminescent bacteria to indicate a measured response to environmental contaminants (Buckler and Granato, 1999). Microbial assays can be used with unprocessed water samples or with extracts of different environmental media, including water, sediment, and biological tissue, and are reportedly sensitive to a wide range of potential toxins. Toxicity is indicated by a measurable reduction in light output as a result of death of the bacteria; genotoxicity is indicated by a measurable increase in light output as a genetically modified strain of the bacteria mutates back to a wild-type bioluminescent bacteria strain (Buckler and Granato, 1999). Fewer than one percent of the detailed reports document use of microbial assays (fig. 22).

Historically, microbiological monitoring has been focused on human fecal indicators in order to assess compliance with standards for protection of public health in swimmable or drinkable waters (Francy and others, 2000). It may be difficult to provide a consistent assessment of the microbial quality of the runoff and receiving waters for regional or national synthesis, because methods and procedures for microbiological measurements depend on the objectives and practices of the parties collecting the data and are continuously being developed or modified. The USGS NAWQA program (in cooperation with the USEPA), however, has recently developed microbial monitoring protocols suitable for national synthesis of bacterial, protozoan, and virus data (Francy and others, 2000). A small proportion of the 218 detailed reports document analysis of one or more indicator bacteria (fig. 23). Several data-quality indices are necessary to ensure that microbial concentrations are valid, representative, and technically defensible (USEPA, 1992; Francy and others, 2000). Use of sterile technique and sterilized sample-collection, -handling, and -processing equipment helps minimize microbial contamination introduced in the sampling process. About 1 and 2 percent of the detailed reports document the use of sterile techniques and (or) sterilized sampling equipment, respectively. Populations of microbes in sampling containers can change rapidly depending on runoff quality, temperature, and other factors. It is critical, therefore, to document sample-holding times and sample-preservation and -storage conditions. About 3 percent of the detailed reports document sample-holding times and about 6 percent of the detailed reports document sample preservation and storage conditions. The USEPA requires collection of grab samples (with either manual or automatic samplers) for microbial sampling in NPDES monitoring programs (USEPA, 1992). In comparison, about 3 and 1 percent of the detailed reports document grab sampling or other sampling methods, respectively. About 13 percent of the detailed reports document concentrations of microbial fecal indicators, but do not indicate the microbial sampling method.

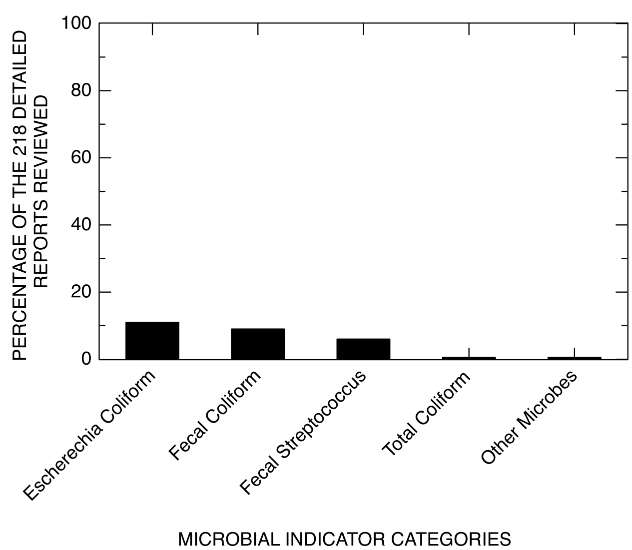

Figure 23. Proportion of the 218 detailed reports that document analysis of microbial fecal indicators.

Eutrophication is the process of increased production of algae and aquatic macrophytes in lakes and ponds in response to increases in concentrations of nutrients, organic matter, and solids in the water column. The eutrophication process can lead to excessive growth of algae and macrophytes, infilling by decayed plants and eroded soils, reduced water clarity, and depletion of dissolved oxygen in deep water with subsequent loss of fish habitat. Runoff may accelerate natural eutrophication processes by providing the nutrients, organic matter, and soil that feed the process. Measures of eutrophication include Secchi-disk depth (for clarity), chlorophyll concentration (indicates primary productivity), and water-quality profiles (such as pH, specific conductance, and dissolved oxygen--to monitor the geochemical effects of the eutrophication process). These and other measures of the eutrophication process are documented in a limited number of the detailed reports reviewed (fig. 24). Fewer than one percent of the detailed reports document explanatory variables for assessment of the eutrophication process. These variables include basin characteristics, a water balance (sources and sinks for water in the pond or lake), and the quantity and species composition of algae and aquatic macrophytes.

Explanatory Variables

Knowledge of relevant explanatory variables is necessary to understand, interpret, and quantify the factors that affect the quality of runoff and the potential for adverse effects in receiving waters. A primary objective of a national synthesis is to predict runoff quality and the potential for adverse effects in the environment at unmonitored sites across the country using

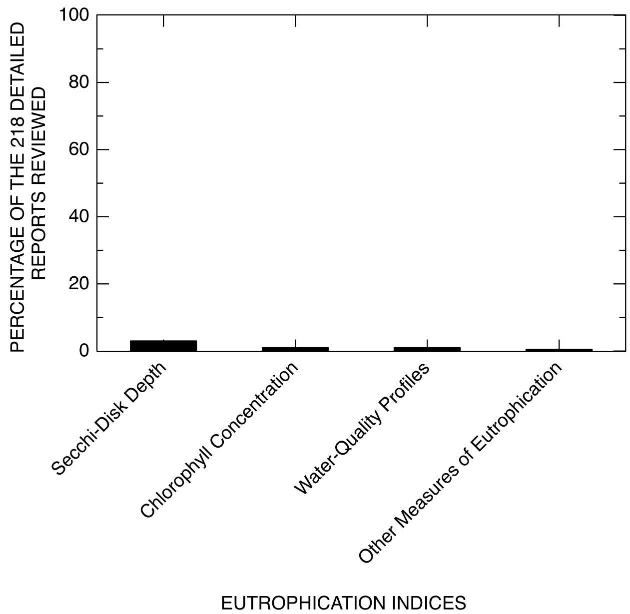

Figure 24. Proportion of the 218 detailed reports that document analysis of selected eutrophication indexes.

readily obtainable site-specific information and data (Tasker and Granato, 2000). It is, therefore, necessary that runoff studies use consistent and complete protocols to document explanatory variables along with sampling and analytical data. The ITFM (now the National Water Quality Monitoring Council) has established a minimum set of explanatory variables that are adequate for regional or national synthesis (ITFM, 1995a,b). Explanatory variables include site-specific location information, temporal information, and precipitation and flow-monitoring data.

Site-Specific Location Information

Location and site characteristics are explanatory variables that can be used to characterize highway runoff and its potential effects on receiving water and biota (Driscoll and others, 1990a; Tasker and Granato, 2000). For example, there are substantial variations in loads of dry and wet atmospheric deposition both locally and regionally across the United States (Colman and others, 2001). Documented location information is necessary to assess the potential repeatability and comparability of a study. For example, in a review of existing water-quality data collected by Federal, State, and local water-quality-monitoring entities, Hren and others (1987) determined that detailed documentation of location information was necessary to interpret differences among sites and to allow repeatable sampling efforts when data were suspect, or information on changes in water quality with time were required. Most of the 218 detailed reports document runoff concentrations from sites in the United States but, because some of the more recent highway runoff research has been conducted in Canada, Europe, and Asia, about 33 percent of the research cataloged is from sites outside the country (fig. 25*A*). Research results that are relevant to the study of highway-runoff quality are available for sites in about 70 percent of the 50 States (fig. 25*B*). Among the 994 sites cataloged in the metadata review, about 70 percent had highway/roadway information, about 48 percent were directly identified as highways, about 8 percent were characterized as being near a highway, and about 1 percent were identified as some other transportation-related land use.

Location coordinates are critical for interpreting study results in terms of geographic characteristics, water quality, climate, and ecological region characteristics (Smieszek and Granato, 2000; ITFM, 1995a, b). The precise location of a data-collection station must be documented in a standard format to ensure that sampling efforts at any given station can be repeated. During the metadata review, each site was assigned latitude and longitude coordinates in degrees, minutes, and seconds. The accuracy of latitude and longitude coordinates was determined from site-location information contained in the reviewed reports (Dionne and others, 1999). When coordinates were presented in tables, the significant digits expressed in the tables were used to estimate the accuracy of reported coordinates. When site maps (with geographic coordinates) were provided, the computer program for point location and calculation of error (PLACER) was used to interpolate site coordinates and estimate the uncertainties in these values (Granato, 1999). When it was necessary to determine latitude and longitude coordinates indirectly, however, it was difficult to assess the accuracy of the estimated coordinates for each site and a rule-based system was applied to assign an estimated accuracy (Dionne and others, 1999). The geographic-coordinate accuracy distribution (fig. 26), in part, reflects the system used to assign coordinates during the review process, but more importantly, indicates the small proportion of sites that were documented with precise and repeatable location coordinates.

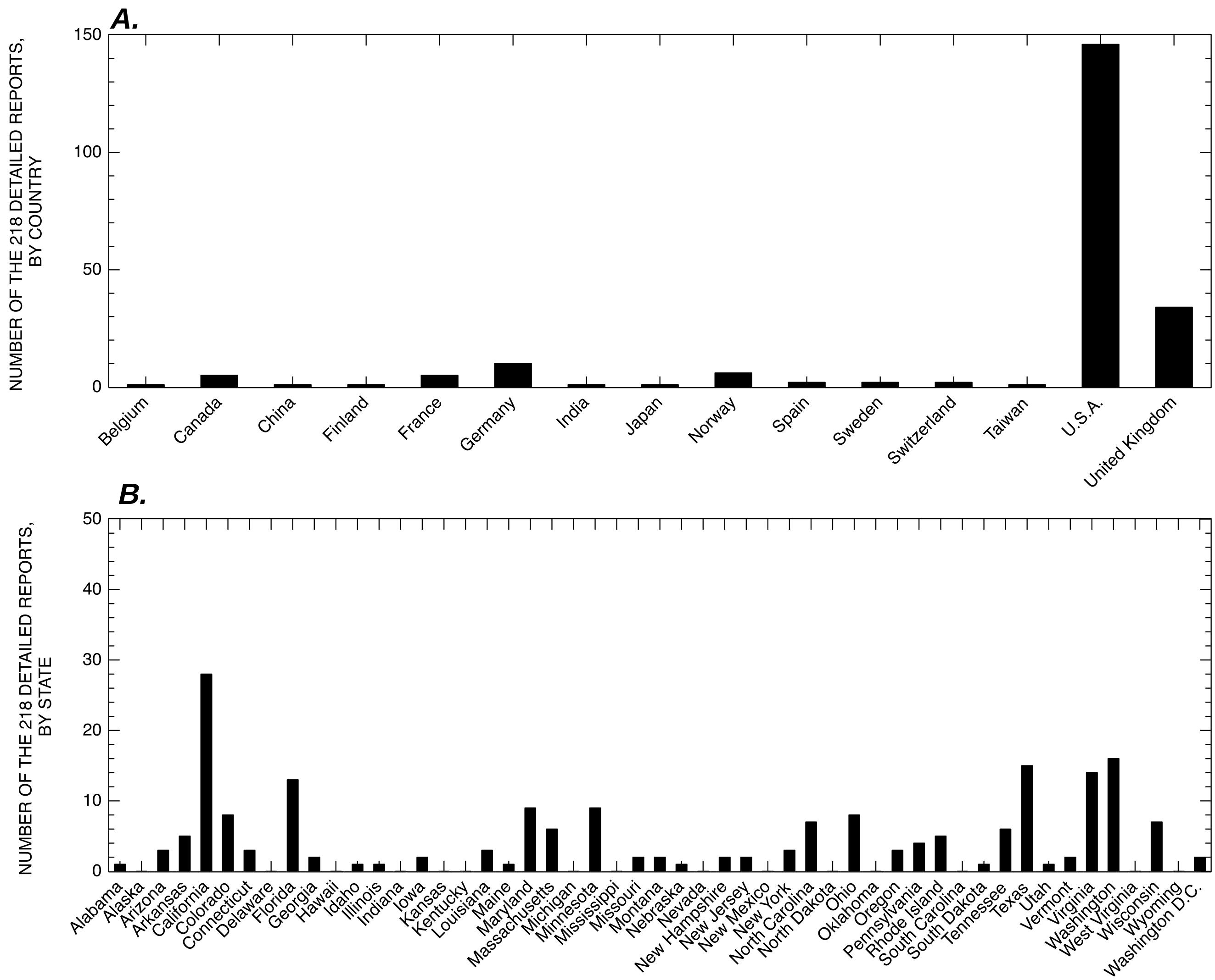

Figure 25. Number of the 218 detailed reports that document sampling efforts in (*A*) different countries, and (*B*) different States (and the District of Columbia).

Site-specific explanatory data have proven especially useful in past evaluations of highway-runoff quality. For example, Gupta and others (1981b) established that the concentrations and loads of constituents in highway runoff were affected by site characteristics including:

- highway-design features,
- traffic characteristics,
- climatic conditions,
- maintenance policies,
- surrounding land use,
- percentage of impervious area,
- type of pavement material,
- average age of automobiles in the study area,
- enforcement of littering and vehicle-emission laws,
- use of additives in vehicular operation (including fuels, lubricants, brakes, and tires),
- types of soils and vegetation along the highway, and
- local and regional atmospheric deposition.

Many of the same site features have also been used as explanatory variables in subsequent investigations of the characteristics of highway runoff (Driscoll and others, 1990a; Irish and others, 1996; Thomson and others, 1996; Young and others, 1996). As explanatory variables, many of these site features also indicate the comparability of data collected at different sites.

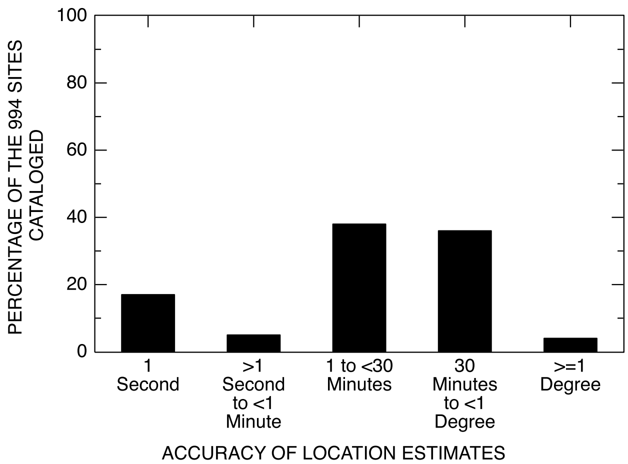

Figure 26. Proportion of the 994 sites cataloged in the 218 detailed reports reviewed in terms of the accuracy of location estimates.

Although Gupta and others (1981b) set the standard for relevant metadata, many of the reports published in the following 20 years did not document basic site-specific information. For example, about 42, 21, 19, 16, and 8 percent of the 994 sites are characterized by drainage area, soil type, geographic conditions (details about the local topography or terrain), local vegetation, and percent pavement (or percent impervious area), respectively, in the 218 detailed reports. Basic site-specific hydrologic information about the number of storms per year, storm volumes, storm intensities, and storm durations are documented for 1, 26, 26, and 5 percent of the 994 sites cataloged in the 218 detailed reports. Wind-speed information, which is important for measurement of precipitation totals (Church and others 1999) and for determination of the fate of constituents in atmospheric deposition that impact the pavement (Colman and others, 2001), is only documented for 2 of the 994 sites cataloged in the 218 detailed reviewed reports. Information about roadway characteristics also is lacking. Average daily traffic counts are documented for about 52 percent of the 694 roadway sites evaluated, but only 6 percent provide counting-method information and only 5 percent document counts for the number of vehicles during storms (VDS). About 33, 28, 27, 26, 24, 24, percent of roadway sites are described in terms of the type of drainage system, the number of lanes, the type of pavement, the local BMP structure(s) receiving runoff, the presence or absence of curbs, and the type of section (for example a bridge, cut section, or fill section), respectively.

Temporal Information

Documentation of temporal information is necessary to assess comparability of different data sets and overall data quality (Dionne and others, 1999). Temporal information, including the study period, the number of sampling events, type of event, and the date and time at which each sample is collected, is necessary for defining a population of water-quality data. Preliminary monitoring at a single site may require only a few samples. Complex scientific investigations designed to characterize physical and chemical processes, to develop predictive methods, or to develop effective BMP designs, however, may necessitate collection of thousands of samples over an extended period of time (Sonnen, 1983). Therefore, the number of samples collected and the duration of the monitoring period must be established within the DQOs of a regional or national synthesis of highway-runoff-quality data. For example, if the objective is to determine site-specific event mean concentrations (EMCs), then requirements for the sampling duration and number of samples collected may be less than if the DQOs also require the detection of trends with time.

A data set that is complete contains enough representative information to characterize the uncertainties in the data and resultant interpreted values. Generally, the number of samples required to estimate the mean of a population depends on the variability of the data and the allowable uncertainty of the estimate defined by the DQOs of the study (Norris and others, 1990; U.S. Department of Agriculture, 1996). More specifically, Thomson and others (1997) analyzed highway-runoff-quality data (collected by the Minnesota Department of Transportation from June 1981 to November 1983) from 69 rainstorms, 34 snowmelt events, and 27 mixed storms (rain and snow) to determine the sample sizes needed for characterizing pollutant concentrations in highway runoff. Thomson and others (1997) used several methods for randomly selecting different numbers of EMCs from individual storms to estimate the mean EMC for this site. They determined that more than 15 sampling events were necessary to characterize site specific EMCs for total suspended solids, total volatile solids, total dissolved solids and zinc concentrations. They also discovered that it was necessary to obtain more than 15 samples representing each season for constituents potentially affected by seasonality. For example, in their analysis of total dissolved solids, it was necessary to sample more than 40 events when all three storm types were combined in one population (because of the effect of road salt on the population); but when the rain, snowmelt, and mixed storms were segregated, these populations could be individually characterized by sampling about 15–20 events. Detection of trends, however, depends on the magnitude of the trend and generally requires many more samples over a longer period of time than does estimation of a mean (Norris and others, 1990; U.S. Department of Agriculture, 1996). Therefore, collection of data from more than 15 storms over a period of at least two years may be considered necessary to characterize runoff quality at a given site with respect to the DQOs for a regional or national runoff characterization study (Dionne and others, 1999). If the objectives include characterization of both current conditions and of trends with time, however, a program with different monitoring periods may be necessary. For example, the USGS NAWQA program commonly alternates two or more 3- to 7-year periods of intensive data collection and analysis with 5- to 6-year periods of less intensive study and monitoring in order to assess both current conditions and trends with time (Hirsch and others, 1988).

A comprehensive analysis of the temporal information documented in the 218 detailed reports indicates that most of the available information in the storm-water-monitoring literature may not meet the DQOs for regional or national synthesis. Many studies did not collect sufficient data to characterize the population of water-quality data at each site. Only about 37 percent of the detailed reports document sampling more than 15 events (fig. 27*A*). About 46 and 21 percent of reports document monitoring durations of more than one year and more than two years, respectively (fig. 27*B*). Among the detailed reports, representation by season was fairly uniform as indicated by the monthly distribution of documented sample collection dates (fig. 27*C*). About 30 percent of the reviewed reports document sampling efforts within each month. The months in which samples were collected, however, is not documented in 41 percent of the detailed reports

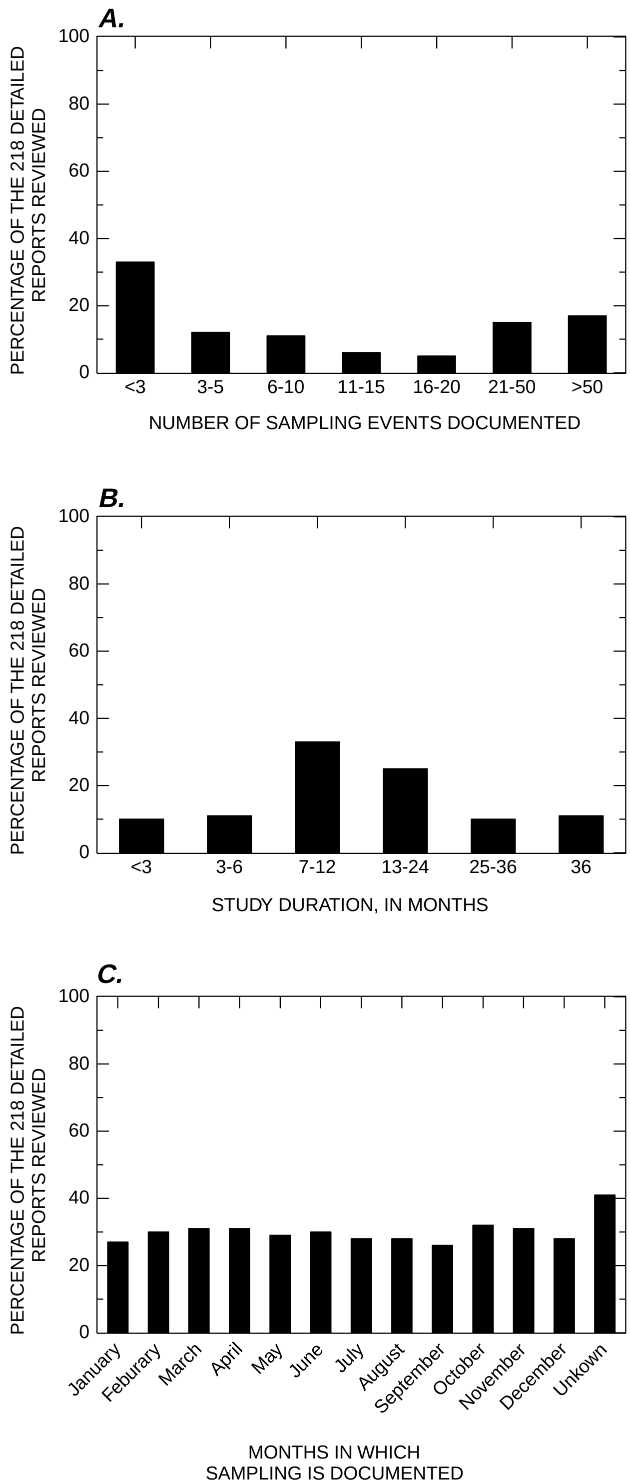

Figure 27. Proportion of the 218 detailed reports that document (*A*) the number of sampling events, (*B*) the study duration in months, and (*C*) the months in which sampling activities occurred.

that were reviewed. Although it may be presumed that most sampling was done during rainstorms, most of the available literature does not explicitly define storm type; only about 21, 6, and 4 percent of reports specify that samples were collected during rain, snow, and snowmelt events, respectively.

The duration of the antecedent dry period is commonly considered an important temporal variable (Young and others, 1996; Tasker and Granato, 2000). Constituents may build up on the roadway during the antecedent dry period. Constituents also may be reduced by evaporation and removal by vehicle-induced wind forces, which may cause a condition of dynamic equilibrium in the accumulated materials after an initial build-up period (Colman and others, 2001). Only about 27 percent of the 218 detailed reports, however, document the antecedent dry period.

Precipitation and Flow Monitoring

Precipitation and stormwater-flow data are crucial for use of individual highway- or urban-runoff study results and for a regional or national synthesis of stormwater-runoff data (Church and others, 1999). Decisionmakers need precipitation and flow data at monitored sites in order to develop water-quality models for predicting concentrations, loads, and potential effects of runoff constituents at unmonitored sites from site characteristics and available precipitation records (Tasker and Granato, 2000). Precipitation and flow monitoring information should include:

- the place in the drainage system where precipitation and stormwater flows are measured,
- the frequency of precipitation and flow measurements;
- the methods used to measure precipitation and flows, and
- the basis for monitoring decisions.

Decisionmakers and others must have this information in order to evaluate the accuracy and representativeness of precipitation and stormwater-flow data (Church and others, 1999).

About 52 percent of the 252 reviewed reports included some precipitation and flow-monitoring information. Flow data are documented as being estimated in about 3 percent of all reviewed reports. These estimates commonly were made from site characteristics and (or) generalized information about average precipitation or stream flows in the area. For example, the national precipitation and streamflow maps provided by Driscoll and others (1990a) may have been used to estimate precipitation and flow at a study site. Flow data are calculated from measurements made at the monitoring site in about 4 percent of the reviewed reports. A calculated flow may be derived from measurements of precipitation and stage (water level) that were used in conjunction with a theoretical or empirical equation without site-specific verification. Quantitative flow measurements are reported in about 45 percent of the reviewed reports. A measured flow, for example, may include measured water-level data and concurrent velocity measurements that are used to develop a site-specific rating curve.

About 56 percent of the 218 detailed reports included some information about precipitation and (or) flow. Figure 28 indicates the availability of information about different types of flow information. Because the purpose and scope of the NDAMS investigation is to assess available information for regional or national characterization of surface runoff, the apparent lack of information for the unsaturated zone and ground water may not represent the potential availability of such information in the literature. The study of evaporation may be important for the quantification of the mass balance of precipitation and constituents from atmospheric deposition on the highway (Coleman and others, 2001). Evaporation data, however, was not included among the detailed reports that were

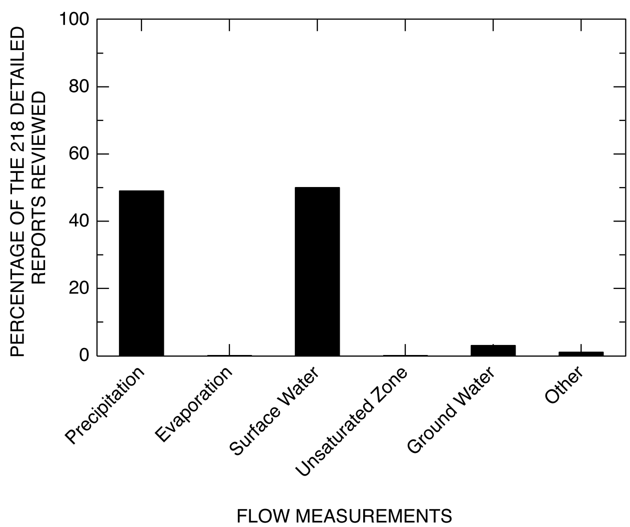

Figure 28. Proportion of the 218 detailed reports that document flow monitoring.

reviewed. Precipitation or surface-water flow information is available in about 50 percent of the detailed reports. Most of these reports (about 45 percent of the detailed reports) contain both precipitation and surface-water flow information (fig. 29).

A more comprehensive analysis of the precipitation and surface-water flow information in the 218 detailed reports, however, indicates that much of this data may not meet the DQOs for regional or national synthesis described by Church and others (1999). For example, Church and others (1999) indicate that the distance between the water-quality sampling site and the precipitation- and flow-measurement stations is important because of the potentially large variations in measured precipitation and flows with distance for highway- and urban-drainage sites. Only about 16 percent of the detailed reports indicate the relative proximity of water-quality, precipitation, and flow measurement stations.

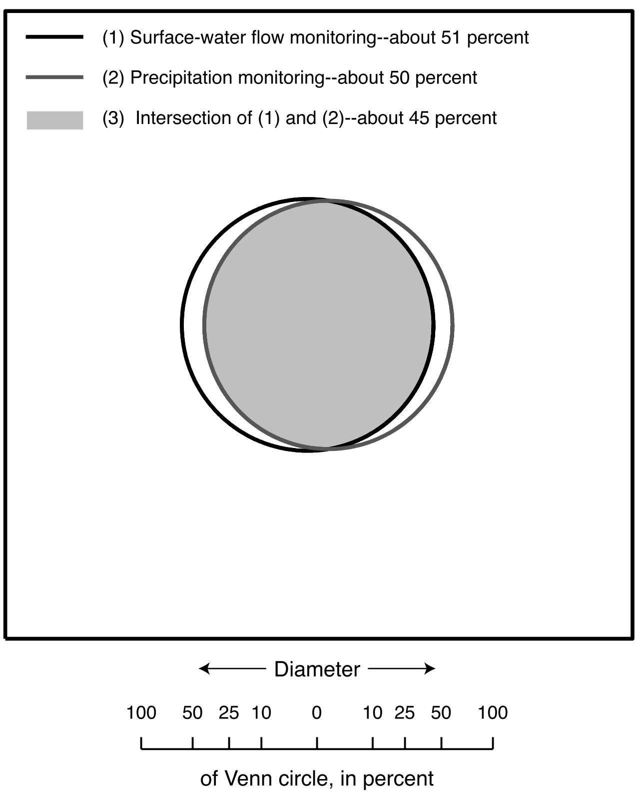

Figure 29. Percentages of the 218 detailed reports reviewed that document efforts to measure surface-water and precipitation.

Metadata necessary for evaluation and use of precipitation data for regional or national synthesis include the type of precipitation measured, the source of precipitation data, the distance from the water-quality monitoring station to the precipitation monitoring station, the type of precipitation measurements collected, and the monitoring method used (Church and others, 1999). Figure 30*A* indicates that most reports document precipitation as rain, but other forms of precipitation are rarely documented. This is probably because it may be more difficult to measure snow and ice at remote highway-monitoring stations (Church and others, 1999). Figure 30*B* indicates the percentage of detailed reports that identify the source of precipitation information. About 38, 11, and 4 percent of detailed reports indicate that precipitation data was obtained by the researchers at one study site, from one or more precipitation gages in a preexisting measurement network, or from one or more gages in a project-related measurement network, respectively. About 5 percent of the reports have precipitation information, but do not identify the source. Figure 30*C* indicates the distance between the precipitation measurement stations and the water-quality monitoring station. About 14, 2, 4, and 1 percent of reports provide documentation indicating that the precipitation monitoring station(s) were within 1,000 ft, between 1,000 ft and 1 mi, between 1 and 10 mi, or were greater than 10 mi from the water-quality monitoring station, respectively. About 31 percent of the reports have precipitation information, but did not identify the distance between the water-quality monitoring station and the precipitation monitoring station(s).

Information about the total precipitation and the intensity of precipitation are important for characterizing the rainfall-runoff processes that affect the concentrations and loads of runoff constituents. For example, two storms may have the same total precipitation and the same duration, but in-storm variations in precipitation intensity may substantially affect the mobilization of runoff contaminants (Church and others, 1999). About 17 and 1 percent of detailed reports document precipitation totals or intensity, respectively. About 23 percent of detailed reports provide both precipitation totals and intensities (fig. 30*D*). About 7 percent of the detailed reports state that precipitation was measured but do not state whether totals or intensities were measured.

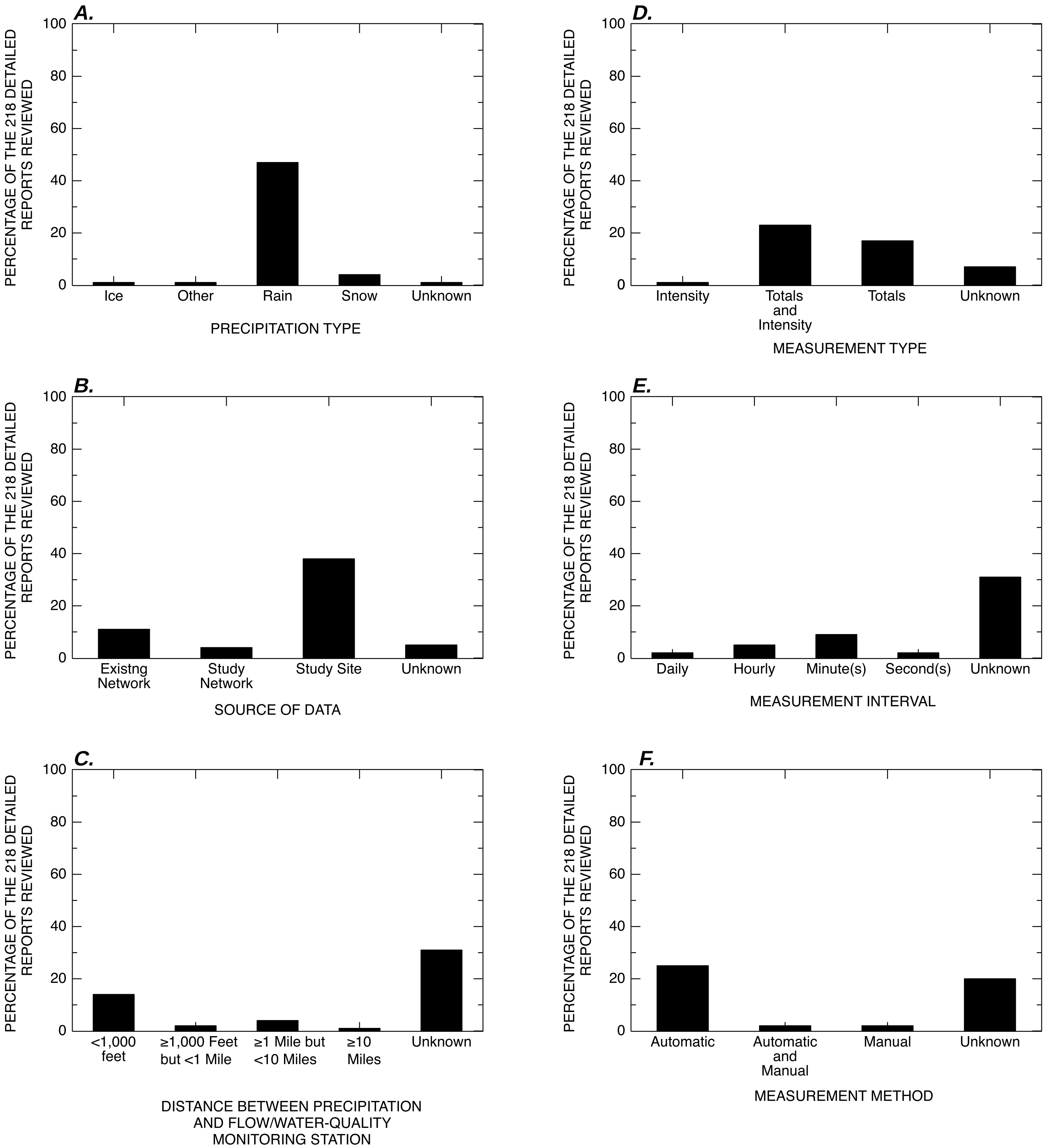

Figure 30. Proportion of the 218 detailed reports that document precipitation monitoring metadata including (*A*) the type of precipitation monitored, (*B*) the source of precipitation data, (*C*) the distance between the precipitation and surface water monitoring stations ,(*D*) the type of measurements recorded, (*E*) the measurement interval, and (*F*) the measurement method.

The comparability and usefulness of precipitation data depends on the measurement interval used to record precipitation and flow data (Church and others, 1999). Generally, finer time resolution is preferred because, for example, data recorded with a measurement interval of a minute can be used to calculate hourly and daily data, but synthesis of detailed data from long measurement intervals may introduce considerable uncertainties. About 2, 9, 5, and 2 percent of detailed reports document precipitation measurement intervals of seconds, minutes, an hour, or a day, respectively (fig. 30*E*). About 31 percent of the detailed reports state that precipitation was measured, but do not provide enough information to determine the precipitation measurement interval.

It is also necessary to know how precipitation measurements were made (Church and others, 1999). Automatic precipitation-monitoring equipment, if properly emplaced, calibrated and programmed, generally provides the most reliable record of precipitation measurements at regular time intervals. Supplementary manual measurements, however, are necessary to periodically evaluate the performance of the automated system. About 25, 2, and 2 percent of detailed reports describe automated, manual, or automated and manual measurements, respectively (fig. 30*F*). About 20 percent of the detailed reports indicate that precipitation was measured, but do not describe how the data were collected.

Metadata necessary for evaluation and use of surface-water flow data for regional or national synthesis include channel type, type of measurement, and the rating development methods (Church and others, 1999). About 13, 11, 8, and 2 percent of the detailed reports document measurement of flow in engineered channels, in pipes, as sheet-flow on the pavement, or in swales, respectively (fig. 31*A*). About 7 and 5 percent of the detailed reports document measurement of flow in streams or rivers, respectively. About 11 percent of the detailed reports document measurement of flow but do not document the channel type. The proper flow-measurement method for a given site depends on the channel type, and information about flow measurement methods is also critical. About 24, 17, and 8 percent of the detailed reports document measurement of stage, discharge, or velocity, respectively (fig. 31*B*). About 3, 3, and 9 percent of the detailed reports document the development of a site rating [a relation between flow volume and measured stage and (or) velocity] using

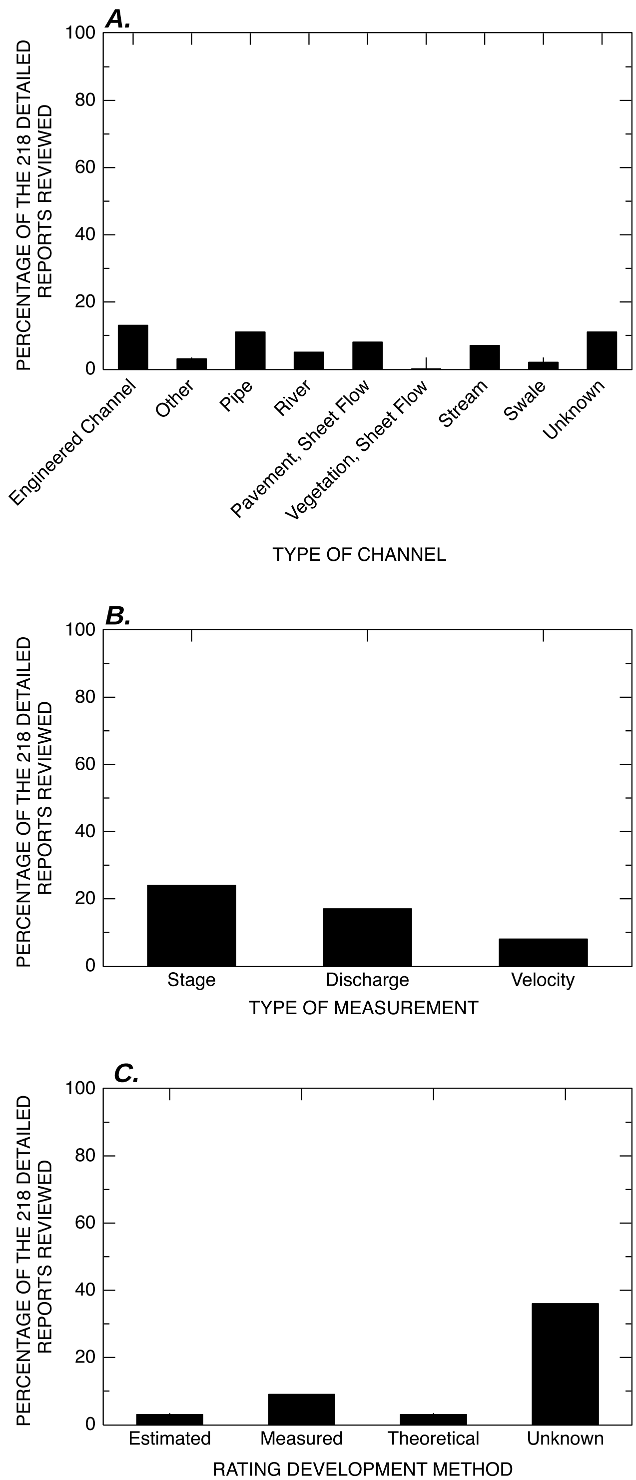

Figure 31. Proportion of the 218 detailed reports that document surface-water flow information including (*A*) the channel type, (*B*) the type of measurements made, and (*C*) the method used to develop a site-specific rating.

theoretical methods, estimate methods, or actual measurements, respectively (fig. 31*C*). About 36 percent of the detailed reports document measurement of flow but do not document flow-rating information. About 3 percent of the detailed reports document verification of a rating by an independent method (such as the dilution methods described by Church and others, 1999). Existence of a stable hydraulic control is an important factor for establishing a unique stage-discharge rating (Church and others, 1999). About 30 percent of the detailed reports document some type of hydraulic control on-site.

Metadata documenting data-quality indices are also necessary for evaluation and use of surface-water flow data for regional or national synthesis. Data-quality indices for measurement and interpretation of stormwater flows include the type of instruments used and the maintenance and calibration of these instruments (Church and others, 1999). About 22 percent of the detailed reports document the type of instruments used to measure flow. Automated monitoring systems with high measurement frequencies are considered necessary in order to characterize rapidly changing stormwater flows (Church and others, 1999). About 10 and 7 percent of detailed reports document use of automated systems and the measurement frequency, respectively. Information about system maintenance and calibration ranges is much less common, however; only about 6 and 2 percent of detailed reports document these data-quality characteristics, respectively. Also, only about 1 percent of detailed reports document the expected accuracy and precision of measured flow values.

Data Quality

Data-quality information is necessary to 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 (Granato and others, 1998). Documentation of basic information, such as compatible monitoring objectives, program design features, and metadata (for example, when, where, and how data were collected as well as who collected and analyzed the data) provides information needed to interpret results. 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. Water-quality data that are documented to be meaningful, representative, complete, precise, accurate, comparable, repeatable, and admissible as legal evidence will meet the scientific, engineering, and regulatory needs of highway agencies (Granato and others, 1998; Jones, 1999).

Water-Quality Monitoring and Sample-Collection Methods

Information about water-quality monitoring and sample-collection methods is necessary to document the quality and comparability of data used in a regional or national synthesis program. Sample integrity depends upon the documented use of proper methods for monitoring water quality and for collection of samples from runoff and receiving waters. Monitoring and sampling methods may substantially affect measurements of most constituents of concern, including major constituents and other water-quality properties that control the geochemistry of runoff and receiving waters (Bricker, 1999), sediments (Bent and others, 2001), trace elements (Breault and Granato, 2000), and organic chemicals (Lopes and Dionne, 1998) in runoff and receiving waters. Monitoring and sampling methods also affect measures of the potential for ecological effects from runoff constituents in receiving waters (Buckler and Granato, 1999). Documented water-quality-monitoring methods are necessary to assess the comparability of the data and overall data quality, as well as to identify explanatory characteristics (Dionne and others, 1999). Data sets may not be comparable unless it has been demonstrated that the different methods used to collect data from the different studies produce equivalent results. Documentation of performance measures for methods indicates that available data are of a known quality and that the research team was aware of the factors important to the data-collection process. When methods are properly documented, the data collected can be explained and related to other data sets in a quantitative manner.

The comparability, quality, and interpretation of water-quality data depend on the design and implementation of the monitoring program. The design of sample-collection efforts will influence how well a data set may characterize the system under study. About 55 percent of the 218 detailed reports document a program in which each storm during the study period was sampled. Other reports document periodic (about 21 percent), random (about 4 percent), or some other (19 percent) sampling designs. About 10 percent do not provide enough documentation to assess the general sampling design.

Continuous monitoring of flow and water-quality properties is critical for understanding rainfall/runoff/wash-off processes and these records are necessary for determining quantitative pollutant loads (Fisher and Katz, 1984; Spangberg and Niemczynowicz, 1992; Church and others, 1996; Granato and Smith, 1999; Church and others, 1999, Bent and others, 2001). About 23 percent of the detailed reports document continuous water-level monitoring in relation to the sample-collection efforts. About 11 percent document continuous water-quality monitoring in relation to the sample collection efforts.

Historically, both manual and automatic sampling methods have been used in stormwater studies. Spatially-integrated manual-sampling methods are preferred for receiving waters because of the expected spatial variation in concentrations of sediment and other runoff constituents in the water column. Manual stormwater-sampling may be sufficient in receiving waters of a larger drainage basin because the longer time of concentration allows for mobilization of personnel for representative sampling during a storm. In small highway and urban drainages, however, obtaining samples that represent the entire hydrograph during a storm can be difficult unless automatic sampling methods are used (Lopes and Dionne, 1998; Church and others, 1999; Breault and Granato, 2000; Bent and others, 2001). Uncertainties in the date and time of the onset of precipitation and resulting runoff, and the extremely short times of concentration for these systems, commonly preclude representative manual-sampling efforts. About 61, 41, and 22 percent of the detailed reports document use of manual, automatic, and manual and automatic sampling methods, respectively (fig. 32*A*). About 21 percent of the detailed reports do not document the sample-collection methods. To characterize the initial runoff from these highway- and urban-runoff catchments, the USEPA (1992) requires first-flush sampling for some regulatory monitoring efforts. In comparison, about 23 percent of the detailed reports document first-flush sampling efforts.

Knowledge of the sample type (discrete or composite spatial and temporal sampling methods) is also necessary to establish the comparability of data from different sources. Detailed, discrete data can be used to estimate runoff processes within storms and can be used to estimate storm loads and EMCs. The high cost of sample analysis, however, commonly precludes discrete sampling for many studies, so a single EMC is determined from a composite sample. The measured EMC may be affected by the sample-collection and compositing protocols used. Time-based protocols include methods for time- and flow-weighted compositing of samples from the same site. Time-weighted compositing is the combination of samples collected during a storm at preset time intervals. Flow-weighted compositing is the combination of samples collected at preset flow intervals (which are commonly at variable time intervals). Flow-weighted compositing methods are the most representative time based protocol for producing storm-event composite samples (USEPA, 1992). About 63, 32, and 17 percent of the detailed reports document use of discrete, composite, and discrete and composite time-based sampling protocols, respectively (fig. 32*B*). Samples also may be composited in space; for example, when several samples are collected at different points in the cross section of flow, or from different sites are combined for analysis. About 74, 9, and 6 percent of the detailed reports document use of discrete, composite, and discrete and composite space-based sampling protocols, respectively (fig. 32*C*). Unfortunately, however, only 24 percent of detailed reports document compositing protocols, with about 14, 10, and 2 percent of detailed reports documenting automatic, manual, and automatic and manual sample compositing methods, respectively (fig. 32*D*).

The materials used to collect and composite samples may affect measurement of trace elements (Breault and Granato, 2000) and organic chemical concentrations (Lopes and Dionne, 1998) in runoff samples. As such, sampling materials should be documented as part of the sample-collection protocols. About 60 percent of the detailed reports provide information about collection materials.

Sample-Handling Methods

Information about field and laboratory sample-handling methods is necessary to document the quality and comparability of data used in a regional or national synthesis program. This information includes documentation of sample collection, processing, shipping, and analysis methods with respect to commonly accepted sample-handling protocols (Dionne and others, 1999). Sample integrity depends upon proper and timely sample-handling methods for monitoring

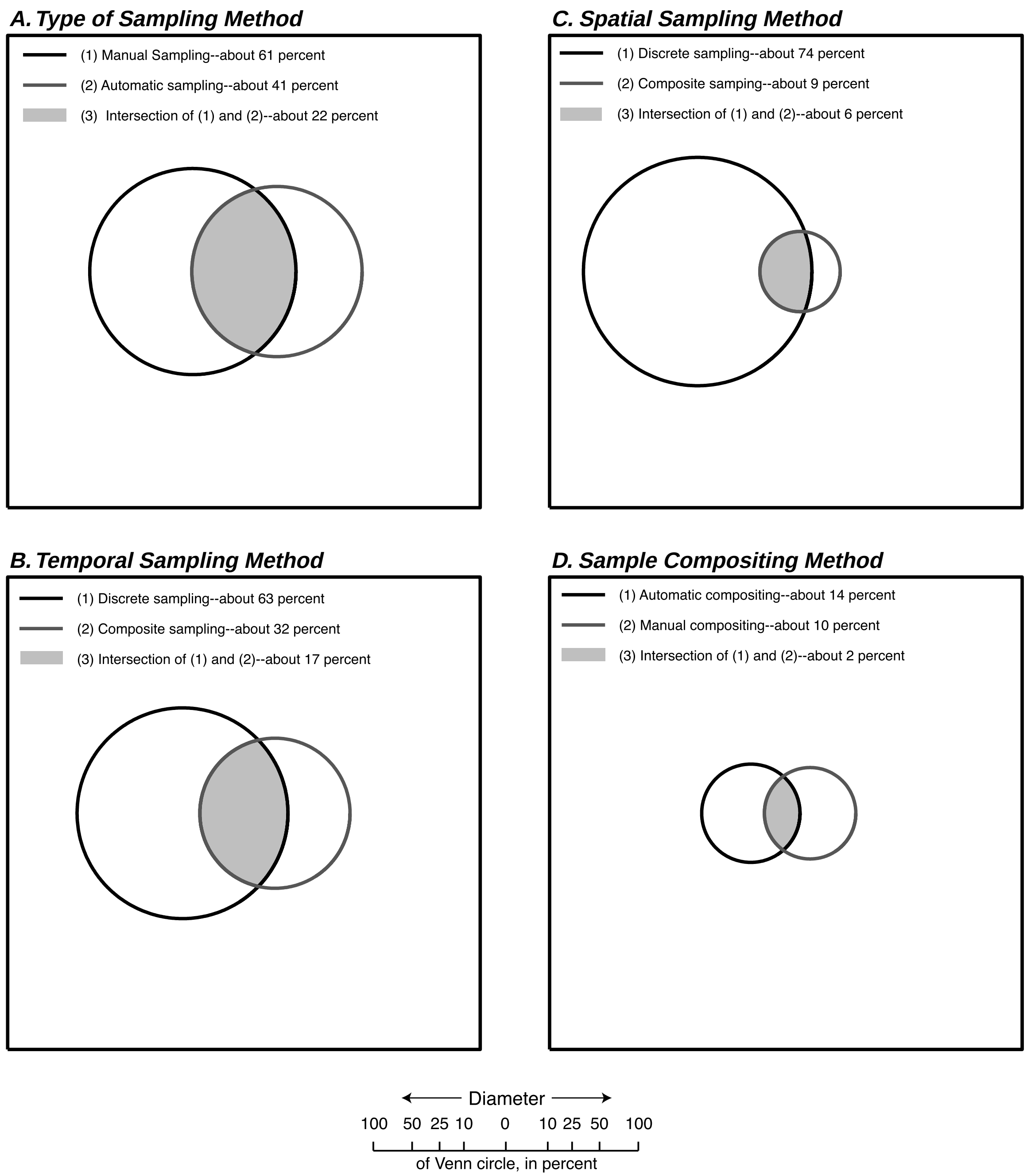

Figure 32. Percentages of the 218 detailed reports reviewed that document sampling methods including the: (*A*) type of sampling method, (*B*) the temporal sampling method, (*C*) the spatial sampling method, and (*D*) the sample compositing method.

most constituents of concern, including the geochemistry of runoff and receiving waters (Bricker, 1999), sediments (Bent and others, 2001), trace elements (Breault and Granato, 2000), organic chemicals (Lopes and Dionne, 1998), microbial indicators (Francy and others, 2000), and the potential for ecological effects on receiving waters (Buckler and Granato, 1999). The effects caused by differences in handling methods can overshadow the real deviations caused by the explanatory variables (ITFM, 1995a). Upon collection, a sample starts to undergo biological, chemical, and physical changes almost instantly (Brown and others, 1970; USEPA, 1992). The quality of the data depends on minimizing and documenting these changes (Jones, 1999). Adverse changes in samples can be minimized in a variety of ways, including chilling samples, the addition of preservatives, selection and use of standard processing materials of known composition and purity, and controlling and documenting sample-holding times. Legal requirements for sample handling may include chain-of-custody documentation and analysis by certified analytical laboratories (USEPA, 1992).

Information about sample-handling methods was examined in the metadata review (Dionne and others, 1998). Sample-handling methods are not documented in many of the 218 detailed reports that were reviewed. About 13 percent of the detailed reports document methods used to homogenize samples prior to splitting and (or) compositing aliquots used for analysis of stormwater constituents. About 39 percent of detailed reports document use of sample-preservation methods. About 20 and 29 percent of the reports document sample-processing methods that were used in the field or in the laboratory, respectively. About 14 and 11 percent of the detailed reports document the shelf life between sample collection and analysis under field and laboratory conditions, respectively. About 6 percent of the detailed reports document use of chain-of-custody protocols. About 38 percent identify the laboratories that were used, but only 16 percent indicate that the laboratories were certified by the USEPA or some other laboratory-evaluation organization.

Quality Assurance and Quality Control

Data are useful for a regional or national synthesis only if the data are collected and analyzed in a consistent manner that is well documented and accepted by the scientific and regulatory communities. Documented QA/QC programs are necessary to ensure that field and laboratory methods for runoff-monitoring programs will yield data that is meaningful, representative, complete, precise, accurate, comparable, repeatable, and admissible as legal evidence (FHWA, 1986; Jones, 1999). Increasingly, data collected for regulatory purposes must be accompanied by sufficient QA/QC documentation to establish the adequacy of the data. Regulators commonly expect the QA/QC documentation to be transmitted as a readily-identifiable section or appendix in published reports of investigations (USEPA, 2000a). More specifically, QA/QC documentation is considered necessary for the collection and reporting of runoff data for precipitation and flow (Church and others, 1999); geochemical indicators (Bricker, 1999); sediment (Bent and others, 2001); trace elements (Breault and Granato, 2000); organic chemicals (Lopes and Dionne, 1998); microbial indicators (Francey and others, 2000) measures of the potential ecological effects of runoff (Buckler and Granato, 1999); and monitoring of atmospheric deposition (Colman and others, 2001). Documentation of QA/QC criteria in the data collection, processing, and interpretation efforts can determine whether models and interpretations based on the data will be admissible in a regulatory framework and as legal evidence (Tasker and Granato, 2000).

Production of defensible data requires a comprehensive and orderly quality system that integrates field and laboratory efforts throughout the complete life cycle of a runoff-quality monitoring project (Jones, 1999). About 33 percent of the 252 reviewed reports refer to at least one element of a QA/QC program. Specifically, about 30, 27, and 20 percent of the 218 detailed reports refer to at least one element of a QA/QC program for laboratory, field, or laboratory and field efforts, respectively (fig. 33). Plans to implement quality systems are considered to be a necessary component of QA/QC efforts. Quality plans include overall management plans for organizations such as analytical water-quality laboratories, and more specific quality-assurance project plans (QAPPs) for individual monitoring projects (Jones, 1999; USEPA, 1998; 2000a). About 8, 5, and 3 percent of the detailed reports indicate that some type of laboratory, field, or laboratory and field quality-management plan was in use during the study, respectively. Publication of quality plans is necessary if data from site-specific studies will later be aggregated from different sources for a regional or national synthesis. About 4, 2, and less than 1 percent of the detailed reports indicate that a quality plan had been published for laboratory, field, or laboratory and field efforts, respectively.

A number of QA/QC activities are necessary to establish, measure, and document the performance of field analysis, sample collection, and processing activities (Jones, 1999). Defensible measurements of trace elements (Breault and Granato, 2000) and organic chemicals (Lopes and Dionne, 1998) depend on documented QA/QC efforts to demonstrate that samples are not substantially biased by field and laboratory operations. Various QA/QC measures are designed to

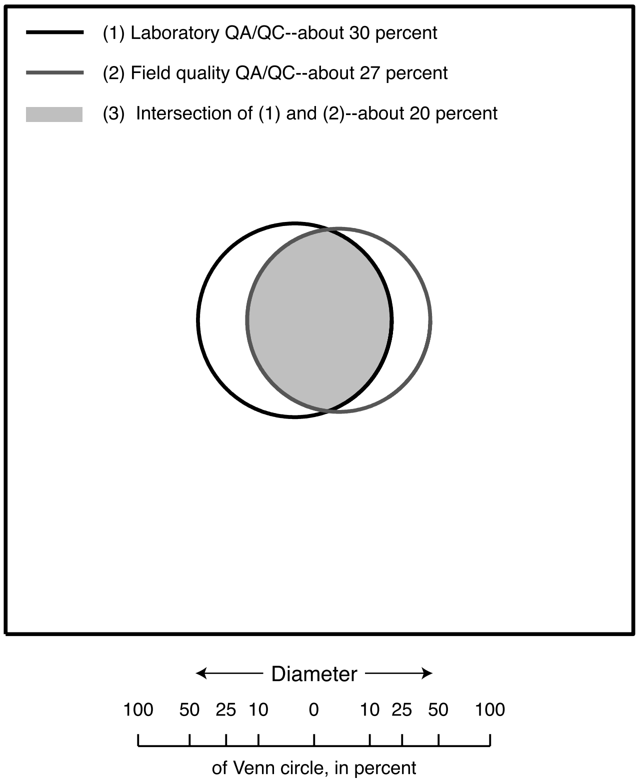

Figure 33. Percentages of the 218 detailed reports that document laboratory and (or) field QA/QC efforts.

address different problems and the measures used in any given study depend on the sampling methods used, the DQOs of the study, and known or potential problems in sample-collection, -handling and -analysis methods (Jones, 1999). About 6 percent of the detailed reports document QA/QC efforts to ensure that field-measurement instruments were operating properly. About 7, 6, and 1 percent of detailed reports include QA/QC information to ensure that sampling equipment, sampling containers, or filters, respectively, did not affect measured concentrations of runoff constituents. About 2 percent of detailed reports document the use of controlled (noncontaminating) preservatives to fix sample chemistry. Fewer than 1 percent of detailed reports document the use of blank samples to ensure the purity of the water used to clean equipment. Replicate sampling programs are designed to assess the repeatability of measurements and the potential for introducing substantial bias caused by field-sampling operations (Jones, 1999). It should be noted, however, that these measures also include the variability inherent in the laboratory analysis process. The types of replicates include submission of concurrent replicates to assess variability in the sample-collection process (about 5 percent), sequential replicates to assess the temporal variability of the system being sampled (about 1 percent), equipment replicates to assess variability in the performance of sampling equipment (about 2 percent), method replicates to assess variability in field methods (about 8 percent), and sampling-team replicates to assess variability in the team's collection, processing, and handling methods (about 1 percent of the detailed reports).

Runoff-quality investigations are highly dependent upon the integrity of the data produced by the laboratories that analyze environmental samples collected during a study. Assessment of the quality of laboratory analysis is a necessary component of the quality-audit process (Friedman and Erdmann, 1982; Pritt and Raese 1995; Glodt and Pirkey, 1998; USEPA, 1999; 2001b; Jones, 1999). The objective of quality assessment is to provide evidence that the laboratory measurement processes are under control. For example, the USGS's National Water-Quality Laboratory (NWQL) uses a three-tier approach to ensure the quality of laboratory data, including method-performance, data-review and blind-sample programs, and participates in performance-evaluation studies managed by local, State, or Federal agencies external to the NWQL (Pirkey and Glodt, 1998). About 16 and 3 percent of the detailed reports document laboratory method performance through method replicates and intralaboratory replicates, respectively. About 8 and 6 percent of the detailed reports document matrix or reagent spike samples, respectively. Blind samples are reference samples used to assess the actual bias and precision of analytical methods (Ludke and others, 2000). Blind samples are disguised as routine environmental samples to reduce the possibility that analysts will recognize them as quality-assurance samples. About 3 and 3 percent of the detailed reports document an internal or an external blind-sampling program, respectively. About 5 percent of the detailed reports document information indicating participation in an interlaboratory performance-evaluation program.

A number of QA/QC activities are necessary to establish, measure, and document the performance of laboratory operations (Jones, 1999). About 8 percent of the detailed reports document calibration of laboratory instruments and 14 percent document methods checks with standards. Only about 7 percent , however, document employment of methods to verify the purity of chemicals used in the analysis process. About 7 and 5 percent of reports document that samples met prescribed holding times and storage conditions prior to laboratory analysis, respectively. Finally, about 4 percent of the 218 detailed reports document assessment of data handling methods to ensure that the results of analysis were properly recorded.

Quality reviews (audits) by the organization collecting and (or) analyzing the samples, by the customer, and (or) by an independent auditor ensure that field, laboratory, and data-processing methods for runoff-monitoring programs are implemented properly according to established quality plans (Jones, 1999). About 3 and 4 percent of detailed reports document a quality-audit process for field and laboratory efforts, respectively. Additionally, about 4 percent document a technical-review process for field efforts and 3 percent document a data-verification program. About 8 percent of detailed reports document at least one component of a field-to-laboratory quality-assessment effort. These efforts include submission of split samples to assess analytical variability (about 6 percent), matrix spike (or synthetic) samples to assess analytical bias (about 5 percent), reagent spike samples to evaluate recovery of the analyte(s) (about 3 percent), and blind reference samples to assess analytical bias (less than 1 percent of detailed reports).

Uncertainty

Consideration of uncertainty (or error analysis) is essential to any decision-making process. Without knowledge of the uncertainty of an experimental result, it is impossible to judge the fitness of the value as a basis for making decisions relating to health, safety, commerce, or scientific excellence (National Institute of Standards and Technology, 2000). The total uncertainty is the sum of errors and losses of information 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 of sample collection, sample analysis, and data interpretation (USEPA, 1986; 2000c; 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 (Granato and others, 1998). The acceptable uncertainty of data and interpretations for a given problem must be evaluated in terms of the regulatory objectives, the decisions to be based on the data, and the possible consequences of making incorrect decisions (USEPA, 1986; 2000c). The total uncertainty increases when data from different reports are combined, because differences in analytical laboratories, methods, and the characteristics of pollutant sources through time are incorporated into the resultant data set. For example, Granato and others (1998) demonstrate that interlaboratory uncertainties can be more than four times the published accuracy of standard water-quality analysis methods. To support decisions, the level of total uncertainty from random and systematic error introduced into the different sampling processes must be less than the variability caused by differences from site to site and study to study.

Knowledge of the uncertainty of input data is necessary to define estimates from regional and national runoff-quality models that are used for the decision-making process (Tasker and Granato, 2000). Models, at best, are only as good as the uncertainty in the input data (Montgomery and Sanders, 1986). Furthermore, there is no guarantee that water-quality data, no matter how carefully collected, will be transferable to other areas and other circumstances (Sonnen, 1983). The success of a water-quality interpretive model depends on uncertain future meteorological, demographic, political, and technical conditions, all of which may affect the future costs and benefits of resulting highway-planning, -design, and -management decisions. If sensitivity analyses reveal unacceptable uncertainty in the predictions, new data and new methods may be needed, or safety factors based on prediction-interval estimates may be used. These criteria will also determine whether interpretations based on the model will be admissible as legal evidence. Classical statistical measures, however, cannot detect problems caused by unexpected uncertainty because statistical analysis is done under the assumption that the calculations are done correctly, that the correct model has been selected for the data, and that the data are representative of the environmental system under study. Decision errors can be easily made with faulty models because the results generated may appear to be more certain, more precise, and more authoritative than they really are when design assumptions and results (even realistic ones) are stated with illusive precision and seeming accuracy. To ensure that decisionmakers can assess uncertainty in the analytical tools, the modeling methods, and the underlying data set, the analyst must document and communicate each of these components in an accessible format within project publications (Tasker and Granato, 2000). These criteria will also determine whether interpretations based on the models developed will be admissible in a regulatory framework or as legal evidence when necessary.

Few of the reviewed reports address the issue of uncertainty in data collection efforts or model development. About 18 percent of all the 252 reviewed reports and about 15 percent of the 218 detailed reports address experimental uncertainty either qualitatively or quantitatively. About 11 percent of the 218 detailed reports express the uncertainty of one or more measurements or interpreted results quantitatively using percent errors, population statistics, and (or) tolerances (fig. 34). In the sample population of detailed reports, uncertainty is commonly expressed for the results of calculations (about 7 percent) or model results (about 3 percent). The uncertainty of field-instrument or analytical-laboratory measurements is documented in 2 and 4 percent of the detailed reports, respectively. Fewer than one percent of the reviewed reports document the uncertainty in terms of precipitation measurements, stage measurements, or other types of field methods. None of the detailed reports addresses the uncertainty in study results in terms of the representativeness of the study site or the reproducibility of flow-velocity measurements. Knowledge of the representativeness of data from individual study sites, however, is necessary to determine the minimum number of data

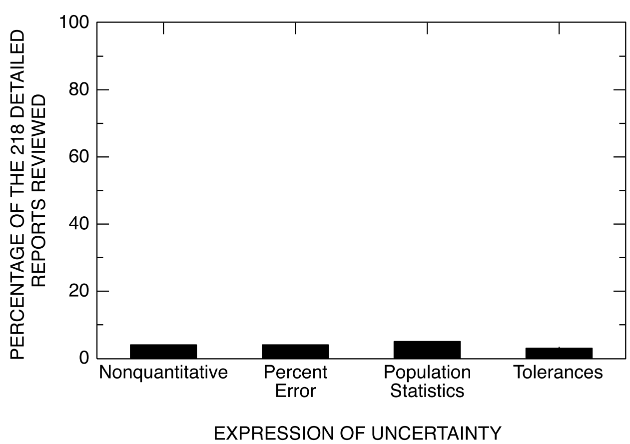

Figure 34. Proportion of the 218 detailed reports reviewed that document one or more aspects of an uncertainty (error) analysis.

collection sites required for a regional or national synthesis. For example, in a runoff study at three comparable sites along Route I-93 in Boston, Mass. (Smith, 2000), median intersite variations on the order of plus or minus 20 to 50 percent for sediment, iron, copper, lead, and zinc concentrations were recorded for 5 storms along this 2-mile section of highway (K.P. Smith, USGS, written commun., 2001).

DISCUSSION

Historically, highway-runoff studies have had diverse study objectives and monitoring goals, which impose different data and information requirements. As these study objectives and monitoring goals increase in complexity, the cost and data requirements increase and the level of acceptable uncertainty decreases (Granato and others, 1998). A regional or national synthesis requires robust data-evaluation criteria to ensure adequate representation of the different characteristics and natural settings of United States highways and maximum utility of data sets for scientific, engineering, and regulatory needs of highway agencies (Granato and others, 1998). 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 decisionmakers 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).

To demonstrate that water-quality data are valid and technically supportable, sufficient documentation must be available to illustrate that the data are meaningful, representative, complete, precise, accurate, comparable, repeatable, and admissible as legal evidence (Alm and Messner, 1984; FHWA, 1986; ITFM, 1995ab; USEPA, 1997). 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, Driscoll and others (1990a) noted the effect of a zinc smelting operation on highway-runoff quality at one site in their national synthesis. A representative data set accurately and precisely characterizes a population, a process, and water-quality variations at a study site. A complete data set contains enough representative information to characterize the uncertainties in the data and resultant interpreted values. Precision implies a high degree of repeatability for samples obtained under similar conditions. Accuracy implies a lack of systematic bias. 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. Environmental data sets are not repeatable in the sense that one may not recreate controlled conditions as is expected for laboratory work. To create repeatable environmental data sets it is necessary to completely document the sampling location, site characteristics, weather conditions, and the protocols used during the monitoring period. 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.

The choice of criteria for this national synthesis reflects the potential difficulties involved in combining data from diverse programs to develop a database that covers broad geographical areas and catalogs consistent and 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 the NDAMS project.

The types and importance of various environmental concerns and regulatory issues related to highway runoff vary among the States and regions of the Nation. These technical and regulatory complexities make it difficult to establish a uniform set of DQOs. It is, however, important to establish criteria that may be used in the data-evaluation process. These criteria also may serve as guidance for the planning, design, implementation, and documentation efforts when national planning and research resources are committed for runoff water-quality studies, so that research results will support regional and (or) national as well as local information needs.

Data-Quality Objectives

The USEPA has developed a DQO process as a systematic planning method for defining performance criteria to determine the type, quantity, and quality of environmental data needed to reach defensible decisions (USEPA, 2000c). DQOs are qualitative and quantitative statements that clarify study objectives, define the appropriate type of data, and specify tolerable levels of potential decision errors that will be used as the basis for establishing the quality and quantity of data needed to support decisions. To implement DQOs successfully, it is necessary to build a team that includes decisionmakers, technical experts, managers, data users (usually with some statistical expertise), a quality-assurance specialist, regulators, and stakeholders (USEPA, 2000c).

The formal USEPA DQO process includes seven steps, each of which is designed to define criteria that will be used to establish an appropriate data-collection design (USEPA, 2000c). These steps include (1) defining the problem, (2) specifying the decision, (3) identifying inputs to the decision, (4) defining the boundaries of the study, (5) developing a decision rule, (6) specifying tolerable limits on decision errors, and (7) optimizing the study designs for data acquisition. The outcome of the DQO process is a design for collecting data (for example, the number of samples to collect, and when, where, and how to collect samples) together with limits on the probabilities of making decision errors. The DQO process is designed to help weigh the costs of data acquisition against the consequences of a decision error caused by inadequate input data. The DQO process also can be used to help weigh the costs and benefits of local short-term monitoring requirements against regional and national long-term information needs (Granato and others, 1998).

Established DQOs are necessary to frame any discussion on the validity, representativeness, completeness, and technical defensibility of existing and future data. For example, a primary goal of runoff studies has been to "characterize highway runoff." In this quest, different studies have measured runoff on the pavement, in a drainage system, within a structural

BMP, and at an outfall. Sedimentation and geochemical processes are expected to affect the concentration and speciation of constituents as runoff flows from the pavement to receiving waters, and these effects are expected to vary widely from site to site depending on the physical, chemical, and hydraulic characteristics of the runoff, the pavement, and the drainage structure at each site (Breault and Granato, 2000). Also, samples collected in drainage structures commonly include runoff from shoulders and median strips, which may have different chemical characteristics than pavement runoff. As such, studies that characterize runoff collected on the pavement would be expected to provide the most consistent results for prediction of pavement runoff quality with a minimal number of sites and samples. Therefore, if the defined problem and decision is to characterize the quality of pavement runoff for national synthesis, then studies that collect samples on the pavement or at the entrance to catchbasins set in the pavement would be most appropriate. If, however, the problem and (or) the decision is focused on the performance of BMPs or the potential effect of runoff quality on receiving waters, then samples collected from drainage structures and at the outfall to receiving waters are necessary. Data from more sites and analysis of more samples at each site would be necessary to achieve the same level of uncertainty for these expanded DQOs, because of the differences in flow paths among sites and in processes that affect runoff quality in drainage structures along these flow paths (Tasker and Granato, 2000). If the question is regulatory compliance, then concentrations in water samples may be sufficient. If, however, the question is about the actual effect of runoff quality on the ecology of receiving waters, then sediment chemistry and direct biological measurements may be necessary (Buckler and Granato, 1999). These examples demonstrate how problem and decision identification affect the scope of the study, the decision rules, the limits on decision errors, and the study design in the DQO process.

Established DQOs, therefore, are necessary to determine quantitatively if the available highway-runoff quality data is sufficient for regional or national synthesis efforts (Granato and others, 1998). It is beyond the scope of the NDAMS project to establish DQOs for the Federal and State Transportation Agencies, Regulatory Agencies, and other public and private stakeholders. Furthermore, the types and relative importance of environmental concerns and regulatory issues differ among the States and regions of the nation. The NDAMS review process, however, was designed to provide the information necessary for decisionmakers to evaluate available highway-runoff data in terms of the DQOs that are formulated to define environmental-information needs.

The following examples illustrate the potential data availability for different hypothetical DQOs based on the results of the metadata review process. The availability of applicable information and data is based solely upon the first step of the DQO process (defining the problem). As the problems and decision rules are further defined by decisionmakers, it will be necessary to evaluate information and data in greater detail.

The physical focus (the type of site–or sites) documented as being sampled in a given report may be evaluated in terms of different DQOs. If, for example, the DQOs focus on potential effects of highway runoff in the coastal zone (FHWA, 2001), then about 1 percent of the 252 reviewed reports may provide information consistent with this issue (fig. 5*A*). DQOs that focus on watersheds may require highway-runoff information in relation to lakes or ponds and (or) rivers or streams, which are included in about 8 (fig. 5*B*) and 15 (fig. 5*C*) percent of the reviewed reports, respectively. Potential effects of highways on wetlands have, historically, been a topic of interest. About 4 percent of the reviewed reports had a physical focus that would address DQOs concerning this issue (fig. 5*D*). About 14, 13, and 3 percent of the 252 reviewed reports may be suitable to address DQOs that are based on a need for information about highway runoff and BMPs (fig. 5*E*), separate sewers (fig. 5*F*), or combined sewers (fig. 5*G*), respectively.

The hydrologic focus (the type of monitoring study based on the four major components of the hydrologic cycle—atmospheric deposition, surface water, the unsaturated zone and ground water) may be evaluated in an a similar manner for different DQOs. For example, to pose a model to predict the quality of highway runoff it may be necessary to monitor precipitation and runoff flows (Church and others, 1999) and to sample atmospheric deposition as well as highway runoff (Tasker and Granato, 2000; Colman and others, 2001). DQOs based on these information needs may include both surface-water and atmospheric-deposition data. About 22 percent of the 252 reviewed reports include both surface-water and atmospheric-deposition data as part of the hydrological focus (fig. 6*A*). DQOs that are focused on protecting drinking water supplies may require the monitoring of ground water as well as runoff, because many public water supplies utilize ground-water resources. About 6 percent of the 252 reports include both surface-water and ground-water information (fig. 6*B*), and about 3 percent of reports include atmospheric-deposition, surface-water, and ground-water information (fig. 6*D*). Potential effects of highways on agricultural land or roadside vegetation management issues (FHWA, 2001) may prompt DQOs to address uptake of runoff constituents by plant roots in the unsaturated zone. About 2 percent of reviewed reports include surface-water and unsaturated-zone data (fig. 6*C*).

The sampling matrix (the type of samples documented as being collected and analyzed) can also be pertinent to DQOs for highway-runoff studies. Concentrations of constituents from analyses of different sample matrixes are not directly comparable (Lopes and Dionne, 1998; Breault and Granato, 2000). DQOs for a BMP study may require sampling of runoff and sediments collected within the BMP structure to assess capture efficiencies and to meet regulatory requirements for disposal of the sediments collected (Shoemaker and others, 2000). About 29 percent of the 252 reviewed reports include analysis of water and sediment (fig. 7*A*) and therefore would be suitable for further evaluation based on these DQOs. The sampling matrix may be considered as part of DQOs established for creating a predictive model to assess relations between runoff quality, accumulation of runoff sediments in receiving waters, and measured biological responses. In a review of the literature pertaining to the potential effects of runoff on the ecology of receiving waters, Buckler and Granato (1999) discovered that although runoff was not typically toxic, measured effects on biological-community structures and elevated concentrations of runoff constituents in biological tissue were evident from samples collected near deposits of runoff sediments in receiving waters. Therefore, DQOs for assessing the potential effect of runoff on aquatic biota may include sampling of water and biota (about 11 percent, fig. 7*B*), sampling sediment and biota (about 14 percent, fig. 7*C*), or sampling water, sediment and biota (about 8 percent of the 252 reviewed reports, fig. 7*D*).

The class of runoff constituents documented as being sampled in a given report may also be evaluated in terms of the DQOs for regional or national synthesis. For example, three constituent classes—sediment, trace elements, and organic chemicals—are of regulatory interest in the monitoring of nonpoint discharges (USEPA, 1992) and may affect biota in receiving waters (Buckler and Granato, 1999). The DQOs for a given study may require the sampling of water, sediment, and (or) biota for analysis of these runoff-quality constituents. Table 3 is a contingency table, which indicates the availability of runoff-quality information documenting sampling of one or more matrixes and analysis of one or more constituent classes as a percentage of the 252 reviewed reports. Most of the reviewed reports document analysis of trace elements (about 74 percent), sediment and solids (about 67 percent), and (or) organic constituents (about 62 percent) in one or more environmental sampling matrixes

Table 3. Contingency table indicating the percentages of the 252 reports reviewed that document sampling of one or more matrixes and analysis of one or more constituent classes

[**Constituent class:** OC-organic compounds; SS-sediment and solids; TE, trace elements. **Analysis matrix:** Biological tissue samples would not be analyzed for sediment concentrations but concentrations of trace elements in biological tissues may, for example, be interpreted in terms of the grain-size distribution of bottom sediment collected with benthic organisms]

Constituent class	Analysis matrix							
	Unspecified	Water	Sediment	Biota	Water and sediment	Water and Biota	Sediment and Biota	Water, sediment and biota
TE	74	64	33	16	25	10	12	8
SS	67	62	30	10	25	7	9	6
OC	62	54	20	7	16	6	5	4
TE and SS	56	52	26	10	21	7	9	6
TE and OC	46	44	16	6	15	5	4	4
SS and OC	44	43	15	4	14	4	3	3
TE, SS, and OC	39	38	14	4	13	4	3	3

(fig. 10). Only about 3 percent of the 252 reviewed reports, however, include analysis of all three constituent classes from all three matrixes. Furthermore, table 3 does not necessarily indicate that all constituent classes were analyzed for each matrix, only that the subject reports included data for one or more constituent classes in each matrix (for example see the head note on table 3). Therefore, Table 3 demonstrates that the number of studies that meet a given set of DQOs decreases as information needs expand.

Geographic Assessment

It is necessary to consider the availability of data from different geographic areas to be included in a regional or national synthesis on highway-runoff quality. Variation in runoff fluxes and the potential effect of highway runoff on the local aquatic environment are expected to correlate with regional factors such as climate, hydrology and ecological habitat, as well as with site-specific factors such as traffic volume, extent of pavement, and right-of-way characteristics. For example, the application of road salts and friction materials in cold areas may substantially increase annual loads of dissolved and suspended solids and may alter local geochemical and ecological processes (Bricker, 1999). Organics may degrade and volatilize at substantially faster rates in regions with higher annual temperatures than in colder regions (Lopes and Dionne, 1998). In addition, atmospheric deposition--and related effects on runoff quality--varies substantially from site to site within the conterminous United States (Colman and others, 2001).

Examination of the NDAMS metadatabase for site information reveals that about 994 study sites are cataloged in the review process. Of these sites, 537 have unique latitude and longitude coordinates across the globe. This data set includes 452 sites in the United States and southern Canada (fig. 35*A*) that could be considered representative of sources and conditions in the conterminous United States (within a rectangle inscribed by latitudes 24 to 49 degrees north and longitudes 65 to 125 degrees west). Of the 537 unique study sites identified, there are 234 unique sites identified as highway sites worldwide, and 197 of these highway sites can be identified as representative of conditions in the conterminous United States (fig. 35*B*). The distribution of these monitoring sites among states and

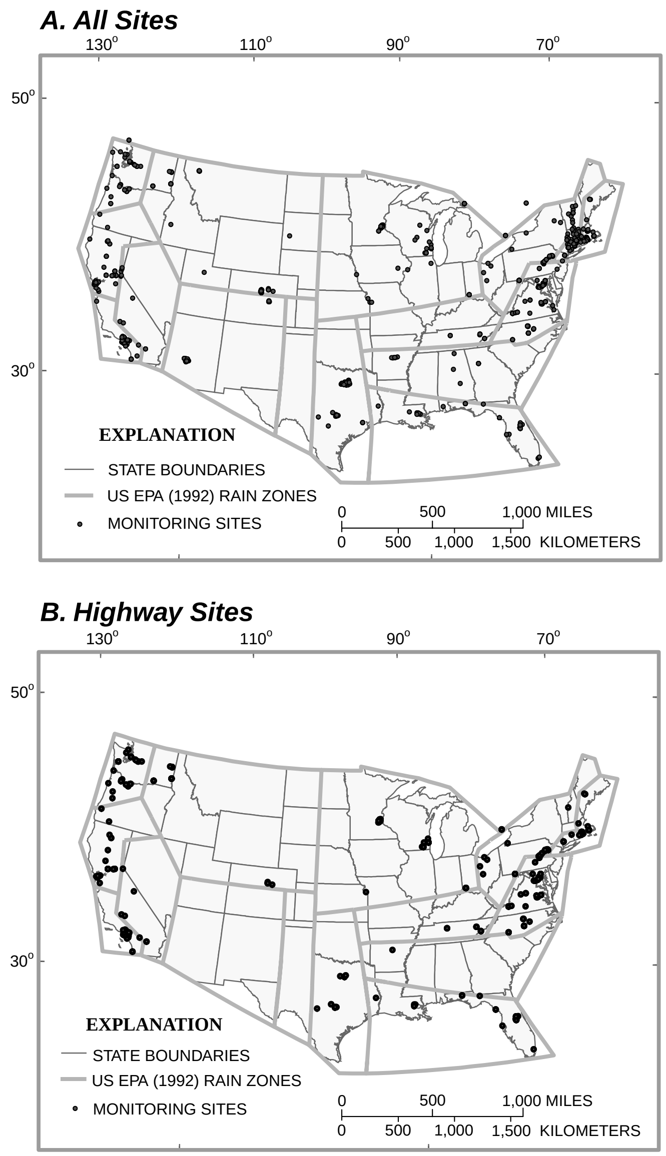

Figure 35. Distribution of (*A*) all sites and (*B*) all highway sites cataloged in the NDAMS review among the USEPA (1992) rain zones in the conterminous United States.

USEPA rain zones (areas with similar precipitation characteristics defined for NPDES sampling efforts; USEPA, 1992), however, is not uniform.

Geographic analysis of the availability and geographic distribution of existing information may reveal gaps in data for different DQOs. For example, the geographic distribution of information may be examined in terms of the sample matrixes, which are the focus of different studies and (or) at different sites across the nation. Figure 36 indicates the geographic availability of information from reports documenting sampling and analysis of the (*A*) water, (*B*) sediment,

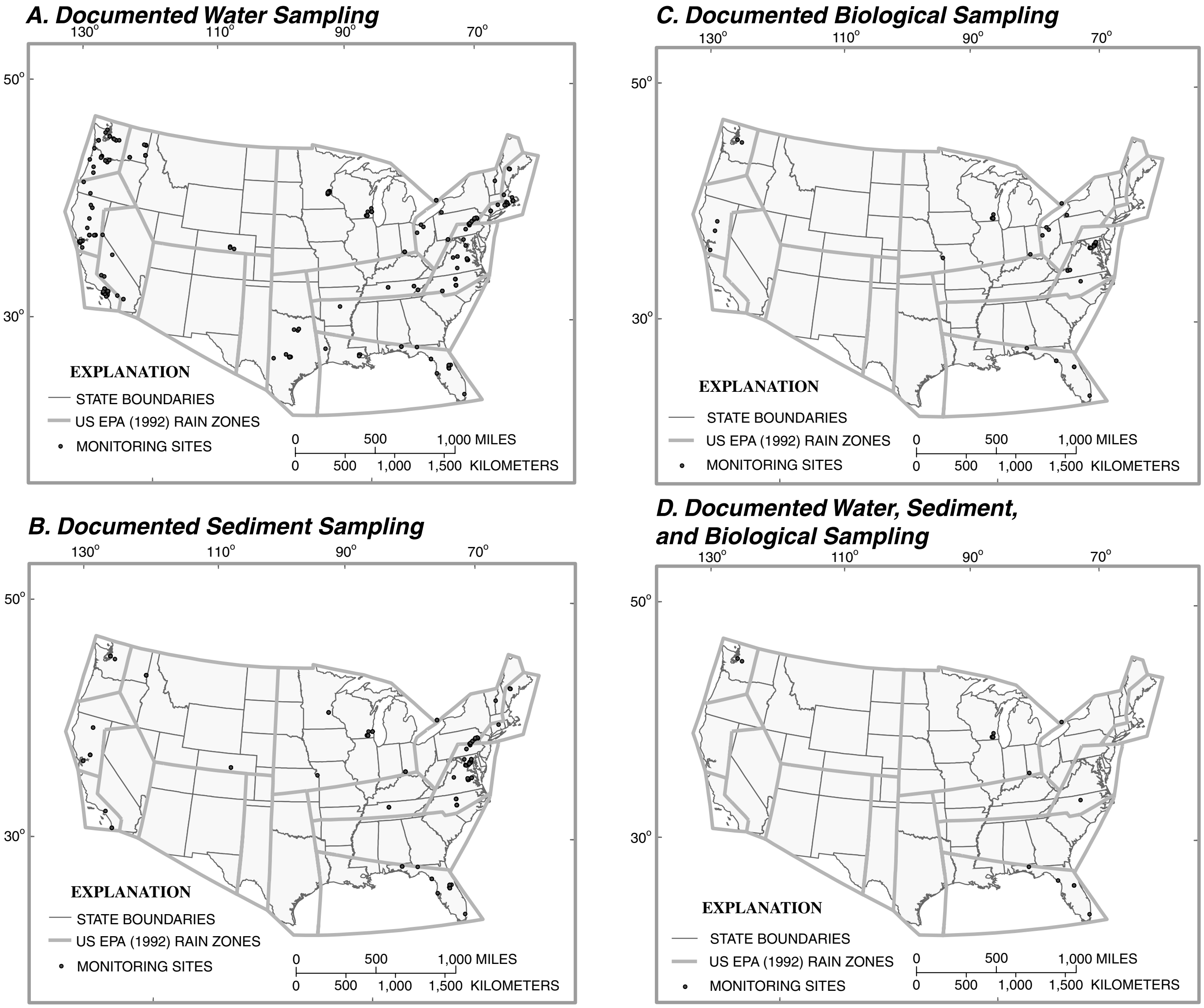

Figure 36. Distribution of highway sites with documented (*A*) water-sampling data, (*B*) sediment-sampling data (*C*) biological-sampling data, and (*D*) water-, sediment-, and biological-sampling data cataloged in the NDAMS review among the USEPA (1992) rain zones in the conterminous United States.

(*C*) biological, and (*D*) all three matrixes at highway-runoff monitoring sites in the conterminous United States and southern Canada. These maps indicate that water-quality-sampling efforts have been the primary focus of most highway-runoff reports, and that there also is geographically diverse sediment and biological data. Few reports, however, document sampling and analysis of water, sediment, and biological matrixes; information that may be necessary for understanding how runoff quality affects biota in receiving waters (Buckler and Granato, 1999).

The quality of available information and data as well as the format of such data are also considerations when compiling a national runoff-quality dataset. Precipitation and o w data are necessary to relate hydrologic conditions at a study site to runoff quality and potential effects of runoff on the quality and ecological health of receiving waters (Church and others, 1999; Buckler and Granato, 1999). QA/QC information is currently considered a fundamental component of a technically defensible dataset (Jones, 1999). Furthermore, availability of reliable runoff-quality data in an electronic format is necessary to facilitate future use and interpretation of data collected (Tasker and Granato, 2000). For example, Driscoll and others (1990a) and Thompson and others (1996) indicate the substantial difficulties involved in the collection, examination, quality assurance, quality control, and computer entry of historical runoff data in their efforts toward local, regional, and national interpretation of highway-runoff data. In comparison, Driver and Tasker (1990) were able to assemble a much larger National Urban Runoff Program (NURP) dataset from the USGS and the USEPA with less effort because these programs were supported by quality-assurance and quality-control measures and the data were stored in readily available national water-quality databases. Figures 37–42 indicate the availability of analytical data for deicers, nutrients, sediment, trace elements, organic compounds, and biological parameters in the

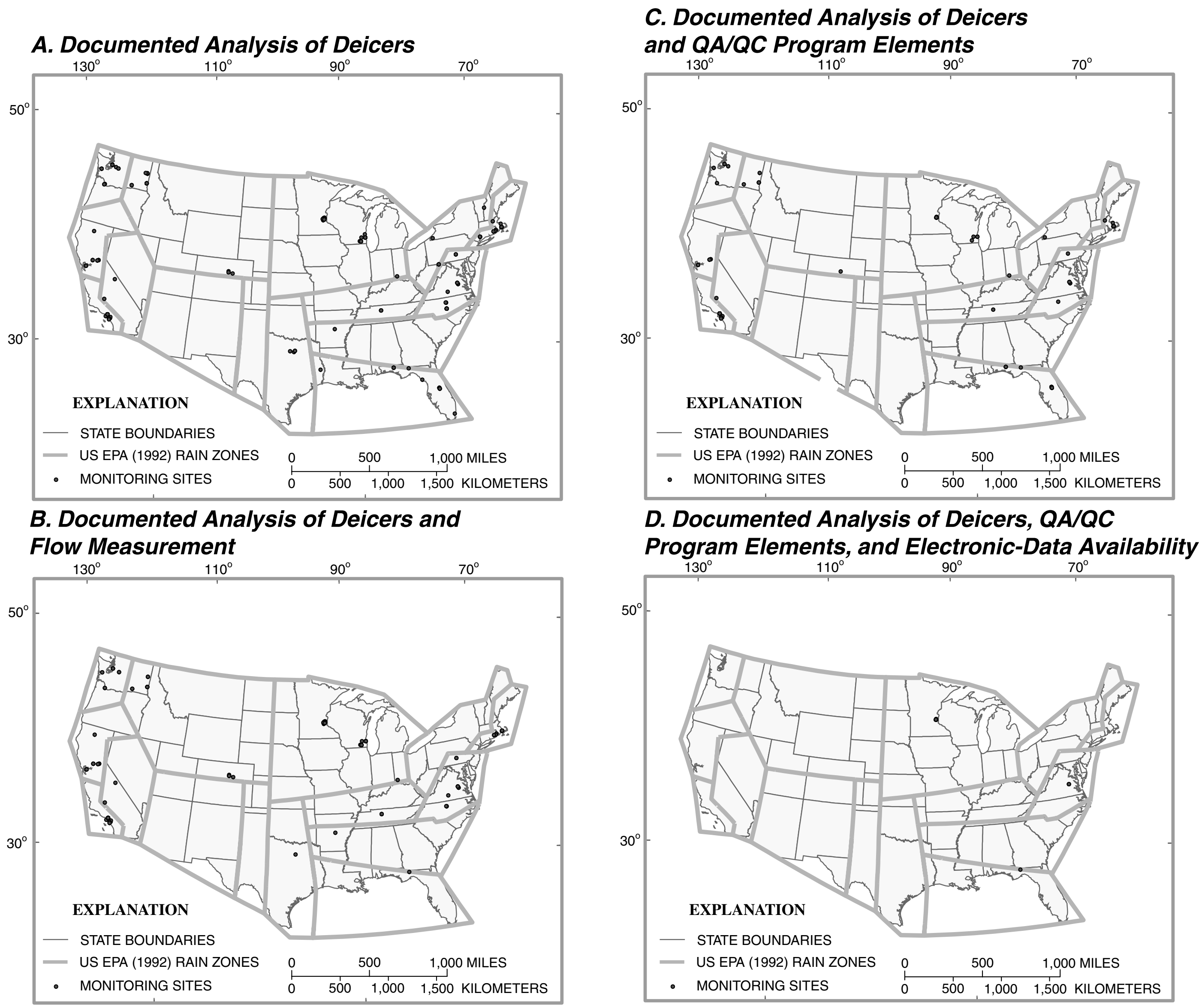

Figure 37. Location of highway sites with documented (*A*) analysis of deicers, (*B*) analysis of deicers and flow measurement, (*C*) analysis of deicers and QA/QC program elements, and (D) analysis of deicers, QA/QC program elements and electronic-data availability cataloged in the NDAMS review among the USEPA (1992) rain zones in the conterminous United States.

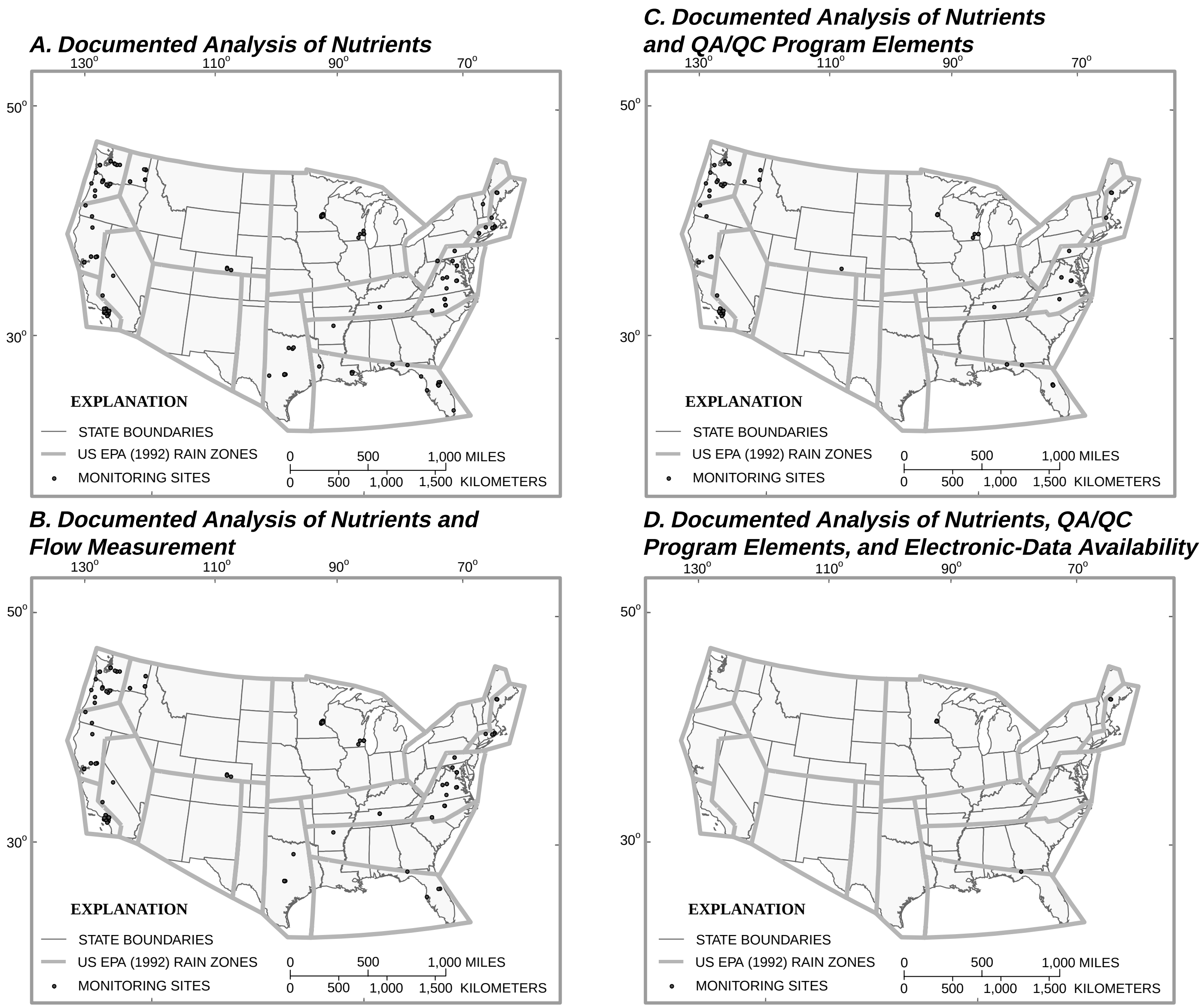

Figure 38. Distribution of highway sites with documented (*A*) analysis of nutrients, (*B*) analysis of nutrients and flow measurements, (*C*) analysis of nutrients and QA/QC program elements, and (*D*) analysis of nutrients, QA/QC program elements and electronic-data availability cataloged in the NDAMS review among the USEPA (1992) rain zones in the conterminous United States.

218 detailed reports at sites in the conterminous United States and southern Canada. Each figure indicates the location of (*A*) all highway sites with data for a given constituent class, (*B*) highway sites from reports that also have precipitation or flow data, (*C*) highway sites from reports that document at least one element of a QA/QC program, and (*D*) highway sites in group (*D*) that also document potential availability of data in an electronic format.

Geographic information is also necessary for formulation and application of runoff-quality models (Tasker and Granato, 2000). For example, in formulating the most current model of highway-runoff loads and impacts on receiving waters, Driscoll and others (1990a,b) used 9 rainfall regions to predict potential contaminant loads, 30 mean annual streamflow regions to predict potential dilution, and 23 regions of total hardness levels in surface waters to indicate potential

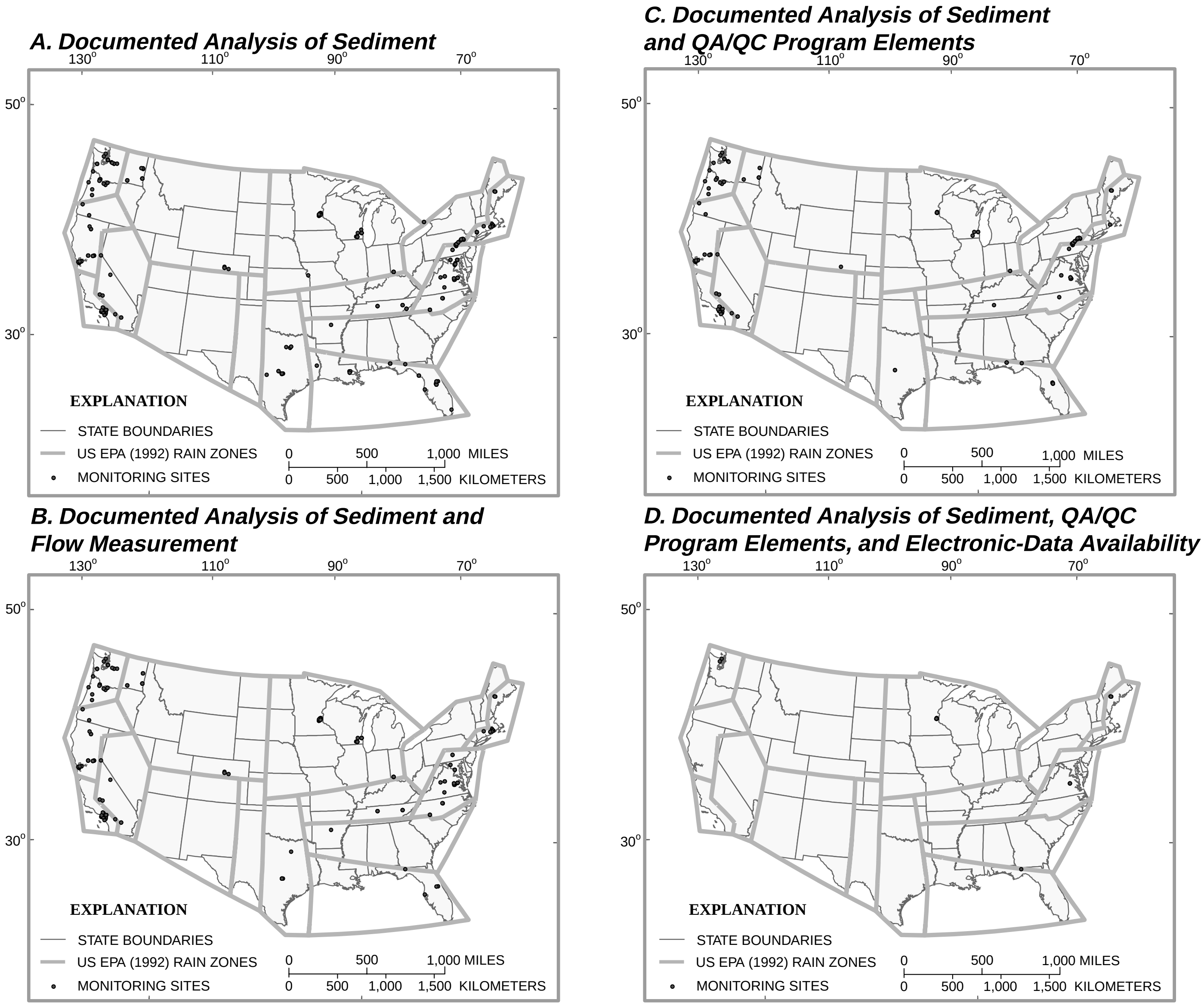

Figure 39. Distribution of highway sites with documented (*A*) analysis of sediment, (*B*) analysis of sediment and flow measurements, (*C*) analysis of sediment and QA/QC program elements, and (*D*) analysis of sediment, QA/QC program elements and electronic-data availability cataloged in the NDAMS review among the USEPA (1992) rain zones in the conterminous United States.

toxic effects from metallic contaminants. Other studies also have found geographic information to be important for interpretation of results on a national or regional scale. Athayde and others (1983) indicated that rainfall characteristics, streamflow, and surface-water hardness were important for assessing the impact of urban runoff in streams during the Nationwide Urban Runoff Program (NURP). Tasker and Driver (1988) conclude that site features, regionalized precipitation characteristics, and mean minimum January temperature are explanatory variables that can be used to formulate generalized least-squares regression models for the prediction of runoff loads at urban sites.

It is necessary to formulate a representative and technically defensible prediction model from data collected in the regions that are to be characterized by the model (Tasker and Granato, 2000). For example, the USEPA (1992) specifies the use of a 15-zone rainfall-characteristics map to plan sampling efforts and interpret stormwater-quality data collected for National

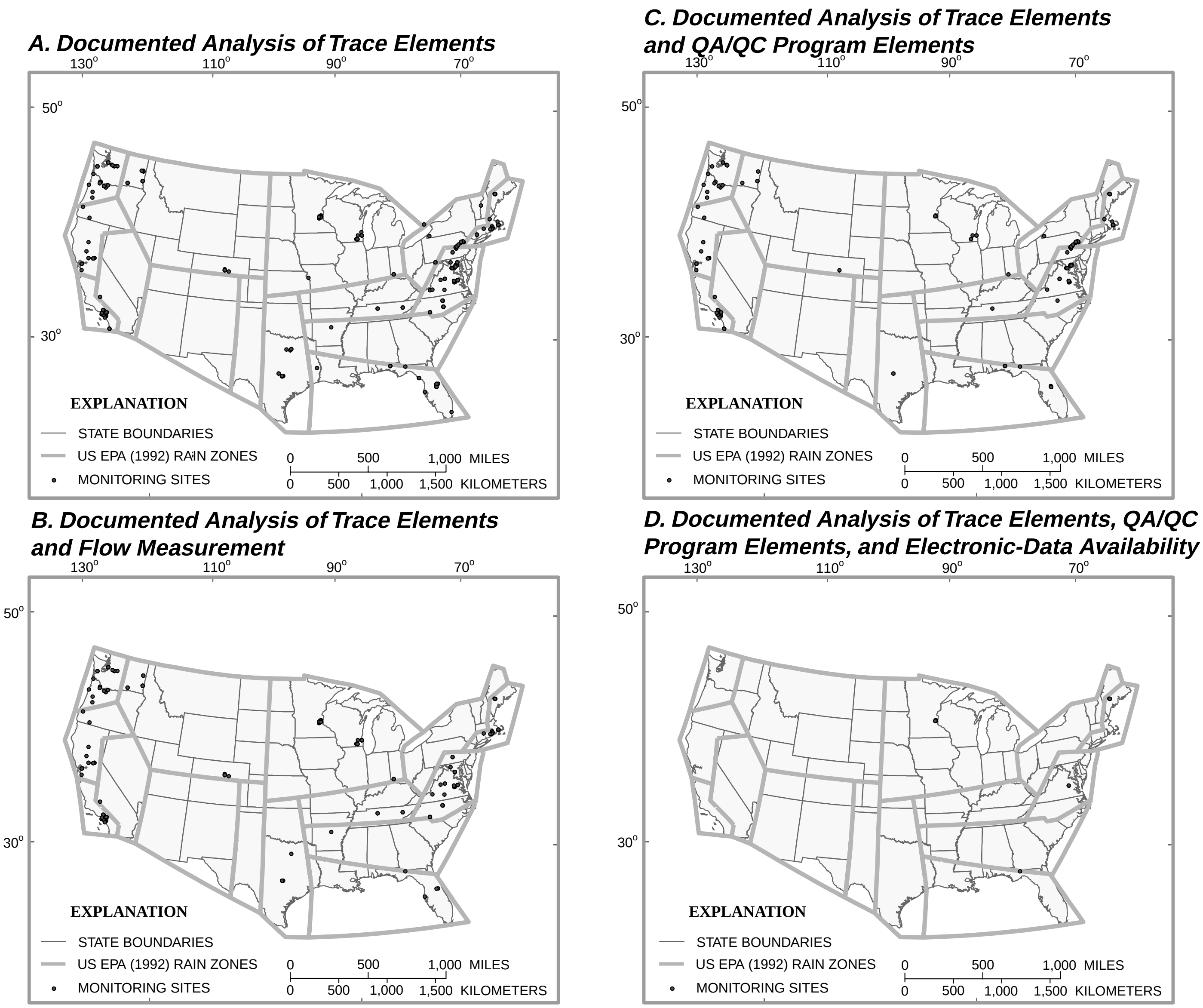

Figure 40. Distribution of highway sites with documented (*A*) analysis of trace elements, (*B*) analysis of trace elements and flow measurements, (*C*) analysis of trace elements and QA/QC program elements, and (*D*) analysis of trace elements, QA/QC program elements and electronic-data availability cataloged in the NDAMS review among the USEPA (1992) rain zones in the conterminous United States.

Pollutant Discharge Elimination System (NPDES) permits. This precipitation map supersedes the 9-zone rainfall map used by Driscoll and others (1990a) to predict highway-runoff quality in the conterminous United States. This 15-zone map may be used as a first approximation to examine the geographic availability of data from study sites described in the 218 detailed reports that were reviewed. To this end, this USEPA precipitation-region map is superimposed on figures 35–42. Examination of the available highway runoff data (fig. 35*B*) indicates that some highway-runoff research has been done in all but two of the current USEPA rain-zone regions. Similarly, data is available for most regions for many of the constituents of concern (fig. 36*A*-42*A*). When flow, QA/QC, and (or) electronic data requirements are applied, however, the number of available sites and the number of regions that are characterized by these sites is commonly reduced by a substantial number (figs. 36*B*,*C*,*D*–42*B*,*C*,*D*).

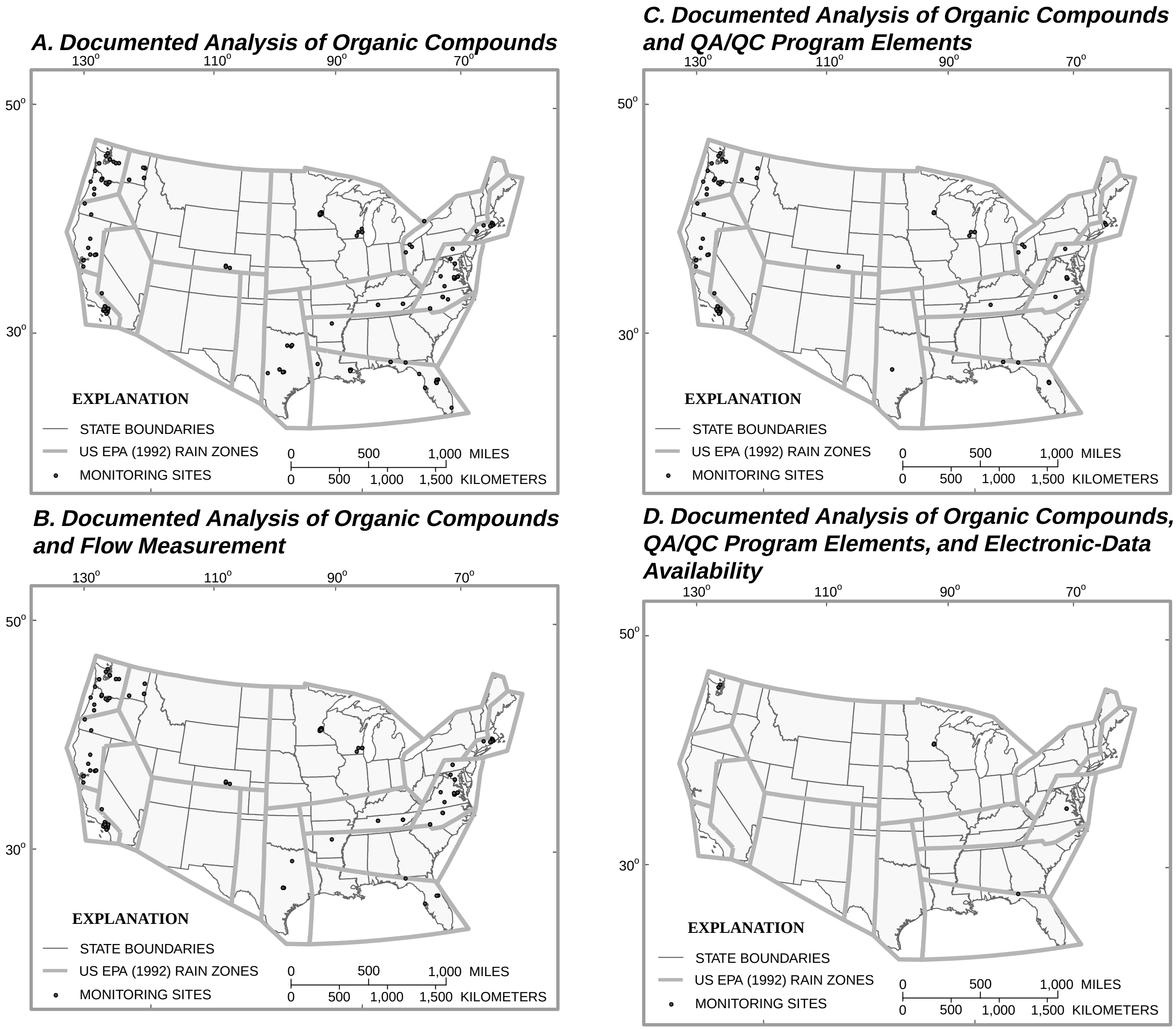

Figure 41. Distribution of highway sites with documented analysis of (*A*) organic compounds, (*B*) organic compounds and flow measurements, (*C*) organic compounds and QA/QC program elements, and (*D*) organic compounds, QA/QC program elements, and electronic-data availability cataloged in the NDAMS review among the USEPA (1992) rain zones in the conterminous United States.

Representative rain zones are but one of many geographic explanatory variables. For example, Driscoll and others (1990a) used streamflow regions to predict dilution of runoff in receiving waters, and total hardness regions to predict the potential toxicity of trace elements in highway runoff. In comparison to the 15 rainfall regions on figures 35–42, the streamflow regions include 30 unique polygons separated into 18 distinct flow ranges and the total hardness regions include 23 unique polygons separated into 6 total hardness ranges (Smieszek and Granato, 2000). Prediction of the potential effect of runoff on aquatic biota at any given site, however, may be more complex than a simple dilution and hardness model. The effect of runoff on aquatic biota depends on runoff quality, sediment quality, and the characteristics of the receiving water. For example, potential effects of runoff may be determined by means of a number of environmental

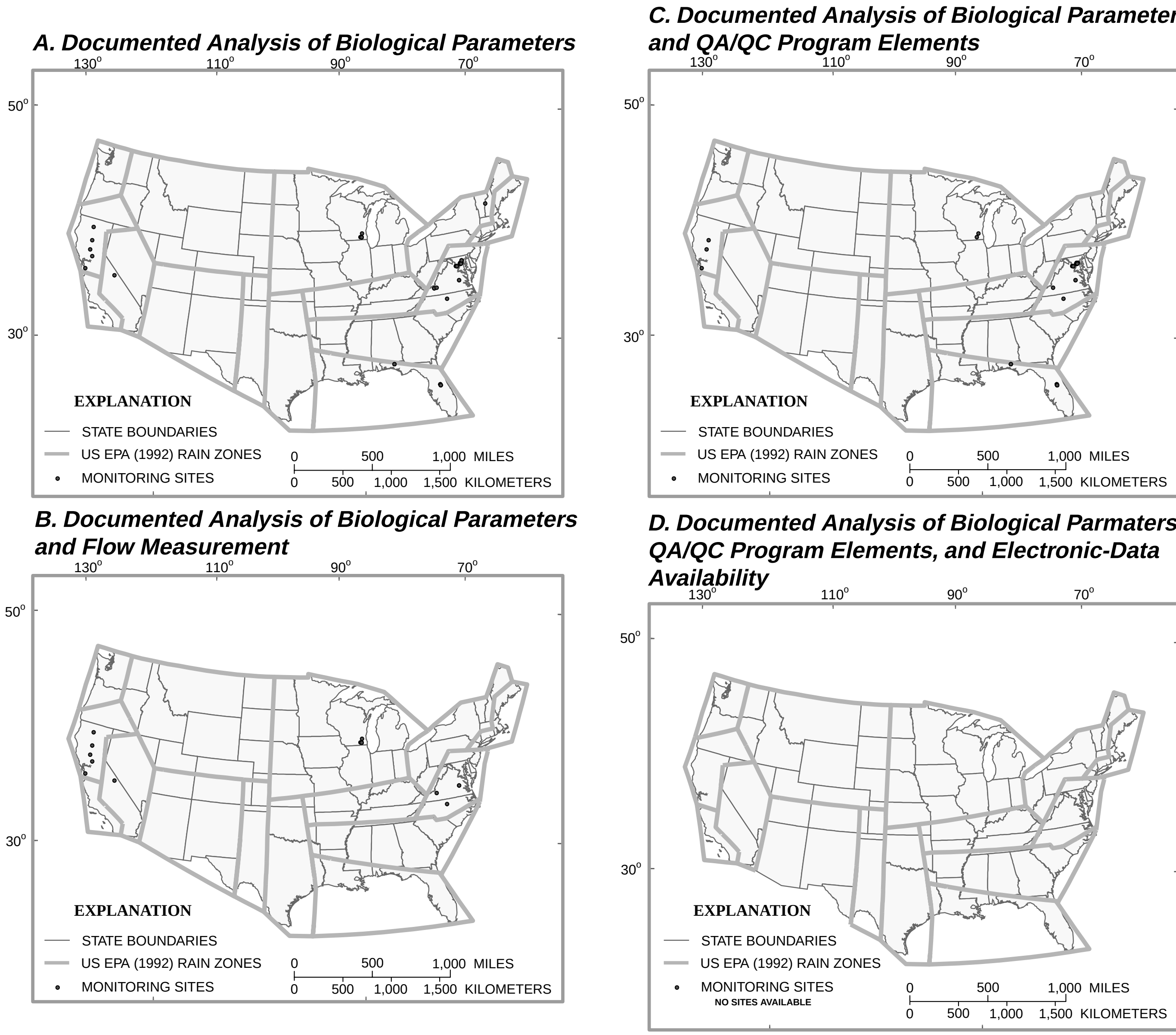

Figure 42. Distribution of highway sites with documented analysis of (*A*) biological parameters, (*B*) biological parameters and flow measurements, (*C*) biological parameters and QA/QC program elements, and (*D*) biological parameters, QA/QC program elements, and electronic-data availability (no sites) cataloged in the NDAMS review among the USEPA (1992) rain zones in the conterminous United States.

and ecological factors that are characterized in an ecoregion map (Buckler and Granato, 1999). The availability of biological-monitoring data at all sites in the conterminous United States and Southern Canada are displayed in relation to ecoregions defined by Bailey and others (1994) in figure 43. The 110 biological-monitoring sites are found in only 16 of the 330-ecoregion polygons. Therefore, the current dataset would probably not support a national model designed to predict the potential effect of runoff constituents on aquatic biota using ecoregion characteristics.

These are generalized examples of the type of geographic assessment that must be done by highway planners and decisionmakers when evaluating existing information on the basis of the DQOs for regional or national synthesis. For example, the flow measurement criteria were based on basic

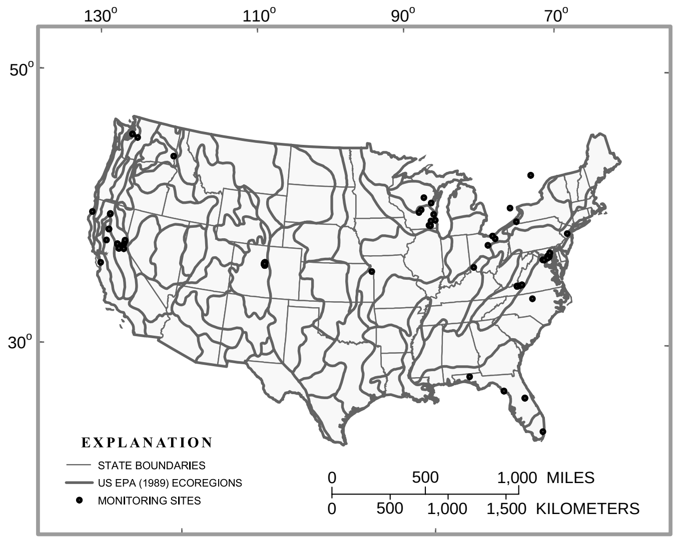

Figure 43. Distribution of all sites with documented biological sampling data cataloged in the NDAMS review among the USEPA (1999) ecoregions in the conterminous United States.

report information from the 52 percent of the 218 detailed reports that mentioned precipitation or flow measurement rather than the more detailed criteria for precipitation (fig. 30) or flow (fig. 31), which were documented in less than 20 percent of the detailed reports. The QA/QC criteria also are based on basic-report information from 38 percent of the detailed reports rather than the comprehensive laboratory and field QA/QC documented in about 20 percent of the detailed reports (fig. 33) or for individual data-quality elements such as participation in an interlaboratory QA/QC program (documented in about 8 percent of the detailed reports).

More specific criteria for documentation of project data, however, are necessary to establish that data are valid, comparable, and technically defensible as well as being representative of a geographic region of interest. The report by Smieszek and Granato (2000), the base-map GIS files in that report, and the GIS coverage (which includes the review data extracted from the NDAMS database) used to create the example maps in this section, are included on the CD-ROM accompanying Volume II of the NDAMS report series. These GIS files are provided to document the geographic analysis, to allow further exploration of the NDAMS data, or for identification of individual reports in any given geographic area.

Documentation Criteria

It is necessary to establish criteria defining the documentation that is required to establish that data are valid, comparable, and technically defensible within a scientific and regulatory framework (Granato and others, 1998). In a review of water-quality data collected by Federal, State, and local water-quality monitoring entities, Hren and others (1987) determined that, 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). It is necessary to document pertinent explanatory variables and to quantify the quality of data collected so that the information and data in a given report can be evaluated in terms of the criteria necessary for local, regional and (or) national interpretation.

The number, rigor, and complexity of required standards for documentation of environmental datasets have been increasing during the last 20 years. Current standards for environmental-data assessment require that all data used in regulatory decision-making processes be verified and validated to ensure the defensibility of data and decisions made with the data (USEPA, 2000b). The verification process is designed to ensure that the data are collected in accordance with approved protocols. Example objectives of data verification include ensuring the integrity and stability of samples collected, evaluating and maintaining the performance of instruments used for analysis of samples, and ensuring that data values are reported accurately (USEPA, 2001a). The validation process is designed to ensure that data quality is documented, that the data meet established DQOs, and that documentation is sufficient to allow evaluation in terms of other DQOs. An audit of environmental data is considered necessary by the USEPA to establish that

- the data can be replicated by the original data collector,
- there is sufficient documentation of all procedures used in the data-collection effort to allow for repetition of the effort by a person or team with technical qualifications similar to those of the original data collector,
- there is sufficient documentation to verify that the data have been collected and reported according to these procedures and that documentation is sufficient to allow a potential user to determine the quality and limitations of the data, and
- the data are of sufficient quality for their intended use with respect to the expected bias, precision, accuracy, comparability, completeness, representativeness, and other performance criteria (USEPA, 2000b).

The USEPA data verification and validation process includes a retrospective analysis of all the protocols used, each piece of data collected, and statistical analysis of environmental data and supporting quality-control data (USEPA, 2001a). Environmental data and supporting documentation must be available in an electronic database for this USEPA review process.

The NDAMS review process does not provide the detailed information necessary to verify or validate any given dataset. This metadata review process, however, does indicate how well information and data in the population of available highway-runoff reports would survive the verification and validation processes. The NDAMS metadata-review process indicates that the population of available reports commonly do not have sufficient documentation to initiate the verification and (or) validation process. Few reports document information necessary for use of precipitation (fig. 30) and flow data (fig. 31), despite the fact that these data are critical for characterizing the hydrologic regime at a study site, for implementing a flow-weighted composite-sampling system, and for predicting concentrations and loads at ungaged sites (Church and others, 1999; Tasker and Granato, 2000). Few reports also document information necessary for interpretation and use of concentration data. For example, fewer than half (about 38 percent) of the 218 detailed reports identify the laboratory(ies) used for sample analysis (only about 20 percent of the 151 reports with sediment data identify the sediment laboratory used) and only 16 percent indicate that the laboratory was certified by an independent organization. Also, fewer than half of the reports document any laboratory, field, or laboratory and field QA/QC activities (fig. 33). Fewer than 10 percent of the 218 detailed reports document existence of a quality plan, a published quality plan, or an internal or external audit (fig. 44), which are considered to be fundamental components of a quality system (Jones, 1999).

Many reports do not document critical data elements, which are necessary for data evaluation. For example, knowledge of detection limits is necessary for the use of geochemical (Bricker, 1999), trace-element (Breault and Granato, 2000), and organic (Lopes and others, 1998) constituent data. Also, the analytical uncertainty of measured concentrations increases as they approach the detection limit (Granato and others, 1998), and statistical characterization of runoff-quality data depends upon knowledge of detection limits and proper treatment of values at or below one or more detection limits (Tasker and Granato, 2000). Detection limits were not documented for 74 percent of the 162 reports with trace-element data, 82 percent of the 131 reports with organic-compound data, and 44 percent of the 27 reports with pesticide and (or) herbicide data. Many individual examples, therefore, indicate that the population of available reports does not document the information necessary for regional or national synthesis.

Although individual metadata elements are important, it is also necessary to evaluate the suitability of the available information in terms of a combination of metadata elements necessary to utilize any given

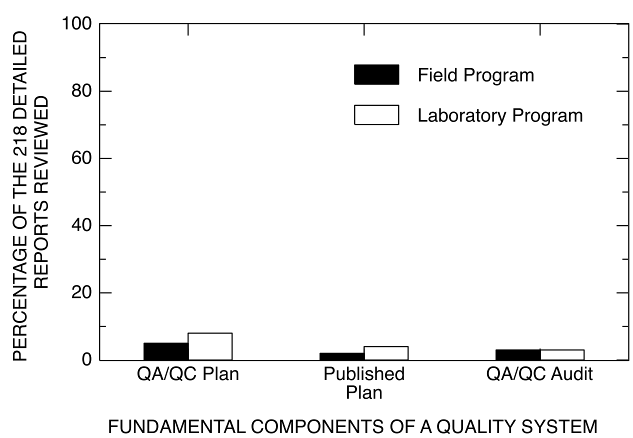

Figure 44. Proportion of the 218 detailed reports that document one or more fundamental components of a quality system.

data set. For example, knowledge of a measure of traffic volume (such as the average daily traffic), water-quality data from more than 15 independent storms (Thomson and others, 1997), and measurements of the storm total and intensity of precipitation at a test site may be used to predict concentrations and loads of constituents in runoff at similar sites (Tasker and Granato, 2000). Although each of these criteria is documented in more than 20 percent of the 218 detailed reports, only about 8 percent of these reports include all three criteria (fig. 45*A*). Furthermore, when the documentation for these selected explanatory variables is examined,

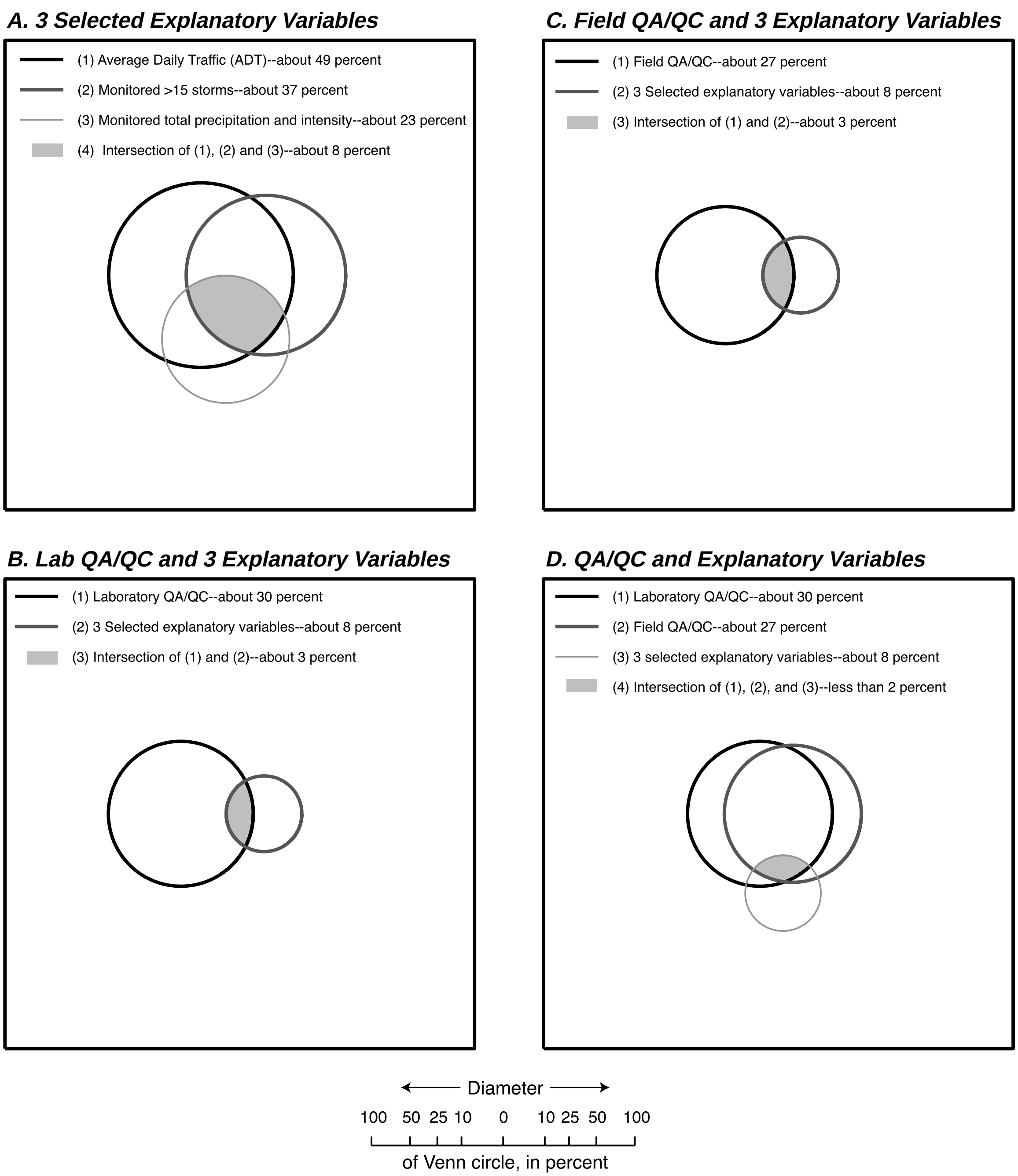

Figure 45. Percentages of the 218 detailed reports that document basic report information including: (*A*) three selected explanatory variables, (*B*) laboratory QA/QC and three selected explanatory variables, (*C*) field QA/QC and the three selected explanatory variables, and (*D*) laboratory QA/QC, field QA/QC and the three selected explanatory variables.

only 3 percent also have laboratory or field QA/QC documentation (fig. 45*B* and fig. 45*C*, respectively) and fewer than 2 percent have laboratory and field QA/QC documentation (fig. 45*D*).

Quality requirements for collection of atmospheric deposition data are more stringent than for collection of runoff data because of the complexities involved in quantifying fluxes of wet, dry, and occult (by sedimentation or turbulent transfer of cloud or fog droplets) deposition (Colman and others, 2001). There is continuing debate about the effectiveness and representativeness of atmospheric-deposition data collected by means of both standard and experimental methods. Methods comparison studies commonly identify considerable variations in the performance of different sampling methods. Also, the magnitudes of material fluxes from atmospheric deposition differ considerably at national, regional and local scales. Therefore, documentation criteria for collection and interpretation of atmospheric deposition data are crucial.

It may be argued that any number of the individual metadata elements included in the NDAMS review are not absolutely necessary for regional or national synthesis. Evaluation of many individual documentation elements, however, indicates that the available literature does not properly document research to a degree that would establish that existing data are valid, comparable, or technically defensible for regional or national synthesis. Furthermore, when individual metadata requirements are combined (as in fig. 45), the proportion of available reports that meet these multiple criteria quickly decreases to the point at which regional or national synthesis is not possible. The fact that a program's data may not meet these screening criteria, however, 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 regional or national synthesis.

RESEARCH NEEDS

Over the past decade, the transportation community has recognized and defined a number of water-quality research needs that may be evaluated in terms of the results from the NDAMS review. The following research needs have been identified by the FHWA, State DOTs, the Transportation Research Board (TRB), and others in the transportation community (Bank 1993a,b; Transportation Research Board, 1993, Bank and others, 1995; Transportation Research Board, 1996, 1997; 2000):

- development of water-quality-monitoring and -modeling techniques,
- assessment of potential trends in the quality of highway runoff in relation to changes in sources of runoff constituents,
- assessment of the effects of runoff on receiving waters and aquatic biota,
- assessment of the performance of BMPs and highway design modifications to minimize the potential for adverse effects from runoff,
- integration of transportation and watershed planning efforts to address water-resources issues, and
- development of a system to facilitate information exchange.

Development of the system to facilitate information exchange is one of the more modest goals and should serve as the foundation for the other research needs. An information exchange system is necessary to establish valid, current, comparable and technically defensible methods and documentation protocols that include DQOs, data collection and review methods, data documentation standards, and methods to document and convey results of investigations. Establishing a system to facilitate information exchange within a regional and (or) national data-quality-assurance system may also ensure that resources expended for other research needs result in collection of defensible data. For example, potential problems with the analytical methods used to generate TSS data raise questions about the veracity of existing runoff-sediment data (Glysson and others, 2000; Gray and others, 2000; Bent and others, 2001). This analytical problem (in which the TSS measurement method tends to underrepresent larger grain-size fractions in runoff) may affect the veracity of datasets, may affect measurements of the efficiency of different BMPs, and may in part explain the widely ranging estimates of BMP treatment efficiencies from different sites with different sources of suspended sediment (Bent and others, 2001). Furthermore, trace-element data is currently considered suspect unless QA/QC documentation exists to demonstrate the veracity of this data (Breault and Granato, 2000)

Results of the NDAMS synthesis generally confirm the continued existence of the research needs identified by the transportation community (Bank 1993a,b;

Transportation Research Board, 1993, Bank and others, 1995; Transportation Research Board, 1996, 1997, 2000) and the rationale behind these research needs. For example, Bank (1993b) observed that it is necessary to develop improved methods, techniques, tools, models, and procedures to evaluate water-quality issues. Results of the NDAMS review process indicate that the existing literature does not consistently document this information to a degree that would support a valid, current, and technically defensible regional or national synthesis. Bank (1993b) also observed that it is necessary to develop the expertise and vision within transportation agencies to produce and interpret hydrologic, hydraulic, and water-quality information and data needed to address water-resources issues. A substantial lack of consistent documentation among the reviewed reports in the NDAMS review process indicates that local runoff researchers need guidance from the FHWA, in order to evaluate and document the information and data necessary for regional or national synthesis efforts. The need for regional and (or) national guidance in local water-quality monitoring programs, however, is not unique to the highway-runoff-research community (Hren and others, 1987; Norris and others, 1990). For example, one might assume that all data collected for NPDES permit applications would be consistent, but research indicates that substantial differences exist among the data collected for different states and (or) USEPA regions (Guerrero and others, 1996).

Results of the NDAMS synthesis may provide information to address the different highway-runoff-quality research needs. For example, the bibliographic database created to catalog the available publications pertinent to the study of highway runoff includes reports that address the topics included in one or more of the listed research needs (Granato and others, 2001). The availability of this bibliographic database on the Internet (Reece and others, 1999) may represent a first step toward a system to facilitate information exchange. Furthermore, the expert chapters, written primarily for defining criteria for the metadata review, also provide information directly related to these research needs. For example, Buckler and Granato (1999) indicate that runoff itself may not have acute effects on test organisms, but runoff sediments may exert chronic effects at sites where the sediments accumulate in receiving waters. Therefore, future studies that are designed to assess the potential for adverse effects from runoff on receiving waters and aquatic biota may need to focus on the relation between runoff quality, runoff quantity, the quality and quantity of runoff sediment near outfall structures, and measurable biological responses in individual organisms and in biological communities, rather than on whether individual constituent concentrations meet or exceed a given water-quality standard.

Collection and documentation of information necessary for regional, national, or expanded use of any given dataset typically requires more resources than those required for local regulatory or information needs. For example, efforts to quantify inputs from atmospheric deposition are not necessary to measure concentrations and loads of constituents in highway runoff flowing into local receiving waters. Atmospheric-deposition data, however, is necessary as an explanatory variable if local runoff-quality data are to be used in a regional or national synthesis effort. This is because atmospheric deposition fluxes vary substantially from place to place, and local (nonhighway) point sources of air pollution can increase runoff-constituent concentrations by orders of magnitude (Driscoll and others 1990a; Colman and others, 2001). The need for additional documentation efforts, however, may not be justifiable within the local context unless regional or national information requirements are specified by organizations and agencies sponsoring or conducting this runoff research. The Transportation Research Board (1996), recognizing the need for data and information, indicated that unless standards are established, the continuation of nonuniform approaches to data collection and documentation will preclude the development of valid conclusions when different datasets are integrated for regional or national interpretation.

Bank and others (1995) indicate that the organization and centralization of water-quality-research efforts is identified by a broad-based committee of Federal and State transportation professionals and highway practitioners as the most important highway-runoff-research need. Development of an electronic clearinghouse of reports, data, and information has been among the top three water-quality-research initiatives identified by the transportation community over the past 6 years (Bank and others, 1995; Transportation Research Board, 1996; 1997; 2000). Results of the NDAMS project, including the bibliographic catalog, results of the metadata review process, technical reports, GIS files, and other tools may be used to form the core of an internet-based information-exchange system. The NDAMS database, however, contains metadata about existing research rather than a national database of runoff-quality data. Furthermore, results of the NDAMS metadata review indicate that the data in the available literature is not documented sufficiently to support current or future regional or national synthesis.

The lack of a substantial body of valid, current, and technically defensible information in the available literature points to the need for national standards. Necessary standards may include:

- requirements that all information and data are collected within a quality system to document verification and validation of all data with internal and external technical audits;
- protocols for collection, processing, and analysis of environmental samples;
- documentation standards for laboratory and field methods, materials, analytical detection limits, site characteristics, and other explanatory variables;
- documentation standards describing the type and format of data to be saved in electronic format; and
- methods for posting all runoff-research reports on the Internet in a centralized location.

Development of these standards by the transportation community may appear to be an overwhelming requirement, but similar standards are being developed within the more general water-resources-research community. The transportation community, therefore, may benefit by adopting or adapting existing standards and by participation in wider efforts toward the development of available and comparable electronic datasets. Examples of existing initiatives to develop national data standards and information-distribution systems include development of:

- a model quality system and many of the detailed QA/QC protocols necessary to produce defensible data (by the USEPA, 2001d);
- protocols necessary for collection processing and analysis of environmental samples by the USGS (for example, USGS, 1999, or National Water-Quality Assessment Program, 2000);
- national documentation standards and performance-based measurement systems to maximize the availability, quality, and comparability of water resources data (by the National Water-Quality Monitoring Council, 2000);
- standards for creation and documentation of geographic information in databases compatible with geographic information system (GIS) software (National Institute of Standards and Technology 1992; Federal Geographic Data Committee, 1998, 2001);
- use of the relational database (RDB) structure—a tab-delimited ASCII format formalized by Manis, and others (1988) that provides for inclusion of metadata elements and is easily transferable among different software packages—by the USGS National Water Information System (2000), to provide surface-water, ground-water, and water-quality data; and
- use of existing electronic report-publishing media, for example the free Adobe Acrobat Reader is used to provide high-quality reports in an electronic format by the U.S. General Accounting Office (2001), the U.S. Government Printing Office (1997), the USEPA (2001c), the Transportation Research Board (2000), the USGS (2001), State departments of transportation (for example, the New York State Department of Transportation (2000) or the Washington State Department of Transportation (2001) and other State and Federal agencies.

A system designed to facilitate information exchange also may better utilize the large but decentralized pool of knowledge and talent that exists among different Departments of Transportation, scientific organizations, and regulatory agencies. Electronic availability of project documentation including DQOs, project plans, protocols, and draft reports would allow feedback necessary to evaluate the results of an investigation. For example, the USEPA (2001e) utilizes the Internet to post information about proposed rules for the NPDES and TMDL programs to solicit public review and comment.

Once a system that addresses the data-quality and documentation requirements is in place, the other highway-runoff-research needs may be addressed in a manner that most efficiently meets information requirements. For example, research projects designed to determine the efficiency of BMPs would, in effect, create runoff-characterization datasets by measuring water quality from the pavement and documenting information necessary to evaluate performance of the individual BMP structures and to predict runoff quality in terms of site characteristics.

CONCLUSIONS

Review and analysis of the metadata collected for the National Highway Runoff Data and Methodology Synthesis indicates that much of the available data is not sufficiently documented for inclusion in a technically defensible regional or national data set. Results of the metadata-review process indicate that few reports document enough of the information and data necessary to establish the quality or representativeness of research results. Also, the number of reports that meet criteria for documentation of project data are substantially diminished when multiple criteria are applied. For example, about 81, 40, and 19 percent of the 252 reports reviewed document efforts to sample water, sediment, or biota, respectively, but only about 8 percent of reports document efforts to evaluate all three sampling matrixes. Furthermore, several technical issues raise doubts about the veracity of existing suspended-sediment, trace-element, and organic-compound data. The fact that a program's data may not meet criteria for regional or national synthesis, however, 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.

National transportation-research organizations need to develop the infrastructure necessary to ensure that environmental research efforts address local information needs and also are useful for regional or national synthesis, especially when Federal funds are applied toward local research needs. It is necessary to establish systematic data-quality objectives, an integrated quality system, and standard protocols for sample collection, processing, analysis, documentation, and publication to ensure that resources expended to meet environmental research needs are used efficiently and effectively. To this end, the transportation community can adopt, adapt, and participate in the development and application of standard methods for data-collection, -processing, and -distribution. Integration of Federal, State, and local regulatory, data-collection, and research programs within a system to facilitate information transfer will provide an economy of scale by making research results available to the entire research community. National standards and a technical audit process are necessary, however, to ensure that data in this system meet documentation and data-quality requirements.

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