U.S. Department of the Interior
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Basic Requirements for Collecting, Documenting, and Reporting Precipitation and Stormwater-Flow Measurements

Open-File Report 99-255

A Contribution to the
National Highway Runoff Data and Methodology Synthesis

U.S. Department of Transportation

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U.S. Geological Survey

Basic Requirements for Collecting, Documenting, and Reporting Precipitation and Stormwater-Flow Measurements

By PETER E. CHURCH, GREGORY E. GRANATO, and DAVID W. OWENS

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National Highway Runoff Data and Methodology Synthesis

Northborough, Massachusetts
1999

U.S. DEPARTMENT OF THE INTERIOR
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PREFACE

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

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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.

Basic Requirements for Collecting, Documenting, and Reporting Precipitation and Stormwater-Flow Measurements

By Peter E. Church, Gregory E. Granato, *and* David W. Owens

Abstract

Accurate and representative precipitation and stormwater-flow data are crucial for use of highway- or urban-runoff study results, either individually or in a regional or national synthesis of stormwater-runoff data. Equally important is information on the level of accuracy and representativeness of this precipitation and stormwater-flow data. Accurate and representative measurements of precipitation and stormwater flow, however, are difficult to obtain because of the rapidly changing spatial and temporal distribution of precipitation and flows during a storm. Many hydrologic and hydraulic factors must be considered in performing the following: selecting sites for measuring precipitation and stormwater flow that will provide data that adequately meet the objectives and goals of the study, determining frequencies and durations of data collection to fully characterize the storm and the rapidly changing stormwater flows, and selecting methods that will yield accurate data over the full range of both rainfall intensities and stormwater flows.

To ensure that the accuracy and representativeness of precipitation and stormwater-flow data can be evaluated, decisions as to (1) where in the drainage system precipitation and stormwater flows are measured, (2) how frequently precipitation and stormwater flows are measured, (3) what methods are used to measure precipitation and stormwater flows, and (4) on what basis are these decisions made, must all be documented and communicated in an accessible format, such as a project description report, a data report or an appendix to a technical report, and (or) archived in a State or national records center.

A quality assurance/quality control program must be established to ensure that this information is documented and reported, and that decisions made in the design phase of a study are continually reviewed, internally and externally, throughout the study. Without the supporting data needed to evaluate the accuracy and representativeness of the precipitation and stormwater-flow measurements, the data collected and interpretations made may have little meaning.

INTRODUCTION

Accurate and representative precipitation and stormwater-flow data are crucial for valid, current, and technically defensible interpretations of highway- or urban-runoff study results. Additionally, results from a number of accurate and representative studies are necessary for developing a regional or national synthesis of stormwater-runoff data. Obtaining such data is not a trivial matter because the stormwater-monitoring environment is complex. Varying rainfall patterns result in runoff flows, constituent concentrations, and constituent loads that vary considerably within and between storm events (Harrison and Wilson, 1985; Hoffmann and others, 1985; Irish and others, 1996). Different antecedent conditions, different storm volumes and durations, and different patterns of precipitation intensity make each storm a unique event. These differences can cause large variations in event-mean concentrations (EMCs) and total constituent loads measured for each storm (Driscoll and other, 1990a; Irish and others, 1996). Models describing highway- and urban-runoff constituent loads will not be quantitative without detailed characterization of these complex physical and hydrochemical processes that govern constituent accumulation and release (Spangberg and Niemczynowicz, 1992).

Knowledge of variations in the intensity and duration of precipitation and the resultant effects on stormwater flows, pollutant concentrations, and pollutant loads is necessary to characterize stormwater runoff from highways, urban areas, and other areas contributing nonpoint-source pollution to receiving waters. The amount of energy available to mobilize and transport dissolved and suspended constituents is a function of rainfall intensity. A tenfold increase in intensity will increase the kinetic energy of rainfall impact by about 15 times (Smith, 1993). Average storm intensity and total flow per unit area were the most statistically significant predictors for all common highway-runoff constituents in a recent study of highway runoff that included a rainfall simulator and natural storms (Irish and others, 1996). Accurate measurement of the intensity and duration of each precipitation event and resultant total storm discharge is important to quantify the pollutant mass balance and effects upon a receiving water body (Thoman and Mueller, 1987; Irish and others, 1996). Characterization of storm intensity and duration are also important to the monitoring process because the accuracy of both time-based and flow-weighted compositing schemes depends on accurate flow measurements (U.S. Environmental Protection Agency, 1992). Also, because automatic samplers commonly used in stormwater studies have a fixed volume for sample collection, it is difficult to match the frequency and duration of the sampling period to variations in the intensity and duration of monitored storms for the optimization of sampling schemes. Data interpretation is also dependent upon knowledge of the intensity and duration of precipitation and resultant runoff because calculation of loads and EMCs (calculated from discrete samples, or composited manually or automatically) all depend upon the accuracy of precipitation and (or) flow measurements.

Problem

Accurate and representative measurements of precipitation and stormwater flow are difficult to obtain because of the rapidly changing spatial and temporal distribution of precipitation in the drainage system and the rapidly changing flows during a storm. The quality of precipitation and stormwater-flow measurements found in the literature is difficult to assess without the supporting data needed to evaluate their accuracy and representativeness. Accurate measurements of precipitation are confounded by difficulties in finding a representative site, the ability of instruments to record data accurately over a wide range of rainfall intensity, concerns with spatial and temporal variability, the reliability of measuring and recording instruments, and problems with freezing conditions at sites where commercial power is not available. Physical and logistical complications also affect the quality of stormwater-flow measurements.

Stormwater-flow rates can range over several order of magnitudes in a short period. Flow regimes (steady or unsteady flow, subcritical or supercritical flow) can change in response to the varying flow rates. Flow durations and intervening dry periods also vary within drainage systems. The resolution of field measurements and commercially available measuring equipment is relatively coarse for measuring flows in small streams, pipes, swales, and sheet flow over pavements and soils. The introduction of a flow-measurement device in a small channel or pipe can disturb the flow being measured. Because storm drainage systems often have little, if any, base flow, erratic measurements can result when measuring instruments are dry; instruments may not be able to accurately measure flow until stormwater flows reach a minimum water level. Also, equipment and instrumentation required for accurate flow measurements may be costly. Selecting a site where flows are consistent with the data objectives, the appropriate frequency and duration of flow measurements to fully characterize the stormwater-flow event can be obtained, and a method for measuring the full range and types of flow in a natural or controlled channel with minimal disturbance is not a trivial task, but is critical to ensure accurate and representative stormwater-flow measurements.

Documentation of the steps followed and the uncertainty involved in the selection of sites for measuring precipitation and stormwater flow, the frequency and duration of monitoring, and the methods, equipment, and instruments used to monitor precipitation and stormwater flow are needed for evaluation of the accuracy and representativeness of the data collected. This evaluation is important for assessing the validity of the data collected because errors in precipitation or flow data result in inaccurate relations between rainfall and runoff, and errors in flow and (or) pollutant concentration result in erroneous calculations of pollutant loads, event-mean concentrations, and total mean daily loads. Validation of the accuracy and representativeness of flow and constituent concentrations data in highway and urban runoff also are important because these data form the baseline on which models developed for prediction of stormwater loads and event-mean concentrations are calibrated (Guerard and Weiss, 1995; U.S. Environmental Protection Agency, 1997; Zarriello, 1998), and from which best management practices are developed. Without the supporting data needed to evaluate the accuracy and representativeness of the precipitation and stormwater-flow measurements, the data collected and interpretations made may have little meaning.

Additionally, it is important that precipitation and flow measurements fulfill a particular need or objective and that this objective and the acceptable uncertainty be clearly stated. Collection of data without a clear data-quality objective may result in collection of marginal or useless data (Whitfield, 1988). The accuracy and representativeness of data collected can be evaluated quantitatively only if information is available about (1) where in the drainage system the flows were measured, (2) how frequently the flows were measured, (3) what methods were used to measure flows, and (4) on what basis these decisions were made. All of this information should be documented in terms of project data-quality objectives. Furthermore, the Intergovernmental Task Force on Monitoring Water-Quality has recommended that flow measurement be a component of water-quality studies and that data from monitoring programs be collected, documented, and reported in a consistent manner (Intergovernmental Task Force on Monitoring Water-Quality, 1995a,b).

Purpose and Scope

The purpose of this report is to present the basic requirements for collection of accurate and representative precipitation and stormwater-flow measurements and the supporting data that must be documented and reported to ensure that these data can be independently validated. Data requirements for determination of accurate and representative precipitation and stormwater-flow measurements are evaluated within the context of building a quantitative national data base that will be used to record and predict highway-runoff pollution (Granato and others, 1998).The methods available for measuring precipitation and stormwater flow are widely reported in the literature, so they are described only briefly here. The information that needs to be documented and reported to allow for independent evaluation of the accuracy and representativeness of precipitation and stormwater-flow measurements, however, is less well described, and therefore, is emphasized in this report. References that provide more detailed guidance for collection of accurate and representative precipitation and stormwater-flow measurements are provided.

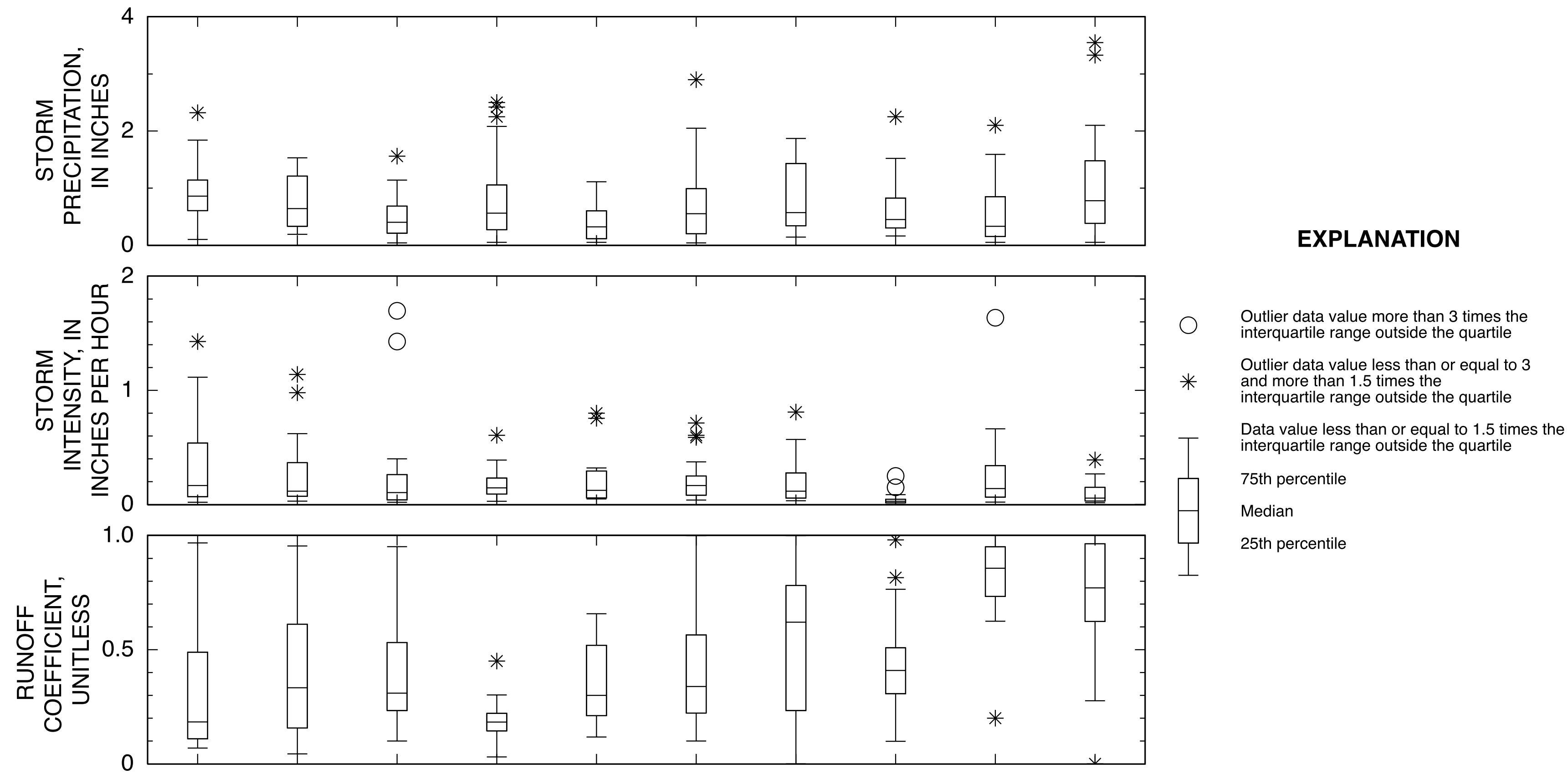
PRECIPITATION DATA

Precipitation is the driving force of the stormwater runoff process and its accurate monitoring is necessary to characterize the rainfall-runoff process. Rainfall can be highly variable in space and in time (Alley, 1977). Precipitation intensity and duration are major factors determining removal of runoff constituents during a storm. Varying rainfall patterns result in runoff flows and contaminant washoff rates that vary considerably within and between storm events (Harrison and Wilson, 1985; Hoffmann and others, 1985; Irish and others, 1996). A positive correlation between the physical and chemical characteristics of rainfall and runoff is expected and well documented (Driscoll and others, 1990a; Irish and others, 1996). Higher intensity rains wash more dissolved and suspended constituents from watershed surfaces than equivalent volumes from lower intensity events (Athayde and others, 1983; Irish and others, 1996).

Theoretically, uncertainty in precipitation measurements should be lower than uncertainty in stormwater-flow measurements because precipitation measurements are direct, whereas many stormwater flow “measurements” are calculated from a stage measurement and a discharge rating. If predictive models are implemented by using regression techniques that do not account for possible uncertainties in the independent variables, then rainfall may be considered a better regressor for water-quality variables than runoff for a given site because of these lower uncertainties in precipitation monitoring (Irish and others, 1996). It is necessary, however, to measure or derive accurate stormflow volumes for the collection and interpretation of runoff-quality data because sample compositing methods and constituent load calculations depend on the availability of runoff-flow volumes.

Examination of precipitation and runoff data from the Federal Highway Administration (FHWA) highway-stormwater-runoff data base (Driscoll and others, 1990b) indicates that precipitation data is a useful, but not a direct, surrogate for measured stormflows. Data including date, total precipitation, storm duration, and total runoff from 264 storms at 9 highway sites and at 1 grassy plot, each having the required data for at least 10 storms, were selected (Driscoll and others, 1990b). Precipitation intensities were calculated as the quotient of total precipitation and storm duration for each storm from these data. Runoff coefficients were calculated as the quotient of total runoff and total precipitation volume for each storm. Boxplots of the data for each of these ten sites are shown in order of increasing imperviousness, and increasing precipitation when percent impervious is the same (**fig. 1**). Although the average annual precipitation among these 10 sites varies from about 15 to about 84 inches per year, total storm precipitation, intensity, and runoff coefficients from the storms monitored are comparable. The boxplot graph of the runoff-coefficient populations is artificially truncated at 1.0 (the point where runoff equals precipitation) because, logically, the total runoff from a storm should not exceed the measured precipitation. Values above a runoff coefficient of 1 may reflect uncertainties in the data, between-storm storage within the highway catchment, base flow from ground water, and (or) contributions from additional drainage areas during some storms. Examination of figure 1 indicates that for these data, there is no single runoff coefficient that can be accurately used to predict total runoff from total precipitation at any given site. For example, the uncertainty in predictions of total stormflow based on measured precipitation would be about plus or minus 50 percent at the Route 384 site in Florida, which had the least variation in runoff coefficients among these 10 sites from the FHWA data set (Driscoll and others, 1990b).The population distributions for different sites in this figure do not indicate a simple relation between the median runoff coefficient and increasing impervious area. Common sense would suggest that catchments with a very high proportion of impervious area would have less variability in the runoff coefficient because runoff from impervious pavement would not be affected by antecedent moisture. The population distributions for runoff coefficients in figure 1, however, do not demonstrate lower variabilities at highly impervious sites.

Differences in rainfall-runoff relations from season to season caused by effects of temperature, precipitation characteristics, and the length of the antecedent dry period may obscure meaningful relations in figure 1. To explore the feasibility of establishing seasonal runoff coefficients that would be characteristic of highways nationwide, the data from the 9 paved highway sites were combined and are shown in **figure 2**. Each of the studies selected from the FHWA data report (Driscoll and others, 1990b) had a duration of about 1 year, but the studies were done in different years and many studies did not sample a substantial number of storms in each month. In these boxplots, total precipitation for each storm seems to be slightly more variable in the winter months than in the rest of the year (except for January, because only four storms were sampled in this month). Also, the population of intensities seems to be more variable in the summer (possibly due to the occurrence of convective storms in the warmer months). The populations featured in figure 2, however, do not indicate a characteristic runoff coefficient for highway sites even when the effects of seasonality are examined. The data reported by Driscoll and others (1990b) is a compilation of two distinct phases of the early FHWA water-quality research and similar studies conducted by transportation departments in several States. Differences in methods, equipment, and measurement installations between these monitoring programs at different sites throughout the Nation may introduce bias and contribute to the variability apparent in figure 1 and figure 2. Therefore, precipitation measurements can provide valuable information for interpretation of results, but may not be a direct surrogate for measured runoff flows, even in small catchments.



STUDY SITE INFORMATION	Rt-45 (Grass), WI	I-81, PA	Rt-45, WI	Rt-384, FL	I-25, CO	I-40, TN	I-30, AR	Rt-270, WA	I-794, WI	Rt-12, WA
Number of Events	12	23	29	45	16	31	15	25	33	35
Percent Impervious	0	27	31	36	37	37	90	100	100	100
Area (Acres)	2.7	18.5	106	58.3	35.3	55.6	1.5	0.25	2.1	0.28
Average Annual Precipitation (In)	27.6	37.7	27.6	62	14.8	45	48.7	18	27.6	84

Figure 1. Population statistics from stormwater data recorded at 10 historical highway-runoff-monitoring sites with available total precipitation, storm duration, and stormwater-flow data from individual events (data from Driscol and others, 1990b).

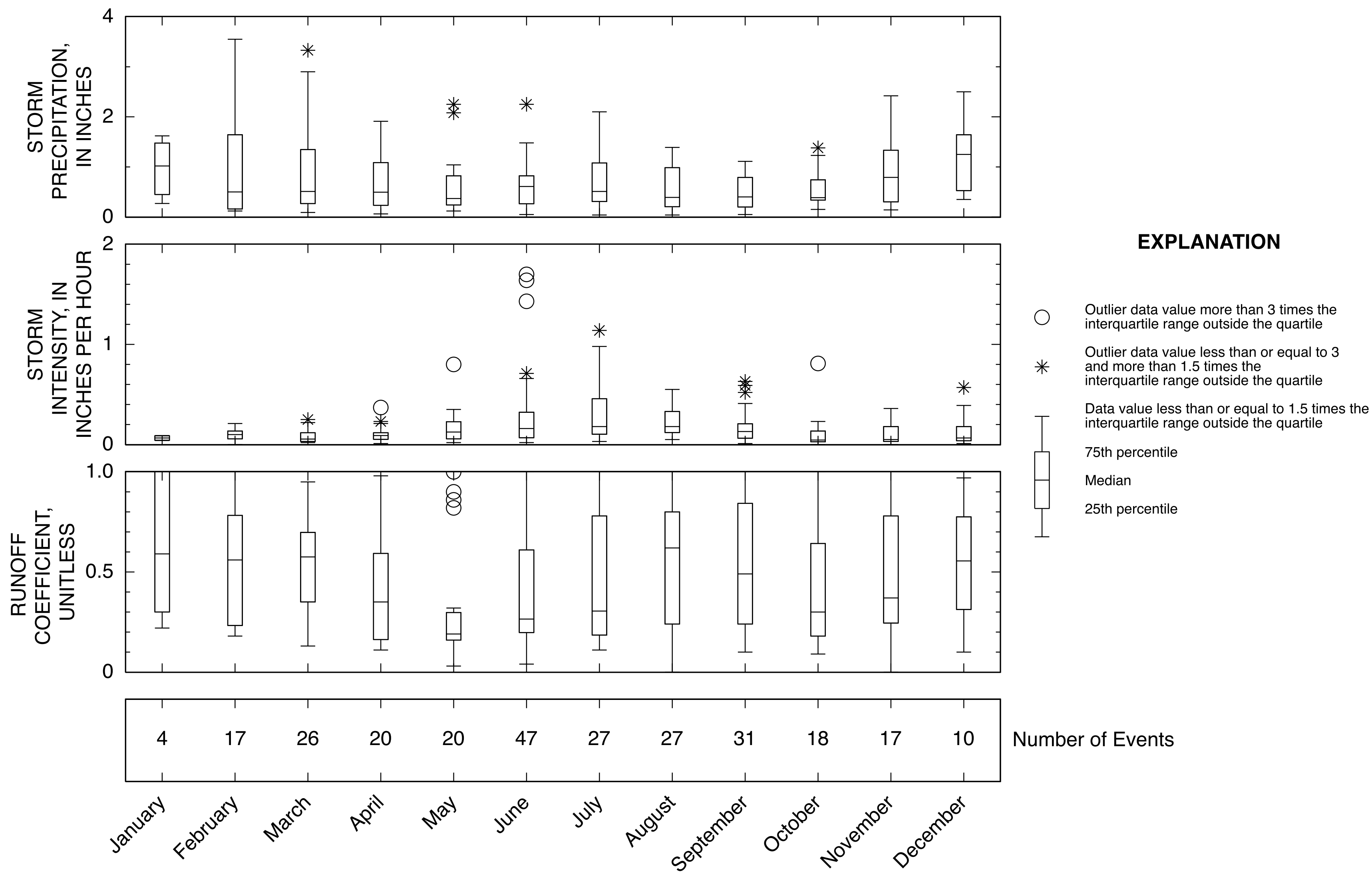


Figure 2. Seasonal population statistics of stormwater data including none highway-runoff sites with available total precipitation, storm duration, and stormwater-flow data from individual events (data from Driscol and others, 1990b).

Many runoff models have been designed and implemented to compensate for the inaccuracies inherent in simple runoff coefficient methods used to predict runoff (Alley, 1977). Results of a recent comparative study, however, indicate that even complex rainfall-runoff models may not deliver high levels of predictive accuracy (Zarriello, 1998). When nine well documented stormwater-runoff models were used to predict stormflow volumes from precipitation data from two small watersheds (by experienced modelers using detailed precipitation and land-use data), the average root mean square model error was about 55 percent and simulated storm volumes differed from observed storm volumes by as much as 240 percent.

Despite recognized limitations in accuracy and representativeness, precipitation data are necessary to document study results in a way that is valid and technically defensible. Although the relations in the existing FHWA data set are not quantitative, it is necessary to establish relations between precipitation characteristics, measured flows, and observed contaminant loads so that results from lengthy and expensive data-collection efforts can be applied to ungaged sites. Also, the ratio of measured runoff to rainfall provides verification data that can be used to identify problems with measurement conditions, changes in stage-discharge relations, storage between storms, variations in the contributing area under different conditions, and other possible problems in the data-collection efforts. Precipitation data are necessary to define each storm and each study period in terms of long-term cycles in precipitation. For example, a 1-year study during a long-term period of drought may not accurately represent concentrations, flows, and loads for more typical wetter years.

Precipitation measurements also serve several useful functions that are not provided by runoff-flow monitoring. A recording rain gage provides detailed information about the intensity and timing of precipitation. Knowing exactly when precipitation starts and stops in relation to the beginning and end of measured flows indicates the time of concentration and the time of travel in the drainage basin. Precipitation gages will record light precipitation events, which may not cause a rise in stage sufficient to activate the stormwater-flow-measurement equipment (in which case the stage threshold for equipment activation may be reduced for subsequent events). Also, if heated gages are used, precipitation gages will record winter events that may not result in immediate runoff.

To collect accurate and representative precipitation data, a number of technical factors must be considered. These factors include the proper siting for the measuring equipment, the selection of appropriate measurement intervals, the collection of enough data to characterize conditions at a site, and the selection of methods that will meet data-collection objectives of the study design. A study may produce a detailed record of precipitation in a study area, but bias introduced by problems in the study design may limit the quality and usefulness of data collected on site.

Site Selection

Proper siting is necessary for the collection of accurate and representative precipitation data. The small drainage areas and large proportion of impervious areas characteristic of highway catchments cause large variations in measured flow within a few minutes of variations in precipitation (Harned, 1988). Therefore, the placement and density of gages in a study are critical factors for interpretation of precipitation data in highway- and urban-runoff studies. Individual placement and precipitation-gage-network density are the two main factors to consider when siting gages for a given study. Proper gage placement will help ensure that accurate and representative precipitation data may be collected at individual gage sites, and sufficient gage density within a network will help ensure the accuracy and representativeness of data for estimates of precipitation in a given area.

The magnitude of errors for each gage is a function of wind speed, siting characteristics, and the type of precipitation (Smith, 1993). High winds are recognized as the greatest source of error for rain-gage-data integrity, so some type of wind shielding is necessary (Alley, 1977; Smith, 1993; U.S. Environmental Protection Agency, 1992). Effects of wind created by vehicles travelling at highway speeds, therefore, is a factor to consider when siting precipitation gages for highway-runoff studies. Precipitation gages should be located near the land surface, not on buildings or other elevated structures because mean wind velocities increase with height above local land surface (Alley, 1977; Smith, 1993). Although buildings and trees provide necessary wind shielding, gages should not be placed nearer than the height of the obstacle so that they do not interfere with the path of falling precipitation (Alley, 1977; U.S. Environmental Protection

Agency, 1992). Poorly exposed gages can underestimate measured precipitation by 5 to 80 percent (Alley, 1977). It is also important to locate gages on relatively level surfaces to prevent bias from poor exposure. In small catchments, a precipitation gage should be placed near the runoff flow gage to ensure close correlation between measurements because variations in measured runoff at the surface-water-flow gage are most sensitive to variations in precipitation near the measuring point (Alley, 1977).

Good precipitation gage locations near highways and in urban areas can be hard to find. Highway structures, slopes, buildings, and trees can interfere with precipitation. Ground-level gages are prone to vandalism and tampering. Electricity for a heated gage may not be available in the highway right-of-way, and water formed as a by-product of combustion in fuel-heated gages can bias results. Winds and spray from moving vehicles can be substantial near the roadway (Irish and others, 1996) and cause bias in measured precipitation near the roadway.

Precipitation is recognized to be highly variable in both space and time. For example, Fontaine (1990) indicated that errors in estimates of basin average precipitation from national network data were often greater than plus or minus 20 percent and that supplemental study-site gages were necessary to increase network density for urban-runoff studies. During the last major FHWA field study in the early 1980's, differences in timing, intensity, and magnitude of precipitation were visible in data records among three stations within a few miles of each other (Harned, 1988). The need for multiple rain gages in studies of areal extent is generally recognized (Alley, 1977). Precipitation-gage density is defined as the number of gages per catchment area. The placement of rain gages in a study network should represent catchment topography, and ideally should tie in with historical stations in a larger network, such as the network operated by the National Oceanographic and Atmospheric Administration (NOAA) (Alley, 1977). National networks typically have density of about 1 gage per 230 square miles. For larger watersheds (greater than 100 square miles), gage density is more important than the design of gage distribution in the network to estimate basin average precipitation (Fontaine, 1990).

Thorough documentation of precipitation-monitoring sites and network design is necessary for the validation of precipitation-monitoring data. Factors pertinent to gage siting, such as wind speed and direction of prevailing winds, site slope, proximity to obstacles, and location relative to surface-water-flow-measurement stations, must be considered. The location should be specified to the extent that the site could be reinstrumented for future studies that may later examine source or land-use changes at a given study area. Therefore, a detailed site map is warranted and it should have land features, a scale, and at least two reference points with latitude and longitude to the nearest second. The location of precipitation-monitoring stations with respect to the location of long-term monitoring networks is important to help establish the relation between precipitation-monitoring records during the study and historical records that would indicate the comparability of precipitation measured in the study period to long-term climatic characteristics.

Frequency and Duration of Precipitation Measurements

The frequency and duration of precipitation-measurement operations is dependent upon the time scales of the processes under study. Requirements for sufficient data are defined by data-analysis techniques, quality of data needed, program objectives and constraints, and the representativeness and variability of the storm events that are gaged and sampled (Alley, 1977). For stormwater-quality studies, the recording frequency must be sufficient to characterize and interpret physical (hydraulic) and chemical processes. In terms of duration, monitoring equipment needs to be able to record an entire event (at least up to a specified design storm) and to be durable enough to operate reliably between scheduled maintenance visits. The duration of the monitoring program must be designed so as to be able to put data into historical perspective. Historically, measurement frequency has been controlled by the sampling budget and the program duration has been controlled by both budget and time constraints. Although these will always be real issues, continuous improvements in automatic-monitoring instrumentation and equipment can improve upon data available from manual measurements.

High-frequency-monitoring capabilities available from state-of-the-art data logger-controlled-monitoring systems have the potential to improve the understanding of physical and chemical rainfall-runoff processes. In terms of the monitoring frequency, the apparent randomness in stormwater processes from storm to storm and from site to site may be related to lack of adequate data, especially related to the time scales of measurement (Spangberg and Niemczynowicz, 1992). The maximum recording interval for individual precipitation measurements depends upon catchment size and can range from less than 1 minute for very small paved catchments to a maximum of about 15 minutes for larger catchments (Alley, 1977; Spangberg and Niemczynowicz, 1992). In theory, the recording interval should not be longer than one-fifth to one-tenth of the time it takes for water from the furthest point in the catchment to reach the flow-gaging station during times of most rapid flows (Alley, 1977). Harned (1988) found that in one highway-runoff study, runoff in the smallest basin (with an area of 0.0032 square miles, including a highway and a rest area) responded within minutes to changes in rainfall intensity, and the maximum discharge coincided with periods of intensive rain. Stormflow recession was brief in this small catchment that had a high proportion of impervious cover and an engineered drainage system (Harned, 1988). Chemical response time for the catchment should also be considered in stormwater-quality studies. In the field studies sponsored by the FHWA that were designed to characterize highway-runoff quality, precipitation data were recorded on a time scale of about 5 minutes (Shelley and Gaboury, 1986). When Spangberg and Niemczynowicz (1992) examined relations between measured precipitation, turbidity, pH, specific conductance, and flow rate (measured on a 10-second time interval on a 0.0001-square-mile paved parking lot), cross-correlation analysis indicated that changes in water quality occurred with changes in precipitation intensity and flow rate on a time scale of less than 1 minute. Although the high costs for collection and analysis of water samples are a limiting factor for many projects, costs for installation and operation of automatic precipitation, flow, and water-quality instruments do not vary with monitoring frequency. Relatively high-monitoring frequencies provide substantially more detail and insight, but do not necessarily require substantially more labor and resources for data collection, storage, processing, and interpretation. The main drawback to high-monitoring frequencies—the possibility of the loss of data by exceeding the storage capacity of the data recording device—can be avoided by use of a regular station maintenance schedule coupled with available technology for remote data retrieval by telephone, cellular telephone, radio, or satellite link.

The required station maintenance schedule for precipitation-monitoring studies is defined by the storage capacity of the data recording device. Automated monitoring stations can be programmed to minimize measurement activity during dry periods and to maximize data collection frequencies during periods of stormwater runoff (Church and others, 1996). Additionally, many precipitation gages only record data when activated by measured precipitation. The frequency and duration of expected events in a given area are important factors in these determinations. It is important to characterize even small events because when the frequency distribution of storms of different size and duration are grouped, the proportion of annual precipitation is about equal for the different storm-size classes (Brown and others, 1995). A compromise between high-resolution monitoring and duration can be achieved using programming that measures on a high frequency but only records measurements at high frequencies during storm events when flows and water-quality measurements are changing rapidly (Church and others, 1996).

On a longer time scale, the duration of precipitation-monitoring studies is limited by the duration of the project. Studies have shown that decades of rainfall and streamflow data are necessary to generate design storm statistics in a catchment, but it is also recognized these monitoring durations are impractical for most stormwater projects (Alley, 1977). Theoretically, over long periods of time, the random variation of storm patterns in time and space in an area will be equal to reference stations and, therefore, population statistics will be similar. There are several standard methods for record extension when data from one site can be correlated to a monitoring site with a long period of record (Helsel and Hirsch, 1992). Long-term monitoring data for record extension are available from a national weather-monitoring network maintained by the NOAA (Alley, 1977). Long-term precipitation records may also be available from municipal governments, water and wastewater treatment plants, universities, airports, news organizations, and other sources. Daily precipitation values, however, are often based on a sampling day (for example, 9:00 a.m. one calendar day to 9:00 a.m. the next calendar day), so direct day-to-day correlation may be difficult if daily data is not synchronized among data sources.

Thorough documentation of the frequency and duration of data from precipitation-monitoring stations is necessary to ensure the validity and usefulness of data collected. Comparison of the characteristics of measured precipitation during the study period is necessary for immediate and future users of the data in order to put observations made during the study period into a long-term perspective that will improve the interpretive/decision-making process. Supporting data or the source of published data (such as the NOAA records from a given monitoring station) and the comparative analysis should be documented in published reports for future use.

Methods for Measuring Precipitation

Methods that allow accurate monitoring of precipitation intensity and total accumulated precipitation are necessary for planning, design, collection, and interpretation of results for stormwater-quality studies. Historically, a 0.01-inch (0.25-mm) precision level has been considered to be comparable with distortions in precipitation catch encountered in urban areas, the areal variability of precipitation, and the precision level of other stormwater-monitoring instruments (Alley, 1977). At least one recording gage is necessary to provide the detailed precipitation information needed at each study site, but data from nonrecording gages can supplement this information, and (or) be used to build correlations among established precipitation-monitoring sites.

Nonrecording precipitation gages (manual measurements) are generally sufficient for measuring total precipitation during the measurement period. These gages do not directly provide information about the actual timing, duration, or intensity of precipitation that occurs during the measurement period. Any open container with an established rating between precipitation catch and either weight or depth of precipitation collected can be used as a nonrecording gage (U.S. Environmental Protection Agency, 1992). Nonrecording precipitation gages can provide excellent verification (Quality Assurance and Quality Control) data because they are easily constructed and (or) inexpensive to obtain. One or more nonrecording gage(s) can be used in conjunction with a recording gage to provide substitute information in case of equipment failure. A number of these devices can be emplaced to supplement recording gages and used to examine assumptions about the areal distribution of total precipitation in and around a study area. Data from these gages can be biased by evaporation or by overflow conditions if the time between manual measurements is substantial. Results from visual gages can be biased by parallax, and water displacement, or absorption upon insertion of a measuring stick. When using nonrecording gages, records for snow events must be derived from measurements of snow depth and water content (Alley, 1977). Representative snow measurements from nonrecording gages in highway rights-of-way may be difficult because of variations caused by natural and vehicle-induced winds, as well as by snow removal/deicing operations.

Recording precipitation gages (automatic measurements) have several advantages over nonrecording gages. Recording gages can record the timing, duration, and intensity of precipitation that occurs during the measurement period, as well as indicate the total precipitation for each storm. Depending upon the design of the gage, evaporation is either not an issue or evaporation between events can be determined from data records. Also, automatic gages are generally designed to prevent or reduce errors from overflow. Most rain gages, however, have a tendency to under record when rain is greater than 3.0 inches per hour (Alley, 1977). Studies in areas with large variations in precipitation intensities may require more than one gage, each with different resolutions, at each monitoring site (Spangberg and Niemczynowicz 1992).

Weighing, float, and tipping-bucket gages are the three main types of recording precipitation gages that are widely accepted and readily available (Alley, 1977; FHWA, 1985; U.S. Environmental Protection Agency, 1992). Weighing gages measure and record the weight of water in the collector at each time interval. Float gages measure accumulated rain by recording the position of a float in a collector. Float gages can be emptied by a siphon tube or by an automatic pump when full. Tipping-bucket gages measure precipitation by recording the actuation of a small seesaw each time the receptacle (the bucket) at an end of the pivot fills, tips, and empties. Tipping-bucket gages have a long record of proven ability, commercial availability, and are the most widely used (Alley, 1977).

Snow is more difficult to measure than rain. Weighing gages are generally better for snow than other gages. Float gages and tipping-bucket gages are not suitable for measuring snow unless they are heated. Requirements for heating gages raise logistical and interpretive complications due to the necessity for fuel or power for heating and accounting for the precipitation lost to condensation as a result of this heating.

Improvements in collection and interpretation of weather radar and satellite data over the last 10 years should be considered to provide information about local precipitation characteristics when planning a study or verifying data collected. Radar has high temporal (as small as 5 minutes) and spatial (as small as 0.386 square mile) resolution and range over a range of up to 130 miles (Smith, 1993). Radar measurements are subject to a number of sources of uncertainty, and so may not be sufficient as a primary precipitation-monitoring system, but they may be obtained from the National Weather Service, news organizations, and airports. Many of these organizations post these data to the internet. Precipitation estimates from satellite measurements are based upon infrared imagery of cloud-top characteristics. Although these estimates are not precise, this information may be used to estimate rainfall in areas not covered by data networks using more precise methods (Smith, 1993).

Thorough documentation of precipitation-monitoring methods and measurement equipment used is necessary for the validation of precipitation-monitoring data. Factors pertinent to manual and electronic recording device, such as calibration and maintenance records, the maintenance schedule, the measurement interval, and equipment malfunctions, should be documented and archived in project records. Details about equipment construction and operation of gages (including equipment specifications) should also be documented and archived in project records. Precipitation records in published reports should include the measurement interval and equipment specifications that are relevant to interpretation and calibration of the data. Simply recording the make and model of a device will not be sufficient if specifications change or if detailed information may not be available from the manufacturer.

STORMWATER-FLOW MEASUREMENTS

The accuracy and representativeness of stormwater-flow measurements for computation of pollutant loads and event-mean concentrations, whether from a natural stream channel, an engineered channel, a highway or urban drainpipe, sheetflow from a parking lot, or overland flow from a grassy swale, are based on many common factors that all contribute to the uncertainty of the data set. These factor include:

- The representativeness of the site selected in relation to the contributing area of concern,
- The ability to obtain accurate flow measurements at the selected site,
- The timing, frequency, and duration of flow measurements, relative to the timing, intensity, and duration of the storm, to fully characterize the flow event, and
- The ability of the flow-measurement method to accurately measure the full range of flows at a frequency required to fully characterize the flow event.

Selecting representatives sites, ensuring their suitability for accurate flow measurement, determinating appropriate measurement frequencies, and selecting the best method for measuring flows may require a significant effort, but are critical for the measurement of accurate and representative flows. For example, when receiving waters are also monitored, the stability of the stream channel bed and banks up and down gradient of the proposed site must be assessed before the site can be assumed to consistently yield accurate streamflow data. Selecting a representative section of pipe for measuring flow requires analysis of the pipe network above the site to identify all contributing areas, and analyses of the pipe network below the site to identify potential for backwater flow. The flow regime (steady- or unsteady-state flow, subcritical, supercritical, or pressure flow) and changes in the flow regime with stage need to be evaluated for selection of the appropriate method for measuring the flow. As many stormwater-flow measurements are made for the determination of pollutant loads, factors that may affect water-quality properties and constituents, and collection of water samples also must be considered in selecting a site and in determining frequency of flow measurements. Although this report is focused on stormwater flow in small streams and in highway- and urban-drainage systems, many of the principles upon which accurate and representative flow measurements are obtained in large streams are applicable to flow measurements in small streams and drainpipes, and are therefore included in this report.

Documentation and reporting of the supporting data from which decisions were made as to where along a stream channel or within a highway- or urban-drainage network flow will be measured, how frequently flow will be measured, and what method will be used to measure the flow are required for internal and external evaluation of the accuracy and representativeness of the flow data. Important questions that must be addressed in the selection of a representative site where accurate and complete flow measurements can be obtained are listed in the following sections. Although the time and effort expended to address these questions to ensure accurate and complete flow measurements at a representative site may be considerable, documentation and reporting of this effort should be a rather simple task if each step in the process is described in detailed field notes during the selection process. To ensure that the accuracy and representativeness flow measurements can be evaluated, the supporting data and information used to make the final decisions must be documented and communicated in an accessible format, such as a project description report, a data report or an appendix to a technical report, and (or) archived in a State or national records center.

Site Selection

Selecting a location for obtaining flow measurements within the drainage network requires evaluation of the representativeness of the site in yielding flow data that are consistent with the objectives of the investigation, and the hydraulic and physical suitability of the site where accurate flow measurements can be expected to be obtained. The importance of proper site selection cannot be overstated. No matter how accurate the flow data, if the site does not provide information to meet project objectives, the data have little meaning (Whitfield, 1988). Ideal sites rarely exist, however, and a compromise between many factors must be made in selecting the best site. The basic questions that need to be addressed in selection of the best, or most representative, site are:

- Will flow measured at this site represent the contribution from the area of study?
- How are the flow velocities distributed?
- How stable is the flow regime?
- Can a stage-discharge relation be developed?
- How steady would this stage-discharge relation remain over time?
- Is access to the site acceptable?
- Can equipment be installed?
- Can manual measurements of flow be made?
- Is floating debris manageable?
- Is the site safe for personnel and equipment?

Consideration of the above questions in selecting a site may require a significant amount of office and fieldwork. The time and effort expended, however, will ensure that the site selected, from among other potential sites, will yield stormwater-flow data most representative for the project objectives. The risk of having selected a poor or non representative site is significantly reduced by this initial investment. Additionally, the information obtained during the site-selection process must be clearly documented and included in a data report or in another accessible format to allow for independent evaluation of the selected site, and for potential use of the site for future investigations. Guidelines for site selection of gaging stations along streams are provided by Carter and Davidian (1968), Rantz (1982a), the Federal Highway Administration (1985), and the Natural Resources Conservation Service (1996).

The initial site selection (whether along a stream channel, within a highway- or urban-drainage network, or from a paved surface or grassy swale) and alternative site selections should include review of reports and other documents concerning the hydrology of the drainage area, examination of maps or highway- and urban-drainage network plans, and personnel communication with State and town transportation agencies and residents living near the proposed site. Drainage-basin area, relief, slope, elevation, stream-network pattern, and locations of tributary streams can be determined from topographic maps or readily available geographic information system (GIS) data bases. Land use may be inferred from these maps as well. Drainpipe network, pipe slope, locations of catch basins and manholes, pervious and impervious areas, slopes of paved areas and grassy swales with drainage catchments, and other physical structures can be determined from as-built, or pre-built site plans, although in older built areas this information is sometimes difficult to find. This initial information in site selection is necessary because it provides a general understanding of the flow system, identification of location within the drainage system where the most representative data can be collected, and an initial evaluation of upgradient and downgradient factors that may unduly influence flow measurements at the selected location.

Field inspection is required to ensure that the site is hydraulically and physically suitable for accurate measurements of flow and that the site can be accessed and data collected safely. The basic hydraulic considerations are the distribution of velocities within the flow and potential changes in flow regime with stage. A uniform velocity distribution in the flowing water throughout the full range of flow, with no change in flow regime, would provide for the ideal conditions whereby the flow rate could be determined from one measurement of water depth. The velocities in most flows are not distributed uniformly, however, and the distribution of velocities and flow regimes may change over the range of flows. To account for this non-uniform velocity distribution and potential changing flow regime in streamflow measurements from moderate to large streams, flow rates are measured in many thin vertical sections along a line perpendicular to the stream channel (Buchanan and Sommers, 1969; Rantz, 1982a). In small streams and in highway- and urban-stormwater drains, however, multiple measurements are typically restricted by space and time. The small number of flow measurements attainable due to the narrow widths, and sometimes shallow depths, are insufficient for accurate flow measurements, and due to the rapidly changing flow, each individual measurement could represent part of a different flow rate and velocity distribution. In these types of flows, flow-control devices, such as weirs and flumes, are commonly used (Buchanan and Sommers, 1969; Marsalek, 1973; Alley, 1977; Kilpatrick and Schneider, 1983; Kilpatrick and others, 1985; Federal Highway Administration, 1985; Natural Resources Conservation Service, 1996). Flow measurements from these devices typically require only one measurement of stage-per-unit time because they produce a consistent distribution of velocities throughout the nearly full range of flows.

Physical considerations are generally related to selecting a site where the distribution of velocities in the flowing water is minimally disturbed, and is expected to remain so over the period of investigation. Although multiple flow measurements are used in stream-discharge measurement and flow-control devices are used for flow measurements in highway- and urban-drainage systems to account for the non-uniform distribution of velocities, evaluation of the distribution of velocities remains an important part of the site selection process. Therefore, field inspection includes an upstream and downstream evaluation of flow characteristics and factors that may affect the flow in space and time, such as the stability and uniformity of the stream-channel-bed and bank sediment, the stability of the channel bank and adjacent flood-plain vegetation, the straightness of the channel, lateral location of the channel within the flood plain, flow pattern within channel, variations in channel width and depth, and the proximity of small tributaries, rivulets, seeps, and physical structures that are not shown on the map of the area, and the presence of floating or submerged debris. Visual inspection of land use and its possible effect on flow and flow measurements should be done. For highway- and urban-drainage systems, the locations and elevation of catch basins, manholes, pipe intersections, and outfalls should be checked with the plans, and corrected on the plans if needed. Although validation of location of underground pipes in highway- and urban-drainage networks may be difficult, the flow routes can usually be determined by visual inspection of the elevation and direction of pipes, and their material composition, diameter, and number, from which flow enters and exits catch basins and manholes. Field inspection should also include an estimate of the relative amount of pervious and impervious area within the catchment area. Thorough field inspection will ensure that a site of minimal-flow turbulence is selected, or can be constructed, for measurement of flow representative of the expected sources of runoff.

As the measurements of stormwater flow in highway-runoff studies are used primarily for determination of pollutant loads, factors affecting measurements of water-quality properties and constituents and sample collection should also be considered in the site-selection process. For example, sufficient flow depth for complete submergence of water-quality probes is necessary, and factors such as backwater from downstream controls that may affect the temporal representativeness of samples and water-quality measurements need to be evaluated. If project objectives allow, select a site where data may be applicable to more than one investigation, or where data collected in the future can be used to evaluate trends.

Maps, tables, and written descriptions of the hydrologic features of the stream or drainpipe network are necessary to evaluate the quality of flow data with respect to the appropriate location of the flow-measurement features. A report should clearly indicate the position of the flow-measurement station with respect to the catchment area, local and surrounding land uses, and the relative amount of pervious and impervious areas contributing. It is important to document the location and characteristics of the natural or constructed flow-control features. It is also important to document the slope of the stream/pipe/swale to help establish the flow regime. Where overland flow is measured, detailed information about the surface characteristics and flow-concentration structures are necessary.

This careful and thorough review of maps or construction plans and field inspection will help ensure that reasonably accurate and representative flow measurements can be obtained. Documentation of the initial site evaluation and the field inspection will ensure that the site located for collection of flow measurements can be validated. It would be unusual if an ideal site was found. But by documenting the information obtained during the site-selection process, archiving the documentation, and including pertinent information in a published project description or data report, or in an appendix to an interpretive report, a level of certainty of the data collected and interpretations made may be evaluated.

Frequency and Duration of Stormwater-Flow Measurements

The timing, frequency, and duration of flow measurements are critical factors in monitoring accurate flows in small streams and highway- and urban-drains because of the rapid response to stormwater runoff and the wide ranges of flow over short periods of time. As with precipitation, frequency and duration of flow measurements are dependent upon the time scales of the process under study. Additionally, flows in response to stormwater runoff typically rise more quickly than they fall, and pollutant concentrations have been shown to rise and fall more quickly than the flow in which they are transported (Vanderborght and Wollast, 1990; Spangberg and Niemczynowicz, 1992; Barrett and others, 1993). This phenomenon, referred to as the first flush or initial wash off, is especially prominent in highway- and urban-drains. Irish and others (1996) found that most of the constituents in highway runoff are attached to fine-grained sediments that tend to accumulate within 3 feet of the curb during dry periods. This proximity to the curb allows for the sediment and chemical constituents to be entrained in the pavement runoff and curb flow, and discharged into the drainpipes in the early part of a storm. The magnitude and extent of this first flush also can be affected by the nature and solubilities of the constituents being transported in the water (Hvitved-Jacobsen and Yousef, 1991). Although pollutant concentrations may be considerably less in the latter part of the runoff events than in the first part, pollutants may continue to be discharged, necessitating flow measurements throughout the entire duration of the event (Barrett and others, 1993). Stormwater flows respond differently to different types of storms and may respond differently to the same type of storm in different seasons of the year. Therefore, it is critical that measurements of flow start at the beginning of the storm, continue through the duration of the event, and are measured at a frequency corresponding to the rate of change of flow and constituent concentrations to ensure the accuracy and representativeness of the resultant flow and pollutant loads. Collection of water-quality data should be synchronized with the timing of flow measurements so that concentrations can be directly applied to measured flows.

A general understanding of the rainfall-runoff relation in the region (area) is needed to evaluate the timing, frequency, and duration of flow measurements that will ensure accurate and representative stormwater-flow data. The basic questions that need to be addressed in selecting the timing, frequency, and duration of flow measurements include:

- What is the time of concentration of flow and pollutants in relation to storm intensity?
- What is the rate of change of flow?
- What is the range of flows?
- How do rates of changes of flow and ranges of flow differ between storm types and seasons?
- Can flow measurements be synchronized with collection of pollutant samples?

Guidance in the initial selection of frequency of flow measurements, whether measuring flow in a highway drainpipe or in a stream channel, can be obtained by examining historical precipitation and hydrologic data from near the proposed site, or from other similar sites within the same type of physiographic region. For highway- and urban-drains, data should be available from the engineering firm that designed the drainage networks, or from the State or municipal agency responsible for maintaining the drainage system. Pipe diameters were likely designed for a maximum open-channel-flow depth for a specific storm intensity, duration, and recurrence interval. Field observations of flow during and after storm events can be very useful. Additionally, a numerical method for approximating the minimum frequency of flow and concentration measurements for meeting a desired accuracy is available (Nesmerak, 1986). However, a more accurate method for selecting frequencies of flow measurements to ensure the accuracy and representativeness of flow volumes and pollutant loads measured in stormwater runoff is use of continuous electronically measured and recorded-stage and water-quality measurements, such as specific conductance and (or) turbidity, in response to storm events. The times of concentration of flow and constituent concentrations can be interpreted from the electronically recorded data, and the frequencies of measurements needed at various stages and times throughout the event can be determined. Continuous measurements and recording of stage and water quality at different times of the year, during different types of storms, or under different antecedent conditions, will provide data needed to optimize recording and sampling frequency under a variety of conditions and at similar sites.

In a study in which the constituents of road salt in highway runoff were measured in the trunkline drainpipes of a six-lane highway (Church and Friesz, 1993; Church and others, 1996), stage and specific conductance measurements in the approach sections of Palmer-Bowlus flumes were electronically measured every minute, but only recorded every hour at times of minimal-to-zero flow. To account for the initial rapid flush of the road-salt constituents during runoff, flow recording and water-quality-sampling frequencies were automatically increased to a minimum of 10 minutes and a maximum of 1 minute in response to changes in stage and specific conductance (**fig. 3**).

Data used to establish the timing, frequency, and duration of flow measurements need to be documented and reported to help ensure that the flow data can be validated. These data include the type of drainage system (i.e., stream, highway, or urban drainage), drainage area, stream channel or pipe slope, percent impervious area, climatic and meteorological data, and, if pollutant concentrations and loads are to be measured, the source, amount, distance to monitoring station, and when pollutants are released.

Methods for Measuring Stormwater Flow

Methods have been developed for measuring flow in many types of conduits (flow in natural channels, engineered channels, pipes, sheetflow, and overland flow) under various flow regimes (steady- or unsteady-state flow, subcritical, supercritical, or pressure flow). Most of these methods have two parts: a primary device that directly interacts with or controls the flowing water, and a secondary device for measuring water depth or pressure (Marsalek, 1973; Alley, 1977). Selection of the most appropriate method for collection of accurate flow data that are representative of the particular site requires knowledge of the flow regime(s), range of flow and flow depths, rapidity of changes in flow, channel geometry, and the capabilities and accuracies of the methods available for measuring flow.

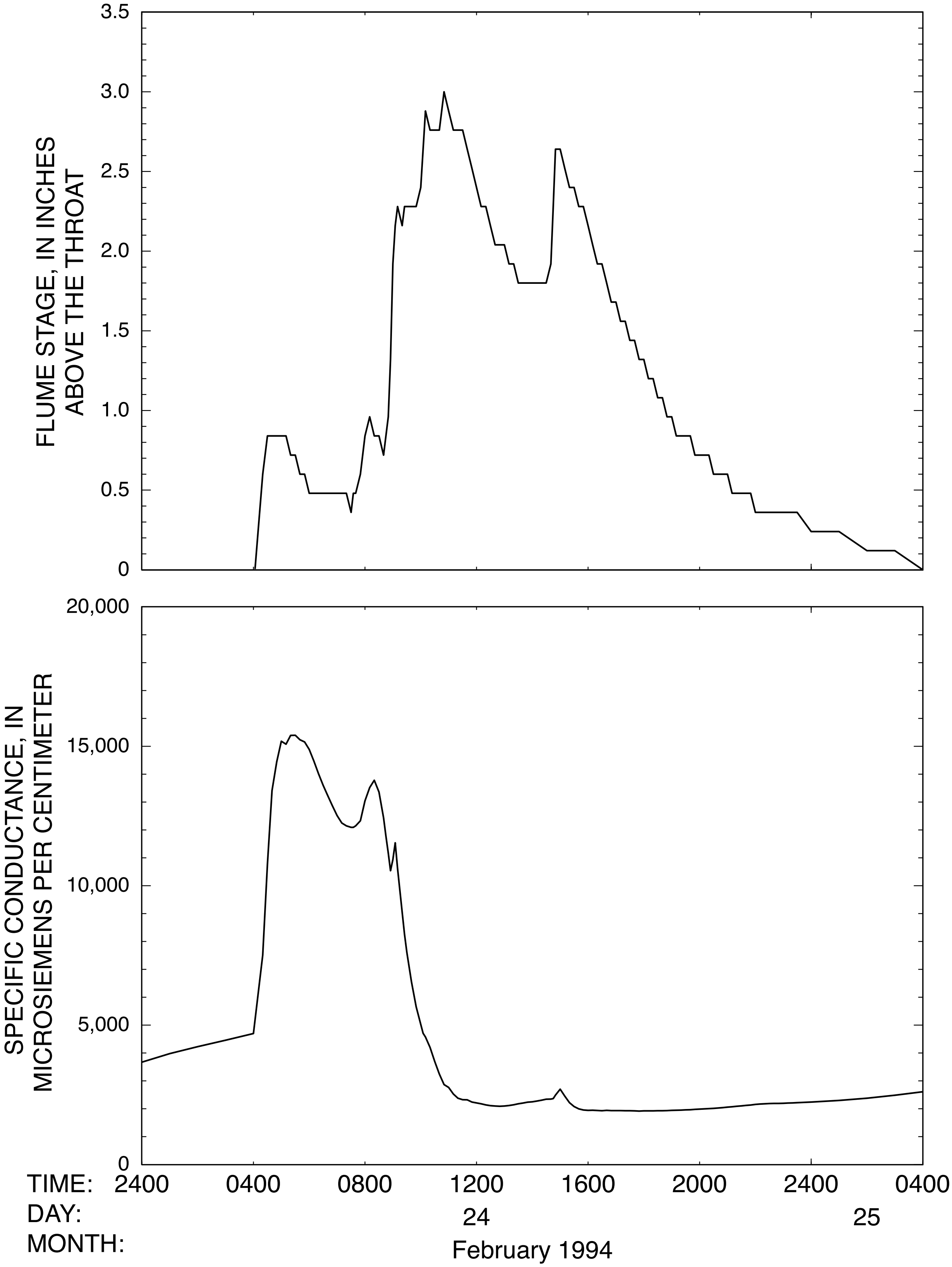


Figure 3. Stage and specific conductance monitored at various frequencies in response to changes of stage and specific conductance (Church and others, 1996).

Assuming that the flow and channel characteristics were assessed in the site-selection process, the important questions that remain are:

- Is the flow measuring method applicable to the flow and channel characteristics at the site?
- Is the flow measuring method capable of measuring the full range of flows?
- Is the flow measuring method capable of measuring flow at frequencies required to fully characterize the event?
- Will the flow measurements be of sufficient accuracy to meet the objectives of the study?
- Can the accuracy of the flow measurement method be verified with another method?

Data that need to be documented and reported for validation of a selected flow measurement method, and to ensure that the flow measurement method can be independently validated, include the hydraulic characteristics of the flow and the capabilities and limitation of the method. A report should include the observed type of flow and changes in flow type during storm events, ranges of types of flows measured, and the method used to measure the flow. If a flow-control device was used, details as to the construction, installation, depth/flow relation, calibration, and maintenance should be reported. Equipment and instrumentation (primary and secondary devices), and their resolution, tolerance, and design limits, as defined by the manufacturer, should be documented as well as calibration and maintenance records. Modifications to the method and the resultant resolution, tolerance, and design limits also should be documented. With this information, the appropriateness of the selected method, the placement and use of a flow-control structure, and the accuracy and precision of the flow data measured, can be evaluated.

The most common types of flow measurement methods and their applications are described below. Further guidance in the selection of an appropriate method of flow measurement can be found in Marsalek (1973), Shelley and Kirkpatrick (1975), Alley (1977), Federal Highway Administration (1985), and Natural Resources Conservation Service (1996).

Primary Devices/Methods

Channel Friction Coefficient Method

This method is best described by Manning's equation, in which flow is related to the hydraulic radius of the flow cross section, slope of the water surface, and an estimated friction of the channel, referred to as a roughness coefficient. The accuracy of flows determined by Manning's equation are dependent upon steady, uniform flow in straight channels or pipes of uniform shape, slope, and roughness. Manning's equation is useful for estimating flow in ungaged open channels and pipes. The accuracy of the flow determined, however, varies widely. Brown and others (1995) reported of errors up to 15 percent in flow measurement in short, straight channels by use of this method. Others studies have shown that the accuracy of this method, at best, is about 15 to 20 percent (Alley, 1977). Marsalek (1973) stated that under conditions of unsteady, non-uniform flow in drainpipes, typical of flows in highway- and urban-drainpipes, Manning's equation will underestimate flows in the rising stage and overestimate flows in the falling stage. As pollutant concentrations have been shown to peak before the flow in which they are transported (Barret and others, 1993; Spangberg and Niemczynowicz, 1992), errors in pollutant loads are likely to be greater than 20 percent if the flow was determined by Manning's equation.

Index Velocity Method (Current-Meter Method)

In most streams, where flows change slowly with time in comparison to flows in highway- and urban-runoff-drainage systems, point velocities are measured in multiple vertical sections along a cross section of the stream channel by use of a velocity meter or current meter (Buchanan and Somers, 1969; Rantz, 1982a; Rantz, 1982b). The velocity in each vertical section is measured at a depth that theoretically, and field verified, represents the mean velocity in that section. If depth of the flow is sufficient, velocity is measured at two or more depths, the average representing mean velocity. Mean velocities are multiplied by the cross-sectional area they represent, and are then summed to obtain the total flow, or discharge, at that stream cross section. Many velocity/area measurements are taken along the stream cross section to reduce the influences of irregularities in the stream channel and non-uniform distribution of velocities at the stream cross section on the total flow measurement. Rantz (1982a) stated that total discharge at a streamflow section is usually represented by the sum of discharges from 25–30 subsections (**fig. 4**). Relations between stage (the height of the water surface relative to a stable reference point) and discharge are developed and refined as more discharge measurements are made. Secondary devices, such as floats or pneumatic bubbler systems and mechanical or electronic data recorders, are used for continuous monitoring and recording of stage (Buchanan and Somers, 1968; Marsalek, 1973). Continuous records of stage are applied to the stage-discharge relations to generate continuous records of discharge.

The accuracy of a subsection discharge measurement is a function of the accuracies of the measured cross-sectional area of each vertical section, the velocity measurements, and whether the measured velocities represent mean velocities which are based on assumed velocity profiles (Alley, 1977). Errors in velocity measurements arise primarily from poorly calibrated and poorly maintained meters, and from velocity measurements obtained at inappropriate depths or under turbulent flow conditions. The accuracy of the stage measurements is dependent upon the resolution of the equipment and instrumentation, use within their designed ranges, and proper calibration and maintenance. Sauer and Meyer (1992) stated that the error of most discharge measurements using the current-meter method (with vertical axis, cup-type current meters (Buchanan and Somers, 1969)) ranges from 3 to 6 percent. Under ideal conditions, an error as low as about 2 percent can be achieved, but under poor conditions the error may be greater than 20 percent.

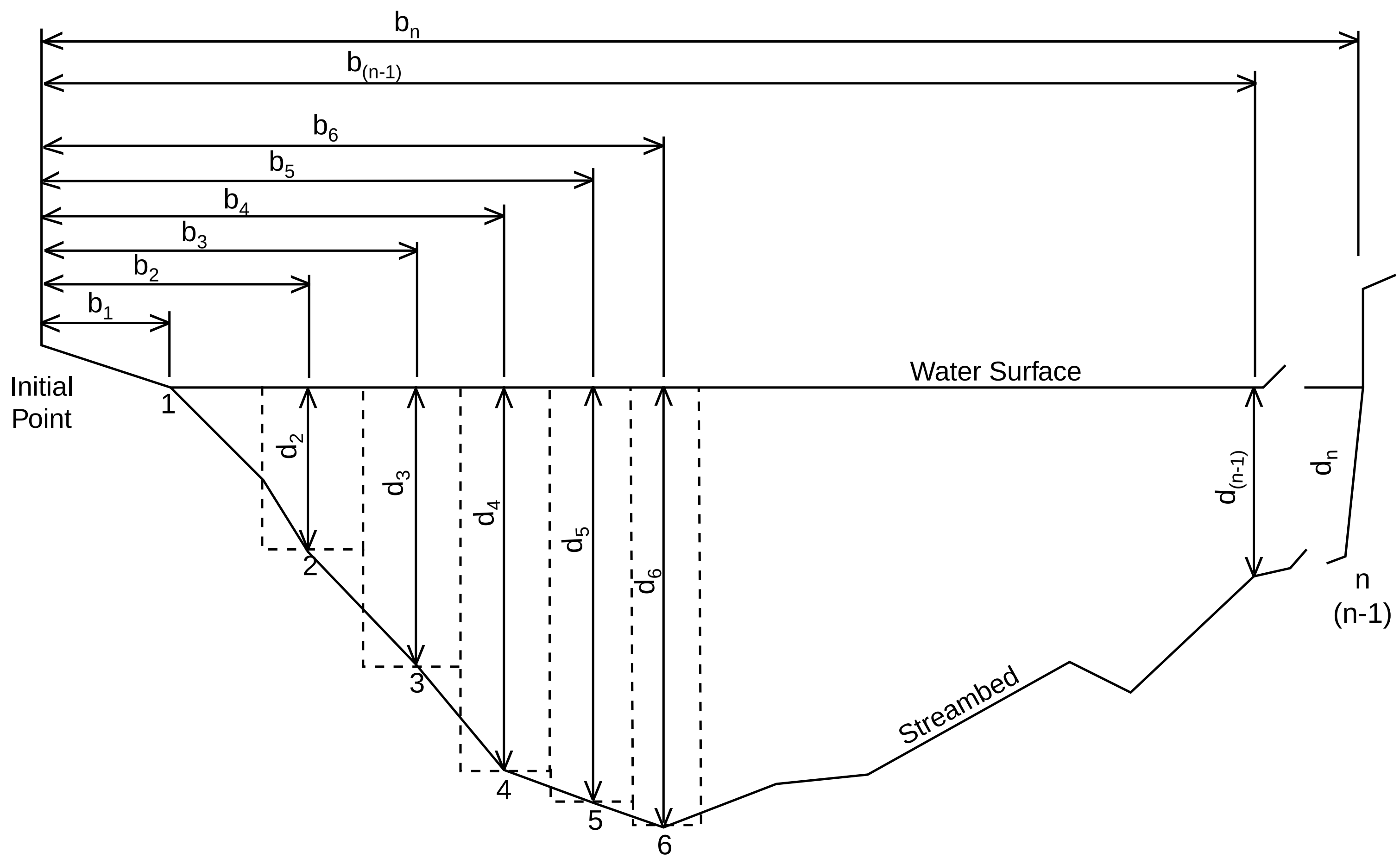
Documentation of the tolerance and resolution of the equipment and instrumentation is needed along with calibration data and service records to ensure that stage measurements can be validated. The importance of accurate and verifiable stage measurements cannot be understated because stage is used as a surrogate for flow in most reported flow measurements. The accuracy of the stage-discharge relation is dependent upon the accuracy of the individual stage and discharge measurements that define the relation, which in turn are dependent upon the accuracy of the many velocity/area measurements that constitute a single discharge measurement. The extent to which the stage-discharge relation can be confidently applied is related to the range of flows measured. Therefore, collection of flow measurements that represent the full range of discharges is desirable.

The current-meter method is used primarily for flow measurements in moderate to large streams, and in small streams with moderate to low slopes. Other methods, such as weirs, flumes, and dye dilution, yield more accurate flow measurements in small streams with high slope, and in highway- and urban-drainage pipes (Katz and Fisher, 1983).

Weirs

Weirs are overflow-control structures installed in a small stream channel or culvert that produce a relation between the depth of water behind the weir and the flow (Marsalek, 1973; Alley, 1977). Weirs are typically made of thin rectangular metal plates set vertically across the channel. Weirs referred to as “broad crested” are constructed with concrete. Flow is forced over the top edge of the metal plate or concrete weir. To measure low flows more accurately, the middle of the top edge of the metal plate is cut to form a V-shaped, trapezoidal, or rectangular notch. Stage is measured with floats or pneumatic bubbler systems and recorded with mechanical or electronic data recorders. Continuous records of stage are applied to the stage-flow relation to generate continuous records of flow. However, the stage-flow relation breaks downs under the condition of submergence or surcharge. Field calibration of the stage-flow relation is necessary.

Weirs are useful for measuring flows in small, low-velocity stream channels where the index velocity method may be inappropriate due to shallow depths and non uniform flow (Buchanan and Somers, 1969) and at outfalls and in open channels (Alley, 1977). Accuracies within 5 percent can be attained if the weir is calibrated (Marsalek, 1973). Although weirs are simple to construct and cost little compared to most other methods, they are not recommended for use within pipes because they restrict the flow and cause excessive backwater and debris accumulation, and are susceptible to submergence and surcharge (Alley, 1977).



EXPLANATION

1, 2, 3 .... n	OBSERVATION VERTICALS
b_1, b_2, b_3 .... b_n	DISTANCE, FROM THE INITIAL POINT TO OBSERVATION VERTICAL
d_1, d_2, d_3 .... d_n	DEPTH OF WATER AT OBSERVATION VERTICAL

Figure 4. Example of stream channel cross section showing current-meter method where flow velocities in subsectional areas are used to measure stream discharge (modified from Rantz, 1982a).

Flumes

Flumes are flow-constriction structures that control the flow hydraulics such that flow is directly related to head (Marsalek, 1973; Alley, 1977; Kilpatrick and Schneider, 1983). Flow in a small stream or drainpipe passing through a flume is accelerated, resulting in decreased depth, by some combination of sidewall contractions, raised floor, or increased slope. Flow exiting the flume decelerates when reentering the channel or pipe. Flumes in which subcritical flow in the approach section of the flume remains subcritical, but at a higher velocity in the contraction (throat), require head measurements at both the approach and throat sections of the flume to compute flow. A direct relation between head in the approach and flow in the throat exists in flumes where flow becomes supercritical in the throat. Due to the need for two head measurements in the subcritical flow flumes, they are seldom used today (Kilpatrick and Schneider, 1983). The most commonly used flumes are the Parshall flume and the Palmer-Bowlus flume, both of which produce supercritical flow in the throat.

The Parshall flume is used for measuring flow in small streams, at outfalls, and in open channels where the index velocity method may not be appropriate due to shallow depths, narrow widths, and non-uniform flow. Due to its rectangular shape, elongated structure, and requirement for a vertical drop through the flume, it is not very useful in measuring flow within drainpipes. The Palmer-Bowlus flume was designed for use in drainpipes, and is not very useful in any other flow conduit. A Palmer-Bowlus flume installed in the trunkline drainpipe of a six-lane highway-drainage system is shown in **figure 5** (Church and others, 1996). Flumes should be installed at sites where the potential for surcharge, full-pipe pressurized flow, and backwater effects are expected to be negligible. Although the Palmer-Bowlus flume acts as a venturi meter under full-pipe pressurized flow, and flow rate can be calculated from head measurements in the approach and throat of the flume, the relation between head and flow breaks down in the transition zone from near-pipe-full to pipe-full flow (Kilpatrick and others, 1985). Advantages of flumes over weirs include less backwater and their self-cleaning abilities.

Theoretical depth/flow relations are developed for weirs and flumes based on their geometry, and in the case of flumes, slope (Buchanan and Sommers, 1969; Kilpatrick and Schneider, 1983, Kilpatrick and others, 1985). The accuracy of these flow measurements is dependent upon the accuracy of the construction and installation of the weirs and flumes in the stream channel or drainpipe (i.e., level in a direction perpendicular to stream channel or pipe, no deformation during construction or installation, no leakage at approach section), and the measured geometry, slope, and friction of flume surfaces. A well-constructed, calibrated, and maintained flume may yield flows with accuracies of 2-3 percent (Buchanan and Sommers, 1969; Marsalek, 1973); however, when factoring in the error of the secondary device used for monitoring stage, the accuracy is about 5 percent (Marsalek, 1973; Alley, 1977).

Differential Pressure Method

The differential pressure method is used to measure full-pipe pressurized flow and, as this flow condition is rare in highway- and urban-drainpipes, it has limited value in highway- and urban-runoff flow measurements (Alley, 1977). Flow-constriction devices, however, have been developed that act as critical-flow flumes under open-channel-flow conditions (the head in the approach section is directly related to flow in the throat section), and venturi meters under full-pipe pressurized conditions when the flow can be calculated from the difference in heads in the approach and throat sections of the flume. One is designed with a single-side wall constriction (Wenzel, 1975) and the other with a U-shaped throat constriction (Smoot, 1975). Flows at near-pipe-full, the transitional zone from open-channel to pipe-full flow, are difficult to measure because the flow pulsates from open-channel to pressurized flow (Kilpatrick and others, 1985). Kilpatrick and Kaehrle (1986) used a modified Palmer-Bowlus flume to measure open-channel and pipe-full flow, and an electromagnetic velocity meter to measure flow in the transitional zone from open-channel to pipe-full flow. They reported that the electromagnetic velocity meter was not successful in measuring accurate flows in this transition zone.

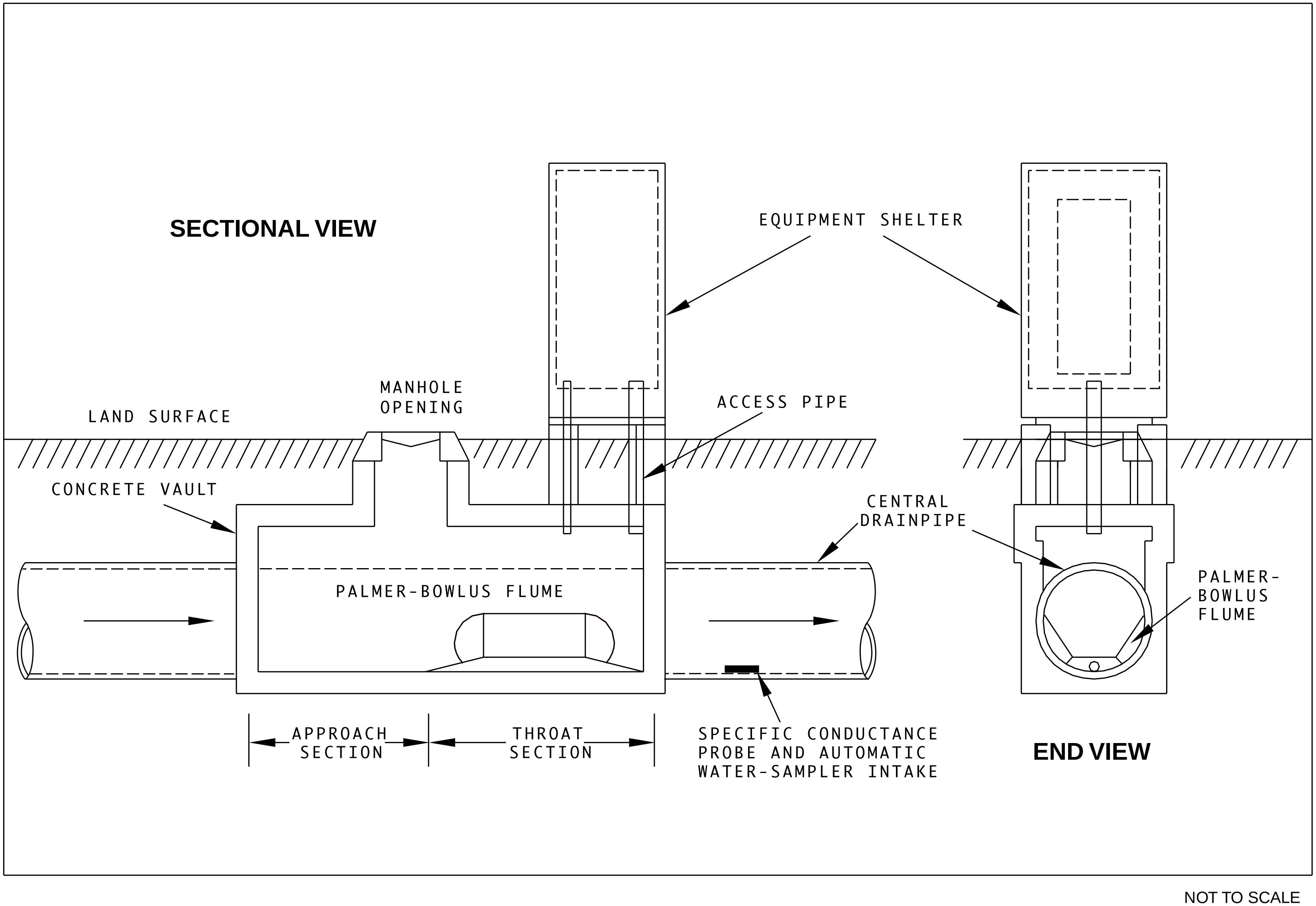


Figure 5. Highway-drainage-monitoring station with Palmer-Bowlus flume installed in trunkline drainpipe of a highway-drainage system (Church and others, 1996).

Acoustic and Electromagnetic Methods

The acoustic transit-time flowmeters (Laenen, 1985; Kilpatrick, and others, 1985; Kilpatrick and Kaehrle, 1986; Burch and Philips, 1994) and electromagnetic velocity meters (Kilpatrick, and others, 1985; Kilpatrick and Kaehrle, 1986) are designed to measure flow velocities under open-channel and full-pipe flow. Flow velocities are multiplied by cross-sectional areas of flow to determine flow rates. The acoustic flowmeter has been reported to obtain flow accuracies of 2–3 percent under open-channel flow, and 0.5–1.0 percent under pressurized flow (Burch and Philips, 1994). However, the acoustic flowmeter was not successful in measuring accurate flows in the transition zone between open-channel and full-pipe flow. As with other primary devices, the accuracy of flows measured with the acoustic and electromagnetic methods decrease when factoring in the error of the secondary stage measurement device (Marsalek, 1973; Alley, 1977).

Dilution Methods

Dilution methods involve injecting of tracer of known volume and concentration into a stream or flowing water in a pipe and measuring the concentration of the tracer in water collected at some short distance downstream (Alley, 1977; Kilpatrick and Cobb, 1985; Kilpatrick and Wilson, 1989). Dilution methods are unique because they do not require a secondary device for measuring stage. There are three types of dilution methods: instantaneous injection with steady-state flow; continuous, constant-rate injection with steady-state flow; and continuous, constant-rate injection with changing flow. The accuracy of the three methods depends upon complete mixing of the tracer by the time it reaches the point of collection and minimal dye loss during transport. The first two methods require multiple samples to provide one measurement of flow. In the third method, each sample of diluted tracer represents a specific flow.

Dye-dilution-discharge measurements have been used to verify stage-discharge relations in streams. Assuming steady-state flow and complete mixing, a streamflow measurement can be made by analyzing the concentration of dye in water samples collected at the measuring section from an upstream instantaneous injection of a known volume and concentration of dye. Flow is inversely proportional to the concentration of the tracer in the diluted sample. Due to the rapid changes in flow in highway- and urban-drains, the continuous, constant-rate dye-injection dilution method must be used (Duerk, 1983; Katz and Fisher, 1983; Kilpatrick, and others, 1985). This method of dye dilution has proven to be effective in calibrating theoretical stage-discharge relation from Parmer-Bowlus flumes (Katz and Fisher, 1983). Ellis and others (1984) used dye-dilution methods to calibrate a velocity-flow meter. Abrahams and others (1986) have used dye-dilution techniques to measure overland flow. In a monitoring study of road salt in highway runoff (Church and Friesz, 1993; Church and others, 1996), theoretical ratings for Parmer-Bowlus flumes were developed based on flume geometry and pipe/flume slope. Bias in the ratings caused by small irregularities in the flume sidewalls and in the floors of the throat sections were corrected by use of constant-rate dye-injection dilution measurements.

Secondary Devices/Methods

Floats

Monitoring the level of floats connected by a cable or a pivot arm in flowing water is a well-known method for monitoring water levels (Marselak, 1973; Alley, 1977). The vertical movement of the float as water levels change is typically recorded on a chart record or recorded electronically. Floats should be used in stilling wells where water-surface oscillations are dampened and the float is protected from floating debris. Under these controlled conditions, accuracy of water-level measurements of 0.01 ft can be attained (Marsalek, 1973). Highway- and urban-drainpipes, however, generally do not provide space for a stilling well.

Pneumatic Sensors

Water levels are measured with pneumatic sensors as gas (air or nitrogen) is forced through a thin tube and slowly bubbles into the water. The pressure of the gas is equal to the static pressure of the water above the orifice of the tube (Marsalek, 1973; Buchanan and Somers, 1968). Water levels are converted from pressure to depth by manometers or pressure transducers. Pneumatic sensors are well suited to measuring water levels in highway- and urban-drainpipes because they can be easily installed, do not obstruct flow, and with the exception of the thin tube, all equipment for measuring stage can be installed above ground. A small drawdown occurs as flow velocities increase; however, this can be accounted for when the stage-discharge relation is verified. **Figure 6** presents an example of how pneumatic sensors were used to measure stage in Palmer-Bowlus flumes (Church and others, 1996). A pressure transducer in an equipment shelter (fig. 5) converts the pressure of the nitrogen gas at the bubble orifice in the approach section of the flume to an electrical signal recorded by the data logger. Also, a calibrated standpipe is located in the equipment shelter for field calibration of the pressure transducer.

Pressure transducers used with the pneumatic sensors are of the non-submersible type. Submersible pressure transducers can be used to directly measure water depth, but, similar to floats, a stilling well may be needed to dampen water-surface oscillations and to protect the transducer from floating debris.

Electronic Sensors

The most commonly used electronic sensors to measure water levels are capacitance probes and dipper probes. The capacitance probe is immersed in the flowing water where the water is part of the electrical circuit. The measured capacitance varies in proportion to the depth of the water. This method has been use with weirs and with flumes in drainpipes. Accuracies of better than 1-percent have been achieved during 6-month periods without failure (Marsalek, 1973). Frequent maintenance was required, however, because of the collection of floating debris. Therefore, the capacitance probe would work best in a stilling well or sidewall cavity of a flume, limiting its usefulness in sewer and storm drains. Also, the capacitance may be affected by the relative high variations of specific conductance expected in highway runoff where deicing chemicals are used.

The dipping probe, hanging from a cable controlled by a precision motor, completes an electrical circuit when in contact with the surface of the flowing water. The probe is retracted slightly by the motor after contact then is lowered again for the next measurement. The depth of flow is recorded as the amount of cable that is is paid out or retracted to meet the water surface. Marsalek (1973) reported that the dipper probe required a significant amount of maintenance and that the time resolution on the chart record was not sufficient for runoff studies.

Acoustic Sensors

Acoustic sensors measure the time of travel of sound that is emitted and reflected back from the water surface. Depth of water is determined from the known depth to the base of the pipe and the measured distance of the sensor to the water surface. The sensors have no contact and do not affect the flowing water. Marselak (1973) reported that the accuracy of an acoustic sensor tested was ± 4 mm. For these sensors to be accurate, however, the water surface must be smooth, so a stilling well may be needed. Additionally, false reflections may be encountered in pipes and narrow channels, particularly at low flows (Marselak, 1973; Alley, 1977).

Comparison of Flow Measurement Methods

An experiment done by the USGS in cooperation with the FHWA indicates that different methods for measuring stormwater flow may not be comparable, and that some methods may have considerable variability and (or) bias. Stormwater flows from about 50 storms were measured in an urban stormwater drainpipe by several different methods at a site in Madison, Wisconsin during 1995. In this experiment, flows were measured using a Palmer-Bowlus flume, the friction coefficient method, acoustic and electromagnetic velocity meters, and acoustic and electromagnetic flow meters. Stage was measured by pneumatic bubbler, acoustic, and electromagnetic methods. Flows from these storms were measured concurrently by each method in a 54-inch-diameter, 200-foot continuous section of drainpipe. A reliable and accurate stage-discharge relation for this site had been previously developed using a Palmer-Bowlus flume, stage measurements from a nitrogen gas pneumatic bubbler system in the approach section of the flume and a pressure transducer, and discharge measurements calibrated using the constant-rate dye-injection dilution method. When different flow measurement methods are compared to this reference method, potential problems associated with the bias and variability among methods is apparent (**fig. 7**).

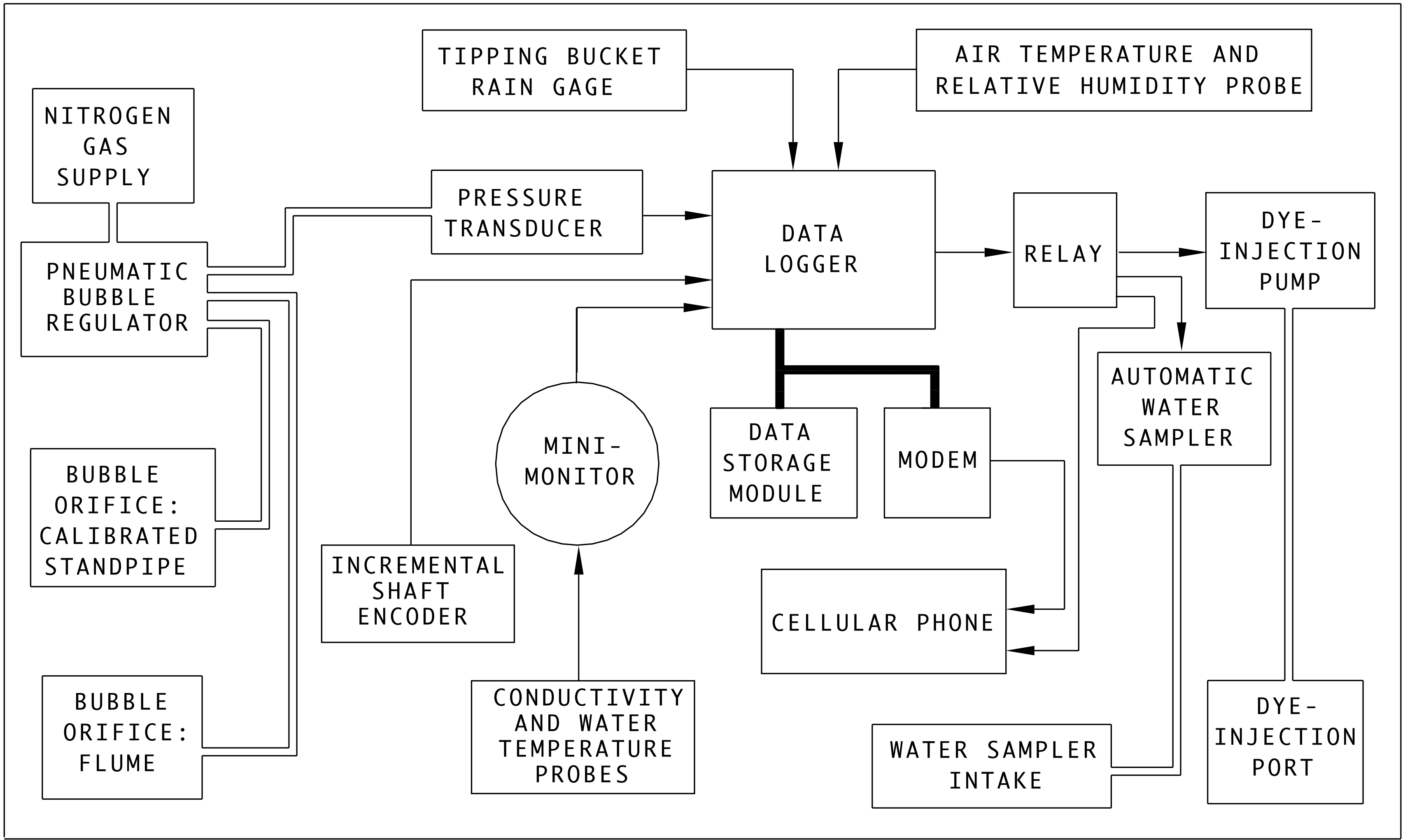


Figure 6. Instrumentation and equipment for measuring stormwater flow in a highway-drainage-monitoring station (Church and others, 1996).

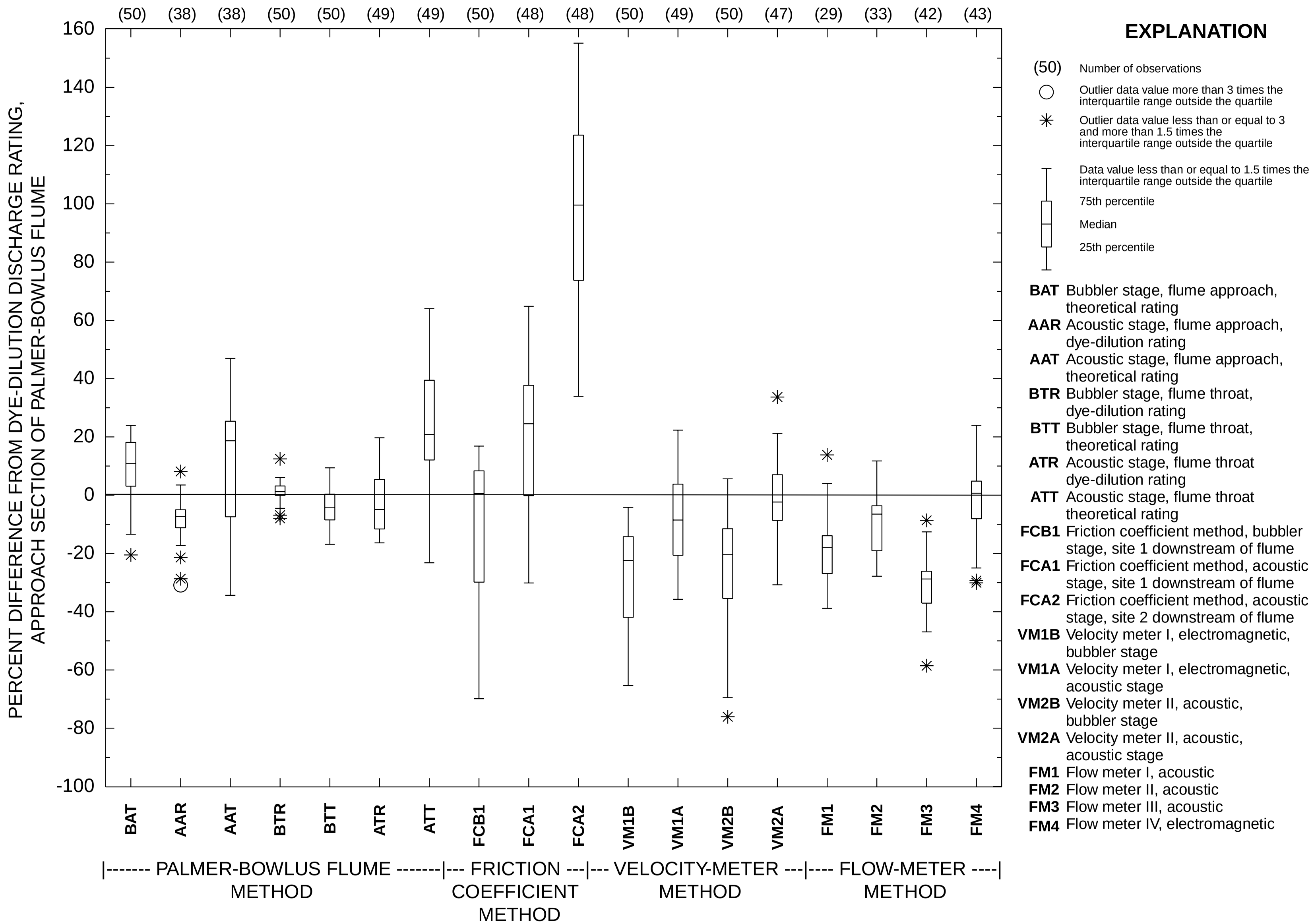


Figure 7. Comparison of results from stormwater-flow measuring methods, 1998, Madison, Wisconsin.

The comparability of stormwater-flow measurements by different methods is poor, and the variability of individual methods ranges widely (fig. 7). The data clearly indicate the need to calibrate a stage-discharge measurement method using check measurements with an independent method, such as dye dilution. Although stage-discharge relations derived from these flow measurement methods can be adjusted (using verification data) to minimize bias, the very large variation of uncertainty in flow measurements exhibited by some of these flow measurement methods is still likely to exist. These variations would add uncertainty to the representativeness of event-mean concentrations derived from flow-proportional-sampling methods, and would also add uncertainty to loads calculated from measured flows. Therefore, this comparison of flow methods emphasizes the importance of (1) selecting a flow measurement method that will yield sufficiently accurate flow data to meet project objectives and goals, (2) verifying all stage-discharge relations with proven, documented methods, and (3) documenting and reporting detailed information about the flow measurement methods and verification methods used in a given study so that the accuracy of flow data collected can be evaluated.

QUALITY ASSURANCE/QUALITY CONTROL

Quality assurance and quality control programs (QA/QC) need to be established at the beginning of a project to ensure that precipitation and stormwater-flow measurements are accurate and representative of the flow system investigated. Clark and Whitfield (1993), Brown and others (1995), and Jones (1999) stress the importance of QA/QC programs for all phases of stormwater flow and water-quality investigations—from project planning through report preparation—and demonstrate how comprehensive QA/QC programs can be developed and implemented.

Addressing, documenting, and reporting the hydrologic and hydraulic factors for selection of (1) monitoring site, (2) frequency and duration of monitoring, and (3) methods for measuring precipitation and stormwater-flow data constitute a QA/QC program for the design of stormwater runoff studies. A QA/QC program for data-collection activities is also necessary to document that the implementation of the study design was successful. An effective QA/QC program for stormwater-flow data-collection activities would include:

- Frequent and routine site visits by trained/experienced field personnel.
- Redundant methods for measuring precipitation and stormwater flow.
- Technical training for project personnel.
- Frequent review by project personnel of precipitation and stormwater-flow data collected.
- Quality audits, in the form of periodic internal reviews.
- Quality audits, in the form of periodic external reviews.

Frequent and routine site visits by trained/experienced field personnel cannot be over emphasized. Field equipment and instrumentation must be maintained in good working order to ensure the integrity of the data collected. The site must be inspected for debris accumulation, natural corrosion of equipment, vandalism, and other potential problems, including the presence of rodents. Debris can affect measurements by interfering with the operation of measurement equipment. Debris accumulation, whether upstream or downstream from the measuring point, may affect the stage-discharge relation. Service and maintenance of equipment and instrumentation and (or) the flow-control structure is necessary for consistency in the measurements and in the stage-discharge relation. Frequent calibration of equipment and instrumentation is necessary because of the difficult monitoring environment. Standard field forms designed to record who visited the site, the date and time of each visit, site conditions, the status of equipment and instrumentation, records of instrument calibration, and other information pertinent to the operation of the station are necessary for data verification. These field forms should be archived with project records, and at the least, use of these forms should be mentioned in the QA/QC documentation in project reports.

Redundant systems for measuring precipitation and stormwater flow can be used to ensure that the data collected are correct and complete. The difficulties in measuring and recording data in a stormwater-monitoring environment create a high probability for an incomplete record, even when stations are well maintained and the instruments are properly calibrated. Redundant systems provide for comparison of primary and backup data for detection of errors and backup data collection in the event of failure of the primary system. For example, Church and others (1996) used a data-logger-controlled pressure transducer as the primary stage measurement and recording system, and a float-arm assembly with a shaft encoder as the backup stage measurement system (fig. 6). The float-arm assembly was also connected to a mechanical strip-chart recorder to serve as the backup data recording system. In this study, relations between measured stage and discharge among co-located stations were also useful as a defacto backup system for data interpretation and verification. This investigation also collected precipitation measurements near each station, which were compared to long-term data from a NOAA network station.

Training is an essential part of QA/QC programs. Consistent and correct flow data are necessary to assemble a national and (or) regional highway-runoff-quality data base. To ensure that data are valid, current, technically defensible, and comparable from project to project, a standard training program is necessary. A continued program of organized training for project chiefs and experienced field personnel is necessary to maintain state-of-the-art knowledge of advances in precipitation and stormwater-flow-monitoring technologies. A series of training sessions for less experienced field personnel is necessary to establish the knowledge base for quality in data collection and interpretation. For example, the Federal Highway Administration designed a comprehensive student workbook devoted to the study of highway-runoff water quality and runoff quantity (Federal Highway Administration, 1985).

Data assessment is an important component of the QA/QC process (Jones, 1999). It is necessary for project personnel to frequently review the precipitation and stormwater-flow data collected throughout the course of each project. It is necessary to do at least a cursory data review to ensure that the system is operational, and that it is collecting internally consistent information each time the data record is collected during a station visit, and (or) when the data are downloaded from a remote location. Periodically, it is necessary to do a more detailed review using the entire data record, field notes, and other available information to detect errors or anomalous data. For example, a comparison between the precipitation and runoff volumes for a given storm could indicate a bias in one or the other measurement system if the relation for this storm departed from normal values for the station in question. Analysis of field records, including calibration records, adjustments to measured values, and other information, when compared to the data record, may indicate systematic bias, long-term drift, or an abrupt change in the performance of the instrumentation.

Quality audits, in the form of periodic internal reviews, are necessary to monitor and implement the project QA/QC program (Jones, 1999). Internal audits establish that the project has a QA/QC plan and that it is being implemented and documented. Also, periodic internal reviews serve as a method to provide technical feedback from subject matter experts to examine and address problems and (or) potential problems in the data-collection program. Internal reviews should ensure that trained/experienced personnel are available for frequent and routine site visits, that appropriate and robust monitoring systems are in place and collecting data, and that project personnel are examining and interpreting data using appropriate methods on a timely basis. For example, within the USGS, each project is typically reviewed by subject matter experts within individual organizational units at the proposal stage and then again when the project is about 10-, 40-, and 70-percent complete, or at fixed intervals, such as quarterly or semiannually.

Quality audits, in the form of periodic external reviews, are also necessary to monitor and implement the project QA/QC program (Jones, 1999). External audits should examine project plans, project data, project records, and QA/QC documentation to ensure that study objectives are being met, and to ensure that study objectives will meet the goals of the monitoring project. External reviews should ensure that the project information is properly documented and that the documentation is accessible. Within the USGS, external quality audits include periodic reviews by technical specialists at different levels in the chain of command above the local organizational unit and by technical specialists from discipline offices such as the Office of Surface Water, the Office of Ground Water, the Office of Quality Water, and the Branch of Quality Systems.

CONCLUSION

Information from stormwater studies may be used to address local issues and (or) may contribute to a regional or national synthesis of highway- or urban-runoff studies. Accurate and representative precipitation and stormwater-flow data are crucial for valid, current, and technically defensible interpretations of highway- or urban-runoff study results. Equally important is knowledge of the degree of accuracy and representativeness of available precipitation and stormwater-flow data. Accurate and representative measurements of precipitation and stormwater flow, however, are difficult to obtain because of the rapidly changing spatial and temporal distribution of precipitation in the study area and the rapidly changing flows during a storm. Many hydrologic and hydraulic factors must be considered in selecting sites for measuring precipitation and stormwater flow that are representative of the objectives and goals of the study. Many hydrologic and hydraulic factors also must be considered in determining frequencies and durations of data collection to fully characterize the rapidly changing rainfall intensities and stormwater flows, and in selecting methods that will yield accurate data over the full range of rainfall intensities and the full range and changing flow regimes of stormwater flows.

Without the supporting data needed to evaluate the accuracy and representativeness of the precipitation and stormwater-flow measurements, the data collected and interpretations made may have little meaning. To ensure that the accuracy and representativeness of precipitation and stormwater-flow data can be evaluated, decisions as to (1) where in the drainage system precipitation was collected and stormwater flows were measured, (2) how frequently precipitation and stormwater flows were measured, (3) what methods were used to measure precipitation and stormwater flows, and (4) on what basis these decisions were made must be documented and communicated in an accessible format, such as a project description report, a data report, or an appendix to a technical report, and (or) archived in a State or national records center. Additionally, a quality assurance/quality control program must be established to ensure that this information is documented and reported, and that the decisions made in design phase are continually reviewed, internally and externally, throughout the duration of the study.

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