Urban Stormwater Runoff— Selected Background Information and Techniques for Problem Assessment, with a Baltimore, Maryland, Case Study

United States Geological Survey Water-Supply Paper 2347

Prepared in cooperation with the Baltimore Regional Planning Council

AVAILABILITY OF BOOKS AND MAPS OF THE U.S. GEOLOGICAL SURVEY

Instructions on ordering publications of the U.S. Geological Survey, along with prices of the last offerings, are given in the current-year issues of the monthly catalog "New Publications of the U.S. Geological Survey." Prices of available U.S. Geological Survey publications released prior to the current year are listed in the most recent annual "Price and Availability List." Publications that are listed in various U.S. Geological Survey catalogs (see back inside cover) but not listed in the most recent annual "Price and Availability List" are no longer available.

Prices of reports released to the open files are given in the listing "U.S. Geological Survey Open-File Reports," updated monthly, which is for sale in microfiche from the U.S. Geological Survey, Books and Open-File Reports Section, Federal Center, Box 25425, Denver, CO 80225. Reports released through the NTIS may be obtained by writing to the National Technical Information Service, U.S. Department of Commerce, Springfield, VA 22161; please include NTIS report number with inquiry.

Order U.S. Geological Survey publications **by mail** or **over the counter** from the offices given below.

BY MAIL

Books

Professional Papers, Bulletins, Water-Supply Papers, Techniques of Water-Resources Investigations, Circulars, publications of general interest (such as leaflets, pamphlets, booklets), single copies of Earthquakes & Volcanoes, Preliminary Determination of Epicenters, and some miscellaneous reports, including some of the foregoing series that have gone out of print at the Superintendent of Documents, are obtainable by mail from

U.S. Geological Survey, Books and Open-File Reports
Federal Center, Box 25425
Denver, CO 80225

Subscriptions to periodicals (Earthquakes & Volcanoes and Preliminary Determination of Epicenters) can be obtained ONLY from the

Superintendent of Documents
Government Printing Office
Washington, D.C. 20402

(Check or money order must be payable to Superintendent of Documents.)

Maps

For maps, address mail orders to

U.S. Geological Survey, Map Distribution
Federal Center, Box 25286
Denver, CO 80225

Residents of Alaska may order maps from

Alaska Distribution Section, U.S. Geological Survey,
New Federal Building - Box 12
101 Twelfth Ave., Fairbanks, AK 99701

OVER THE COUNTER

Books

Books of the U.S. Geological Survey are available over the counter at the following Geological Survey Public Inquiries Offices, all of which are authorized agents of the Superintendent of Documents:

- **WASHINGTON, D.C.**--Main Interior Bldg., 2600 corridor, 18th and C Sts., NW.
- **DENVER, Colorado**--Federal Bldg., Rm. 169, 1961 Stout St.
- **LOS ANGELES, California**--Federal Bldg., Rm. 7638, 300 N. Los Angeles St.
- **MENLO PARK, California**--Bldg. 3 (Stop 533), Rm. 3128, 345 Middlefield Rd.
- **RESTON, Virginia**--503 National Center, Rm. 1C402, 12201 Sunrise Valley Dr.
- **SALT LAKE CITY, Utah**--Federal Bldg., Rm. 8105, 125 South State St.
- **SAN FRANCISCO, California**--Customhouse, Rm. 504, 555 Battery St.
- **SPOKANE, Washington**--U.S. Courthouse, Rm. 678, West 920 Riverside Ave..
- **ANCHORAGE, Alaska**--Rm. 101, 4230 University Dr.
- **ANCHORAGE, Alaska**--Federal Bldg, Rm. E-146, 701 C St.

Maps

Maps may be purchased over the counter at the U.S. Geological Survey offices where books are sold (all addresses in above list) and at the following Geological Survey offices:

- **ROLLA, Missouri**--1400 Independence Rd.
- **DENVER, Colorado**--Map Distribution, Bldg. 810, Federal Center
- **FAIRBANKS, Alaska**--New Federal Bldg., 101 Twelfth Ave.

Urban Stormwater Runoff—Selected Background Information and Techniques for Problem Assessment, with a Baltimore, Maryland, Case Study

By GARY T. FISHER and BRIAN G. KATZ

Prepared in cooperation with
the Baltimore Regional
Planning Council

U.S. GEOLOGICAL SURVEY WATER-SUPPLY PAPER 2347

DEPARTMENT OF THE INTERIOR
DONALD PAUL HODEL, Secretary

U.S. GEOLOGICAL SURVEY
Dallas L. Peck, Director

Any use of trade names in this publication is for descriptive purposes only and does not imply endorsement by the U.S. Geological Survey

UNITED STATES GOVERNMENT PRINTING OFFICE : 1988

For sale by the
Books and Open-File Reports Section
U.S. Geological Survey
Federal Center, Box 25425
Denver, CO 80225

Library of Congress Cataloging-in-Publication Data

Fisher, Gary T.
Urban storm-water runoff.

(United States Geological Survey water-supply paper; 2347)
"Prepared in cooperation with the Baltimore Regional Planning Council."
Bibliography: p.
Supt. of Docs. no.: I 19.13:2347
1. Urban runoff—Environmental aspects—Maryland—Jones Falls Watershed—Case studies. 2. Water quality—Maryland—Jones Falls Watershed. 3. Storm sewers—Maryland Baltimore Region. 4. Watershed management—Maryland—Baltimore Region. I. Katz, Brian G. II. Baltimore Regional Planning Council (Md.) III. Title. IV. Series: U.S. Geological Survey water-supply paper; 2347.
TD225.J75F57 1989 628.1'68 88-600176

CONTENTS

FIGURES

TABLES

aquifer. A water-bearing geologic formation; a source of ground water.

base flow. Low flow in a stream which occurs after all storm runoff has ceased; streamflow is sustained by ground-water discharge.

concentration. An amount of a substance entrained or dissolved in another substance; in studies of water, a mass of a constituent dissolved in a volume of water, for example, milligrams per liter.

correlation coefficient. An indicator of the degree of interdependence between two variables.

discrete sample. A water sample taken at a single instant in time.

eutrophic. Refers to over-enrichment of a body of water by nutrients, primarily nitrogen and phosphorus, to a point where excessive algal growth occurs.

event-mean concentration (EMC). The total mass of a substance in runoff divided by the total volume of runoff; the average concentration for a storm.

flow-weighted composite sample. A single water sample representing an entire storm.

frequency analysis. A determination of the distribution of values that a variable has within a data set.

hydrologic cycle. The water cycle; a representation of all hydrologic processes and their interaction in the atmosphere and on and below the surface of the Earth.

impervious surface. A surface which will not permit water to pass through, such as concrete or asphalt.

land treatment. The practices being applied to a land use.

load. The total amount of a substance contained in a given volume of runoff.

NAWDEX. NAtional Water Data EXchange, an inventory of water data from participating agencies maintained by the U.S. Geological Survey.

pollutant. Any undesired material not indigenous to an environment.

runoff. The portion of precipitation that, after reaching the ground surface, runs off to a water body.

significance level. A measure of the certainty that can be associated with a statistical determination.

STORET. STOrage and RETrieval system, water-quality data base of the U.S. Environmental Protection Agency.

urban runoff. Any water draining from an urban area; as used in this report, it only includes surface runoff resulting from rainfall, although in some areas it may include snowmelt.

variable. A physical quantity whose value can vary freely.

washoff. The total amount of a substance washed from an area by surface runoff.

water pollution. Any condition of a body of water that reflects unacceptable water quality, usually due to human influences.

watershed. A boundary defining an area of the Earth's surface where all precipitation drains to a common point.

WATSTORE. WATer data STOrage and REtrieval system, hydrologic data base of the U.S. Geological Survey.

METRIC CONVERSION FACTORS

For the convenience of readers who may prefer to use metric (International System) units rather than the inch-pound units used in this report, values may be converted by using the following factors:

Multiply inch-pound unit	By	To obtain metric unit
	Length	
inch (in.)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
acre	4,047	square meter (m^2)
square mile (mi^2)	2.590	square kilometer (km^2)
	Volume	
cubic foot (ft^3)	0.02832	cubic meter (m^3)
	Flow	
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
	Mass	
pound (lb)	0.4536	kilogram (kg)
	Miscellaneous	
pound per acre (lb/acre)	0.0001121	kilogram per square meter (kg/m^2)
pound per acre-inch (lb/acre-in)	4.415	milligram per liter of runoff (mg/L)

Urban Stormwater Runoff—Selected Background Information and Techniques for Problem Assessment, With a Baltimore, Maryland, Case Study

By Gary T. Fisher *and* Brian G. Katz

Abstract

Urbanization of a watershed can result in increased flooding, reduced recharge of ground-water supplies, and degradation of water quality. To aid in the transfer of new technical information to decisionmakers, some concepts regarding stormwater runoff are explained. A case study is presented to illustrate the problems associated with urbanization and an approach to their analysis. Some techniques for problem assessment are discussed, and sources of more information are identified.

For the case study, data for 36 storms sampled over a 16-month period in the Jones Falls watershed in Baltimore, Md., have been collected, verified, and entered into a U.S. Geological Survey data base. Three small watershed sites (drainage areas of 10.5, 14.2, and 16.9 acres and varying residential land uses) and one main-stem site (drainage area of 59 square miles) were monitored.

Analyses of the case study data indicate that concentrations of eight constituents in urban storm-water runoff exceed selected water-quality criteria most of the time. There are statistically significant (0.95 level) differences among the three small watershed sites for event-mean concentrations of total Kjeldahl nitrogen, total phosphorus, total copper, total lead, and total zinc. There are no significant differences among the small watershed sites for total suspended solids, chemical oxygen demand, or total organic carbon. Stormwater runoff from urban areas contributes more than 60 percent of the total annual load of total Kjeldahl nitrogen, total phosphorus, and total organic carbon in the Jones Falls; more than 70 percent of chemical oxygen demand; and more than 80 percent of total suspended solids, total lead, and total zinc.

Inadvertent detention storage affects water quantity and quality in Reservoir Hill, one of the small watersheds. Evidence suggests that trash accumulated on paved surfaces in the watershed may be a source of this detention.

INTRODUCTION

In recent years, public concern has increased substantially regarding the problems of flooding and water-quality degradation associated with urbanization. Urbanization of the land usually causes increased surface runoff rates with corresponding increases in the total volume of runoff. This larger amount of storm runoff also carries with it constituents that can cause significant degradation of water quality not only in the urbanized area but downstream as well. Because of these concerns, Congress mandated that the U.S. Environmental Protection Agency (USEPA) conduct a Nationwide Urban Runoff Program (NURP) to determine the impacts of urban stormwater runoff. A study of the Jones Falls watershed in Baltimore, Md., was conducted by the U.S. Geological Survey as part of this program.

Purpose and Scope

The purpose of this report is to provide information that will help urban planners and officials identify and assess problems caused by urban stormwater runoff. It is intended to be a reference publication providing basic technical information and additional relevant material. Commonly used data-analysis techniques are presented, and principles of data interpretation are discussed. To illustrate the problems and approaches to their solution, a case study of urban runoff in the Jones Falls watershed is presented. This NURP study in Baltimore, Md., was conducted in 1981 and 1982 by the U.S. Geological Survey in cooperation with local governments. Although several agencies participated in data collection and analyses, only the data collected and analyzed by the Geological Survey are presented in this report.

Acknowledgments

The cooperation of the Baltimore Regional Planning Council, Baltimore City, and Baltimore County is gratefully acknowledged. The authors would like to express their appreciation to the many U.S. Geological

Survey employees who assisted in the project under very difficult field conditions, most notably Robert James, Bernard Helinsky, and John Hornlein, for the installation of equipment. In particular, we would like to thank George Noah for his diligence and dedication in equipment maintenance and storm sampling.

OVERVIEW OF URBAN HYDROLOGY

Runoff[1] is a natural hydrologic phenomenon that is strongly influenced by land use. Runoff also influences land use by helping to shape the land surface, providing water supply, and affecting the suitability of land for development. Runoff transports many substances, including contaminants, from one area to another—ultimately to a receiving water body such as a river, lake, bay, or ocean.

Urban runoff refers to runoff that has been affected by urbanization and includes all water draining from an urbanized area. As used in this report, however, "runoff" refers only to runoff resulting as a direct consequence of rainfall. In some areas, melting snow may also be a significant source of runoff; it is not included in this discussion because it is not generally significant in the case study area. It has long been recognized that stormwater runoff can cause localized flooding—hence, the development of stormwater drainage systems in urbanized areas. More recently, the potential degradation of water quality by urban runoff has also been addressed, particularly by the Nationwide Urban Runoff Program (U.S.Environmental Protection Agency, 1983). Urban land surfaces accumulate contaminants, which, when washed into streams or lakes in sufficient concentrations, can significantly degrade the water quality of that receiving body of water.

When rain falls, it runs off or soaks into the ground, and most of it eventually returns to the atmosphere by way of evapotranspiration—these processes taken together are known as the **hydrologic cycle**. Figure 1 shows the hydrologic cycle with the five principal components—precipitation, runoff, infiltration, evaporation, and transpiration.

Figure 2 shows a comparative water balance of the infiltration/runoff process for forested, rural, and urban land uses. It indicates an additional component of the hydrologic cycle—storage—that is actually a temporary process preceding evapotranspiration. Generally, rainfall reaching the ground surface has three possible short-term fates: it can run off the land surface, infiltrate the land surface and percolate to the ground-water reservoir, or go into storage on or near the surface. Storage includes water that fills surface depressions, is intercepted by plants, or is retained as soil moisture. It is important to note that water in nature is very dynamic—it does not reside in one place for long. Surface runoff, for example, will flow downgradient toward a stream, but on its way, it can infiltrate into the soil or evaporate into the atmosphere. Ground water generally flows slowly toward a point of discharge, such as the ocean, but it can also seep into a stream or flow at a spring.

All three land uses can share a common **watershed** and ground-water **aquifer** and are hydrologically interdependent. Runoff and the substances it transports from upstream areas can eventually move to the lower areas of a watershed—for example, agricultural chemicals such as pesticides can degrade downstream water supplies and fisheries. The quality of runoff from urban areas may be an even greater concern in some watersheds, however, because most urban areas are located near water bodies. Thus there may be little opportunity to mitigate the impact of urban runoff upon those water bodies. With regard to agricultural contaminants from upstream areas, there may be greater opportunity for natural processes to effectively remove contaminants from the environment through deposition, adsorption, or chemical transformation. Also, the concentrations of substances such as organic carbon and metals in urban runoff are generally much higher than in rural/agricultural runoff. Some of the hydrologic effects of urbanization are summarized in table 1.

Figure 2 illustrates a situation common to humid areas in the United States. The arrows indicate the relative proportions of rainfall that run off, infiltrate, and are stored. Generally, very little of the rainfall in forested areas runs off, and therefore streamflow tends to increase only slightly. Runoff is greater from rural/agricultural areas, and the streamflow tends to increase significantly. In heavily urbanized areas, more of the rainfall runs off, thereby increasing the likelihood of flooding in those areas that lack suitable means for accommodating storm runoff.

Figure 3 shows the urban area infiltration/runoff process in greater detail. There are three principal reasons for the increased likelihood of flooding in urban areas: (1) Paving of natural land surfaces with concrete and asphalt (**impervious surfaces**) prevents infiltration, thus increasing runoff. (2) Urban drainage systems deliver runoff much faster than local streams can transport it. (3) Urban development often infringes on natural flood plains, which, when undisturbed, help to mitigate flood damage by providing large areas for temporary water storage. Flood-plain flow is relatively shallow and has low velocity, thereby allowing more time for infiltration. When natural flood-plain areas are

[1] Terminology in **boldface** is defined in the glossary, on p. V.

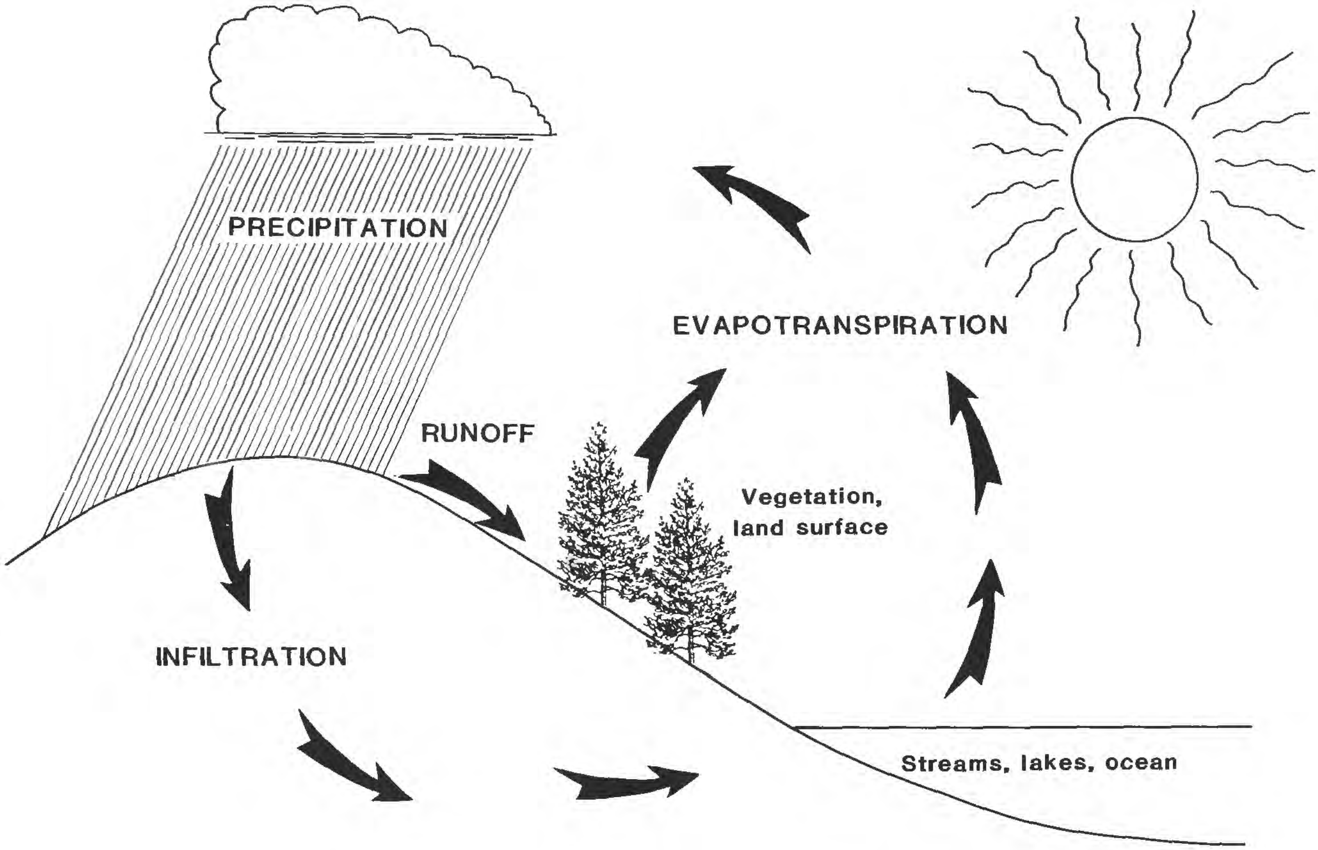

Figure 1. The hydrologic cycle.

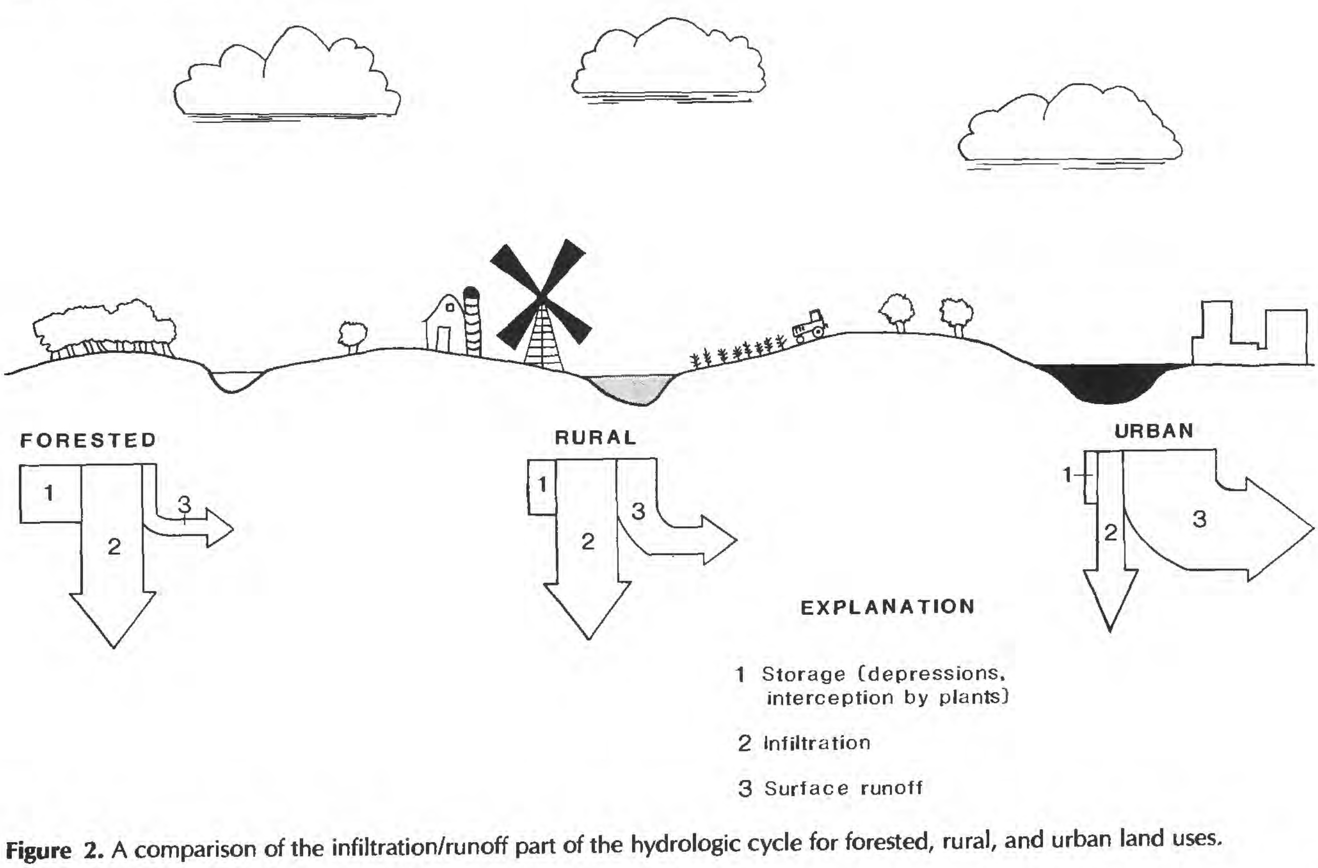

Figure 2. A comparison of the infiltration/runoff part of the hydrologic cycle for forested, rural, and urban land uses.

Table 1. Possible hydrologic effects of changes in land use

[Adapted from Savini and Kammerer (1961)]

Change in land use	Possible hydrologic effect
Removal of trees or vegetation...	Decrease in evapotranspiration and increase in surface runoff; increased sedimentation of streams.
Pumping from wells..........	Lowering of water table.
Removal or disturbance of soil due to grading.	Increased surface runoff and sedimentation in streams; elimination of small streams.
Initial construction of houses, streets, and culverts (paving of pervious surfaces).	Decreased infiltration, resulting in increased surface runoff, lowered water table, and decreased base flow during dry periods.
Complete development of residential, commercial, and industrial areas.	Effects of initial construction are enhanced, with higher flood peaks, increased volume of storm runoff, soil erosion and stream sedimentation, and low water table (with little or no recharge); degradation of water quality is apparent.
Installation of storm drainage systems.	Relieves localized flooding, but faster and more concentrated runoff can contribute to downstream flooding; by delivering runoff directly to a stream, any mitigation of water-quality effects by buffer strips is eliminated.
Installation of water supply and sanitary sewer systems.	Removal of water from natural cycle results in lowering of water table; water pollution results from release of untreated sanitary wastes during overflows or malfunctions.

removed by the construction of dikes, levees, and buildings, increased quantities of flow are forced into the stream channel, causing increased flood flows, velocities, and erosion potential at points downstream.

The paving of natural surfaces and the installation of drainage systems that accompany urbanization are also significant factors in influencing the water quality of urban runoff. Impervious surfaces, such as streets and rooftops, accumulate contaminants, and the increased volume and velocity of runoff provide the carrying capacity needed to transport these materials. Figure 4 depicts the sources of some of these potential contaminants.

In studies of stormwater runoff, it is necessary to express results from various studies in terms that facilitate comparison. Water quality is usually expressed in terms of the **concentrations** of particular constituents. Scientists often express concentration in milligrams per liter (mg/L) or micrograms per liter (μg/L), but the almost equivalent terms of parts per million (ppm) and parts per billion (ppb), respectively, are sometimes used. When the concentration of a particular substance in water is sufficient to produce detrimental effects for the intended use of that water, the substance is called a **pollutant**, and the resulting condition is commonly known as **water pollution.** The definition of pollution in this way is important. Apart from manmade organic chemicals, toxins, or radioactive elements, many substances occur naturally in a wide range of concentrations. It is not usually the presence of a substance by itself that is inherently harmful but rather the relatively high concentration of that substance. Copper, for exam-

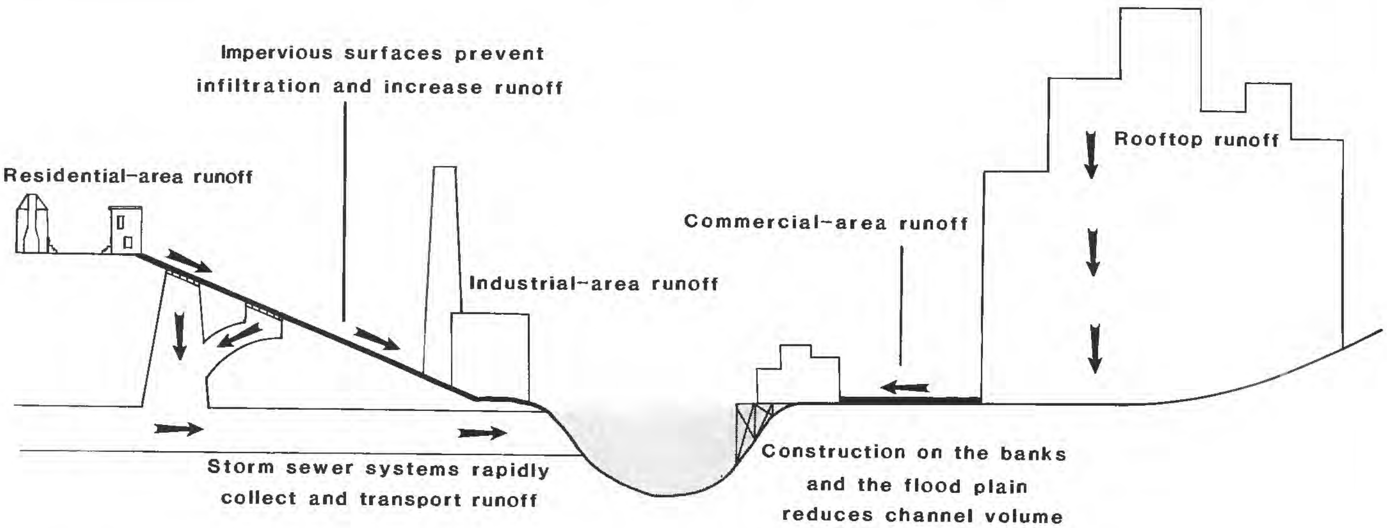

Figure 3. Rainfall/runoff processes in an urban area.

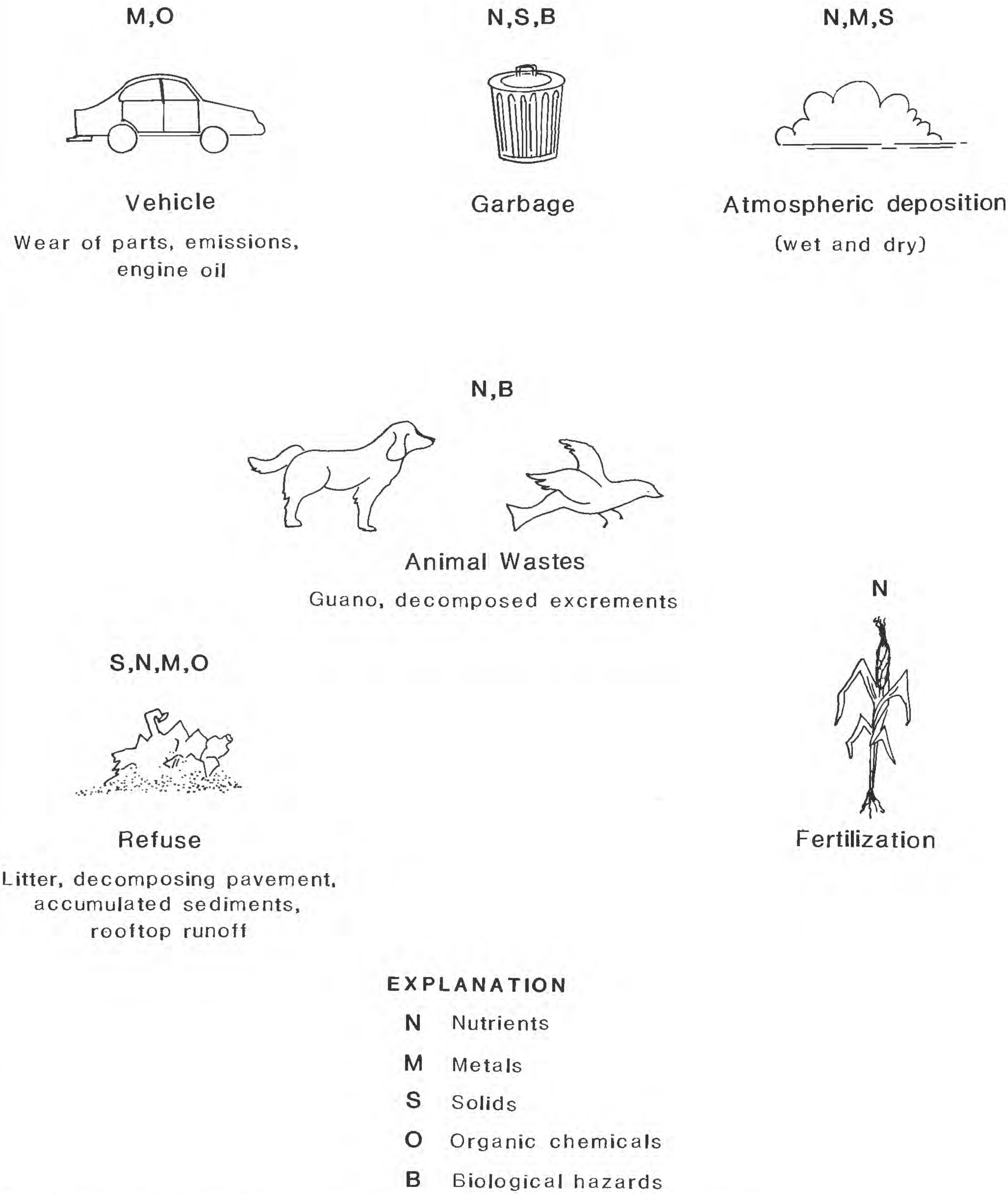

Figure 4. Selected sources of potential water-quality contaminants in an urban watershed.

ple, is an essential nutrient for both plants and animals, but at 0.022 mg/L it is acutely toxic to freshwater aquatic life (U.S. Environmental Protection Agency, 1980). Thus, evaluation of water quality usually involves comparisons of substance concentrations with water-quality standards and criteria.

There are important distinctions between water-quality standards and criteria. A standard is a definitive numerical limitation which a water-quality constituent must not exceed or fall below. Both minimum and maximum values may be set by a regulatory body and usually take the form of law. For example, standards are usually established for the quality of drinking water. On the other hand, a criterion is "a means by which anything is tried in forming a correct judgment regarding it" (McKee and Wolf, 1963). Anything appropriate to the purpose of the data user can be used as a criterion for evaluation of the quality of water. For example, in evaluating a water supply for use as cooling water, an engineer might compare hardness levels in the water with those levels found to cause accelerated pipe corrosion. Of course, the criterion should be backed by scientific verification, but often a criterion not precisely applicable to the user's situation can be used with qualification. For example, to evaluate the suitability of water for raising a particular fish species susceptible to water-quality degradation, a comparison could be made with parameters for the survival of carp. While carp are known to survive in water of poor quality, it could be inferred that if conditions were unsuitable or marginal for carp, then they would also be unsuitable for the more sensitive species.

Concentrations generally provide a measure of water quality at a discrete point in time. (Sometimes an average concentration is used to represent conditions over a period of time.) Over time, an important measure of water quality is constituent **load**, which is a total amount of a given substance in terms of mass. For studies of urban runoff, a technique is needed to enable the comparison of constituent loads between different storms at different locations. Total load, or **washoff**, alone cannot be used for comparison, because large watersheds will generally yield more mass of a particular constituent than similar small watersheds, given similar storm characteristics. As a better indicator of watershed differences, total load per unit area, such as pounds per acre per year of a particular constituent, has been used and works well for long-term comparisons. However, for comparisons of loads from one storm to the next, whose individual characteristics can vary significantly, another method of comparison is needed. Dividing the loading rate, in washoff per unit area, by the volume of storm runoff normalizes the loading for any storm at any location. Typical units used are pounds per acre per inch of runoff. Runoff volume, like precipitation, is usually expressed as a depth of water, such as inches, distributed uniformly over the drainage area. It is a relative unit of measurement where drainage area must also be known to obtain an absolute volume. Pounds per acre per inch (or pounds per acre-inch) is actually a concentration, since acre-inch is a unit of volume. This concentration, expressed in milligrams per liter, can be obtained by multiplying pounds per acre-inch of runoff by 4.415. For NURP and related studies, this concentration was known as **event-mean concentration** (EMC). EMC is a flow-weighted average concentration for a storm: total constituent washoff divided by total storm runoff volume.

SELECTED BACKGROUND INFORMATION AND TECHNIQUES FOR PROBLEM ASSESSMENT

The development of hydrology as a science is relatively recent. Interest in hydrology is as ancient as the first well or irrigation ditch, but prior to the 19th century, only the most basic concepts were known. Urban hydrology is a subdiscipline of hydrology dealing specifically with the effects of urbanization on hydrology. Table 2 lists some major milestones in the study of urban hydrology. Prior to the 1950's, most interest was directed at those concepts involving the quantity of water. More recently, quality of water has become of significant interest. Studies of the quality of urban stormwater runoff have, until very recently, been few. NURP was the first attempt to develop and coordinate a comprehensive national data base.

Sources of Urban Stormwater-Runoff Data

The two largest repositories of urban hydrologic data are the U.S. Geological Survey and the U.S. Environmental Protection Agency. These data are stored in the **WATSTORE** and **STORET** computerized data bases, respectively. In addition, many other Federal, State, local, and private agencies maintain smaller data bases. **NAWDEX** is a computerized index of all hydrologic information available from participating agencies. NAWDEX does not contain the data itself, but consists of data descriptions such as geographic location, type of data, and period of record. Facilities are available to search the index by describing the data desired. The data are obtained directly from the participating agency, usually at little or no cost. NAWDEX is managed by the Geological Survey and can be accessed through any of its Water Resources Division district offices. For example, in Maryland, the Mid-Atlantic District office in Towson can be contacted at 301-828-1535.

Table 3 lists metropolitan areas for which studies were conducted during the Nationwide Urban Runoff Program. The Water Planning Division at the U.S. Environmental Protection Agency headquarters in

Table 2. Selected milestones in urban hydrology

Year or period	Author or agency	Development
1851......	Mulvany	Rational formula (estimates flood peaks).
1889......	Kuichling	First recorded application of rational formula in the United States.
1932......	Gregory and Arnold.	General rational formula.
1932......	Sherman	Unit hydrograph.
1944......	Hicks	Los Angeles hydrograph method.
1951–67...	Johns Hopkins University.	Storm Drainage Research Project.
1965......	Urban Hydrology Research Council.	Engineering Foundation Conference.
1965, 1966, 1968.	Eagleson and March; Viessman.	Unit hydrograph application to urban hydrology.
1967......	American Society of Civil Engineers.	Urban Water Resources Research Project.
1960's to 1970's.	U.S. Geological Survey.	Urban Hydrology Studies Program.
1972......	Public Law 92-500 (Water Pollution Control Act).	Areawide abatement and management of water pollution ("208" projects).
1975......	U.S. Soil Conservation Service.	Technical Release No. 55 – Urban Hydrology for Small Watersheds.
1977, 1978, 1983.	UNESCO	Symposia on international progress in urban hydrology.
1979–83...	U.S. Environmental Protection Agency and U.S. Geological Survey.	Nationwide Urban Runoff Program and related studies.
1979......	Public Law 95-217 (Clean Water Act).	Nonpoint-source pollution studies.
1974–86...	University of Kentucky.	Annual conferences on urban hydrology.

Table 3. Locations of Nationwide Urban Runoff Program (NURP) and U.S. Geological Survey (USGS) studies of the quantity and quality of urban stormwater runoff

Location	Program
Anchorage, Alaska	USGS.
Little Rock, Arkansas	NURP.
Coyote Creek, California (San Francisco area)	NURP.
Fresno, California	NURP/USGS.
Denver, Colorado	NURP/USGS.
Metropolitan Washington, D.C.	NURP.
Tampa, Florida	NURP/USGS.
Miami, Florida	USGS.
Honolulu, Hawaii	USGS.
Champaign-Urbana, Illinois	NURP.
Glen Ellyn, Illinois (Chicago area)	NURP/USGS.
Kansas City, Kansas	NURP/USGS.
Lake Quinsigamond, Massachusetts (Boston area)	NURP.
Upper Mystic River, Massachusetts (Boston area)	NURP.
Baltimore, Maryland	NURP/USGS.
Lansing, Michigan	NURP.
Oakland County, Michigan (Detroit area)	NURP.
Ann Arbor, Michigan	NURP.
St. Paul, Minnesota	USGS.
Kansas City, Missouri	USGS.
Durham, New Hampshire	NURP.
Albuquerque, New Mexico	USGS.
Long Island, New York	NURP/USGS.
Lake George, New York	NURP.
Irondequoit Bay, New York (Rochester area)	NURP/USGS.
Winston-Salem, North Carolina	NURP.
Columbus, Ohio	USGS.
Springfield-Eugene, Oregon	NURP.
Portland, Oregon	USGS.
Philadelphia, Pennsylvania	USGS.
Myrtle Beach, South Carolina	NURP.
Rapid City, South Dakota	NURP/USGS.
Knoxville, Tennessee	NURP.
Austin, Texas	NURP/USGS.
Houston, Texas	USGS.
Salt Lake City, Utah	NURP/USGS.
Bellevue, Washington (Seattle area)	NURP/USGS.
Milwaukee, Wisconsin	NURP/USGS.

Washington, D.C., can be contacted for information on those studies. The table also lists areas for which data are available in the Geological Survey Urban Hydrology Studies data base. The Office of Surface Water at the Geological Survey headquarters in Reston, Va., can be contacted for further information.

The Role of Data Quality Assurance

The validity and reliability of data must be ascertained by the users to ensure that correct decisions are based on adequate data. Any decisionmaking will involve some level of uncertainty. The goal of data quality-assurance programs is to minimize and document this uncertainty. It is the responsibility of the data user to decide on an acceptable level of uncertainty and to ensure that the data used at least meet certain minimum standards.

Evaluating a quality-assurance program should be done by an analyst familiar with data collection and laboratory procedures. In some cases, the reputation of the data supplier may be sufficient to validate the data for most uses. However, no data base is flawless; in every case there must be in place some method for screening the data to prove that they meet some minimum level of reliability and certainty.

Information on quality assurance is not usually available within the data base itself but rather is provided by the agency that collected and analyzed the data. There are four general phases at which quality control should be ensured: field, office, laboratory, and data management. Elements common to all phases are proper recordkeeping and rigid adherence to standard procedures. The field phase includes careful collection, handling, and routing of water samples and documented calibration of field instrumentation and equipment. The office phase basically consists of continuously checking and cross-checking the data. Laboratory quality assurance involves adherence to an approved set of procedures and frequent checking with quality-control samples, such as standards and replicates. Data management is probably the most difficult phase to evaluate. Adherence to procedures is especially important. Since computerized data bases can consist of many thousands or even millions of data values, errors are difficult to detect unless they are very obvious. Data are stored on "soft" media, such as magnetic tape or disk. It is possible to make changes in a data set which, once made, are impossible to detect. As with the office phase, data-management quality assurance requires continuous checking and cross-checking.

Techniques for the Analysis and Interpretation of Urban Stormwater-Runoff Data

Sources of Information

There are many statistical packages, for both large and small computers, available for the analysis of urban hydrologic data. All contain basic statistical techniques. They differ in the computer systems on which they may be used, their level of sophistication in statistical applications, special features, and, most important, the ease with which they can be used. An important and desirable feature in any statistical applications package is widespread availability. One of the most popular packages is the Statistical Analysis System, better known as SAS (Barr and others, 1979), which is a proprietary package available to most IBM-compatible systems. Particular advantages of SAS are its ease of use and its data-management features. Another popular proprietary package is the Statistical Package for the Social Sciences, or SPSS (Nie and others, 1975). Computer systems vendors can be contacted for more information on what is available.

In support of the activities of the urban hydrology studies of the U.S. Geological Survey and the U.S.Environmental Protection Agency, a Data Management System was prepared by the Survey (Doyle and Lorens, 1982). This system is built upon the features of SAS. It includes all of SAS and adds modeling and routines for entry, analysis, and listing of data and results. The system was constructed around a specific format for data collection and analysis associated with the Environmental Protection Agency-Geological Survey urban studies technical coordination plan.

In addition to the Geological Survey activities, the Environmental Protection Agency disseminated information through memoranda, workshops, and consultant reports for NURP. To obtain this information, contact the Water Planning Division at the U.S. Environmental Protection Agency headquarters in Washington, D.C.

Descriptive Statistics and Frequency Analysis

The first step in data analysis is to review the data, which can be done three basic ways: (1) Scan the entire data set, (2) plot the data, and (3) derive statistics. Scanning an entire data set is sometimes useful, but more often it is confusing and time consuming. Plotting—for example, streamflow versus time—gives a good overall picture of the data set but does not provide the analyst with more than a qualitative feel for the information. Statistics can provide a few numbers that represent key elements of the entire data set, simplifying review of the data and comparisons between data sets.

Common descriptive statistics are mean, median, and standard deviation. Mean is an average (the sum of all values divided by the number of values); median is the halfway point in the data (half of the values are less than the median and half are greater); and standard deviation is a measure of the dispersion of the data (the smaller the standard deviation with respect to the mean, the closer the entire data set is clustered around the mean value). When the data set is tightly clustered, the mean and median values are representative of the entire data set. Unfortunately, some data, particularly urban stormwater data, tend to be very dispersed, having a high standard deviation.

Additional statistical techniques can be used to derive a **frequency analysis** of the data. A frequency analysis gives information on the distribution of the data—for example, the value below which 10 percent of the data falls. The common term used for this and other break points is "percentile." Common percentiles are 1, 5, 10, 25, 50, 75, 90, 95, and 99 percent.

Correlation Analysis

Relations between two or more variables can be identified by correlation analysis. In simple correlation, two variables are compared; comparison of more than two variables is called multiple correlation. With either, the interpretation of results is done the same way. When a relation is logically expected, it will usually be verified by correlation analysis. However, the degree to which variables are related is unpredictable and will vary considerably.

Correlation analysis produces two important numbers—the **correlation coefficient** (R) and the **significance level** (p). The correlation coefficient indicates the degree of relation between variables and varies in magnitude from zero to one. An R-value of one indicates a perfect relation; zero indicates no relation. Sometimes an R-value has a negative sign. This sign indicates that the relation is inverse—as one variable increases in magnitude the other decreases. A negative one R-value also indicates a perfect relation.

The significance level is the probability that the true R-value is equal to or greater than the value calculated. If the p-value is high (0.95 or more is generally considered acceptable for most purposes), then the uncertainty associated with the R-value is minimal. Conversely, if the p-value is low, not much certainty can be placed upon the R-value, even if it is high.

Multiple-Regression Analysis

A possible followup to correlation analysis is regression analysis. While correlation analysis reveals the existence of some relations between variables, regression analysis is a technique for determining an actual mathematical relation. A common misunderstanding concerning correlation and regression analysis is that they are essentially the same thing. They use very similar computational procedures, but there are critical differences. Correlation analysis considers the joint variation of two measurements over whatever is the observed range of values. Regression analysis, on the other hand, considers the variation in one measurement as the other is held fixed.

The mathematical relation in regression analysis takes the form of an equation. Mathematical equations involve two types of components, or **variables**. The input to an equation is an independent variable; that is, it can vary freely and does not depend on the outcome of the equation, the dependent variable. Regression analysis between one independent variable, such as time, and one dependent variable, such as streamflow, is called simple regression; when more than one independent variable is involved such as time and precipitation, the analysis is called multiple regression. Multiple-regression analysis is more common in hydrology because most hydrologic phenomena are influenced by more than one input variable. The general form of a multiple-regression equation is:

$$Y = a_1X_1 + a_2X_2 + a_3X_3 + \ldots a_nX_n + b + E$$

where:

Y = dependent variable, value which is unknown;

$X_1, X_2, X_3, \ldots X_n$ = independent variables, values which are known;

$a_1, a_2, a_3, \ldots a_n$ = regression coefficients;

b = intercept term; and

E = error term, the uncertainty in the regression equation.

Often the variables in the equation are transformed before the regression analysis by taking logarithms of all variables. This approach is taken because relations between hydrologic phenomena are often nonlinear. A nonlinear relation is simply one in which the phenomena being compared do not change at the same relative rate. After the transformation is made, and following some simple algebraic manipulation, the final equation looks like this:

$$Y = b(X_1^{a_1})(X_2^{a_2})(X_3^{a_3}) \ldots (X_n^{a_n}) + E$$

where all terms have the same definitions as before.

Some analysts will produce multiple-regression equations for predicting future values of dependent variables on the basis of expected values of the independent variables. When used properly, these equations can be powerful tools for planning. Certain precautions, however, must be emphasized. When independent variables have a high correlation among themselves (for example, rainfall intensity and peak discharge), the regression coefficients obtained can be very unrealistic (DeCoursey and Deal, 1971, p. 49). Regression equations obtained under these conditions may be useful for estimating values within the range of data used for their generation but may not be useful as a general model nor as a basis for defining the influence of the independent variables upon the system modeled (Riggs, 1968, p. 20). In the case study described in this report, for example, exponents of −99 and +16 were obtained for antecedent 24- and 72-hour rainfall depths, respectively. Not only are the magnitudes of the exponents unnaturally large (exponents in equations which describe hydrologic systems seldom exceed about 5), but also the signs are opposite. For variables as closely related as these, it is expected that at least the sign of the exponents should agree.

CASE STUDY—THE JONES FALLS WATERSHED, BALTIMORE, MARYLAND

Scope of Study

The following case study of the Jones Falls watershed describes the analysis and interpretation of data collected over a 2-year period in an urban watershed located in the Baltimore, Md., metropolitan area. The work was conducted by the U.S. Geological Survey as part of its participation in the Jones Falls Urban Runoff Project, a cooperative effort with the Baltimore Regional Planning Council, Baltimore City Water Quality Management Office, and Baltimore County Health Department. The project was one of 28 studies in the NURP program, which was coordinated and primarily funded by the U.S. Environmental Protection Agency. Specific objectives of the NURP studies were to determine the impact of urban stormwater runoff on water quality and to study the influence of basin and storm characteristics on stormwater quality.

The Jones Falls project was one of the most comprehensive studies of urban hydrology done for a city the size of Baltimore. It was also the only one of the 28 NURP studies to investigate highly urbanized, inner-city areas. Besides the data and interpretations given in this report, additional work was performed by the cooperators, including monitoring at additional sites. The Baltimore Regional Planning Council may be contacted for information regarding this additional work.

Local, Regional, and National Perspectives

The centerpiece of the urban revitalization for the city of Baltimore has been its Inner Harbor, which sits astride the mouth of Jones Falls. What was formerly little more than an open sewer is today surrounded by the nationally renowned Harborplace, the National Aquarium, and a thriving convention, tourist, and mercantile center. Jones Falls, which has endured over 300 years of man's influence, is again of interest for its economic value. With the environmental initiatives of the last few decades, water quality has improved. Because of the millions of dollars of investment surrounding the stream, it is desirable to foster and maintain this improved water quality.

Jones Falls represents not only an economic resource to the Baltimore area but also has significant implications for the Chesapeake Bay, a major regional resource and an undisputed national treasure. Jones Falls is just one of many urban streams draining into the bay, itself representing only about 0.1 percent of the bay drainage basin. However, it is estimated to contribute about 1 percent of total nitrogen and phosphorus entering the bay (Fisher and Katz, 1984, p. 46). Also, urban runoff generally contains elevated concentrations of metals (U.S. Environmental Protection Agency, 1983) and is likely a significant source of metals in the bay. Although the total impact of urban runoff on the Chesapeake Bay is undocumented, it may be a major source of pollutants. The situation becomes analogous to that faced by water-resources managers during the 1970's. At that time, point-source discharges of pollutants were being cleaned up, yet it was found that water quality was still being degraded by diffuse, or nonpoint, sources of pollution such as agricultural and urban runoff. The emphasis on pollution control in the Chesapeake Bay region in recent years has been on eliminating the remaining point sources and nonurban nonpoint sources of pollution. The results of the case study presented in this report suggest that urban nonpoint sources are also significant. Urban sources of pollution may be amenable to control because they are closely clustered.

Project Description

Study Area

The Jones Falls watershed encompasses 59 mi^2 in Baltimore City and rural sections of Baltimore County, Md. (fig. 5). It is considered to be heavily urbanized, with 54 percent of the total area developed to some extent. Upstream of Lake Roland (fig. 5), the watershed is primarily rural or agricultural. Figure 6 shows typical land use and a stream segment in the upper part of the watershed. The southernmost part, about 16 mi^2, is the most heavily urbanized, with about 84 percent in urban use. Figure 7 shows typical land use and a stream segment in this section of the watershed. About 46 percent of the land south of Lake Roland is classified as low-, medium-, and high-density residential. Streets and alleys constitute 21 percent of total land area in this section.

The climate is generally warm summers and mild winters. The coldest period is usually in late January and early February, and the warmest is in the last half of July and early August. The distribution of monthly precipitation is fairly uniform throughout the year, and the average yearly precipitation is 42 in. Long-duration storms predominantly occur during the cold season (December through March). Average precipitation intensities are highest in June, July, August, and September

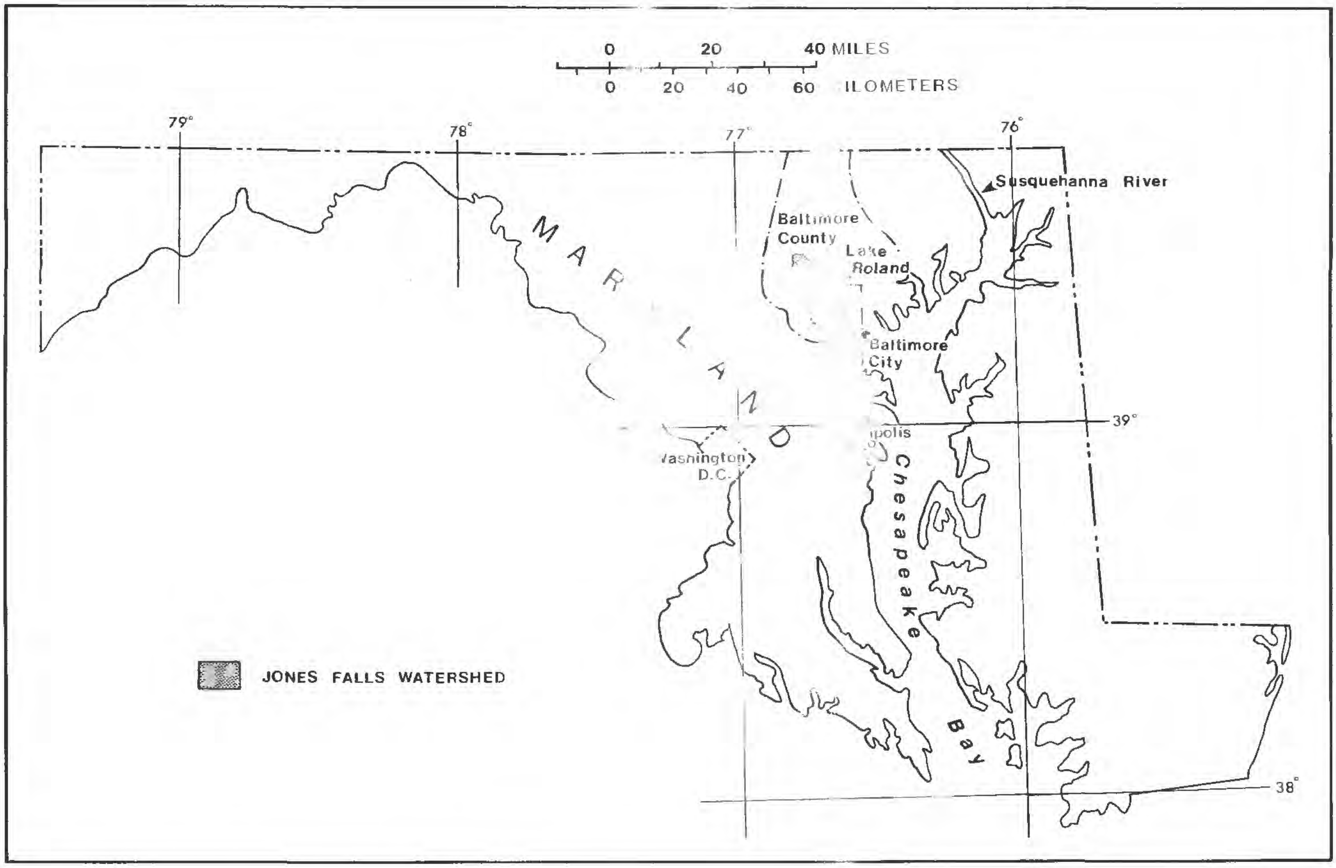

Figure 5. Location of Jones Falls watershed in Maryland.

(0.08 to 0.13 in/hr), whereas the lower intensity storms usually occur in December through April (0.03 to 0.05 in/hr).

During cold-weather months, prevailing winds are from the west or the northwest. Southerly winds predominate during warm months. The average annual wind speed is about 10 mi/hr, with the highest frequency of strong winds between late winter and early spring.

The work described in the case study focused primarily on high-density residential land use, although one watershed investigated included commercial areas. Several different neighborhoods were studied to learn whether water-quality characteristics of urban runoff vary with differences in land treatment. **Land treatment** refers to practices such as refuse disposal, street sweeping, lawn and garden fertilization, pesticide use, and other practices which could influence the presence or distribution of potential pollutants on the land surface. It also includes factors such as population density, traffic patterns, building materials, and proximity to public-works facilities.

Figure 8 shows the location of the areas studied within the Jones Falls watershed. A monitoring station was maintained near the mouth of the Jones Falls (Biddle Street) to obtain data on runoff and water-quality for the entire watershed. Three small watersheds (Hampden, Reservoir Hill, and Bolton Hill) were also studied, each representing a different type of land treatment. These four stations were operated by the U.S. Geological Survey. The other monitoring stations shown in figure 8 (Mount Washington, Homeland, Lake Roland, and Stoney Run) represent lower density land uses and were operated by the Baltimore Regional Planning Council. The station names correspond to the names of the city neighborhoods or areas around the watersheds.

Characteristics of the watersheds are listed in table 4. The Hampden (fig. 9) neighborhood was originally a village that grew around some of the many mills along the Jones Falls. The age and style of houses in Hampden varies, although most are modest-size rowhouses. There is a strip of retail-commercial area along its principal street (fig. 9). The area is generally free of surface litter

Figure 6. A stream reach and representative land use upstream from the urban part of the Jones Falls watershed.

Figure 7. A stream reach and representative land use in the urban part of the Jones Falls watershed.

and is swept on a schedule by a Department of Sanitation "hokey-man." A hokey-man consists of a single person who uses a push-broom, shovel, and cart to keep the street gutters free from litter. This technique of street sweeping is particularly effective for litter control because the gutters are cleaned better than with a mechanical sweeper. Much of the material that becomes available for transport by runoff accumulates in the gutter area.

The housing in Reservoir Hill (fig. 10) is very similar to that found in Bolton Hill (fig. 11), consisting mainly of Victorian rowhouses (townhouses) built about 1880 to 1890. While both were originally affluent and well- maintained neighborhoods, they decayed with time and changing economic conditions, but they are now experiencing a revitalization. Reservoir Hill's renovation, however, is well behind that of Bolton Hill. Many of the living units in Reservoir Hill are rentals, so there is little incentive for major capital improvements by the residents. There is no street sweeping within the Reservoir Hill watershed. Bolton Hill has rental housing also, but many homes are owner-occupied. Bolton Hill has a much lower population density, and there is scheduled street cleaning by hokey-cart.

Data Collection

Rainfall, runoff, and water-quality data were collected in 1981 and 1982 at the watershed sites described above. The data consist of rainfall and runoff at 1-minute intervals for the small watershed sites and streamflow at 5-minute intervals for the Biddle Street site. Water-quality data were collected as either **discrete samples** or **flow-weighted-composite samples**. In addition, a network of eight supplemental rain gages was maintained in the watershed to better define watershed rainfall and to help estimate missing data at the monitoring sites. Continuous rainfall data were collected at 5-minute intervals at the supplemental rain-gage sites.

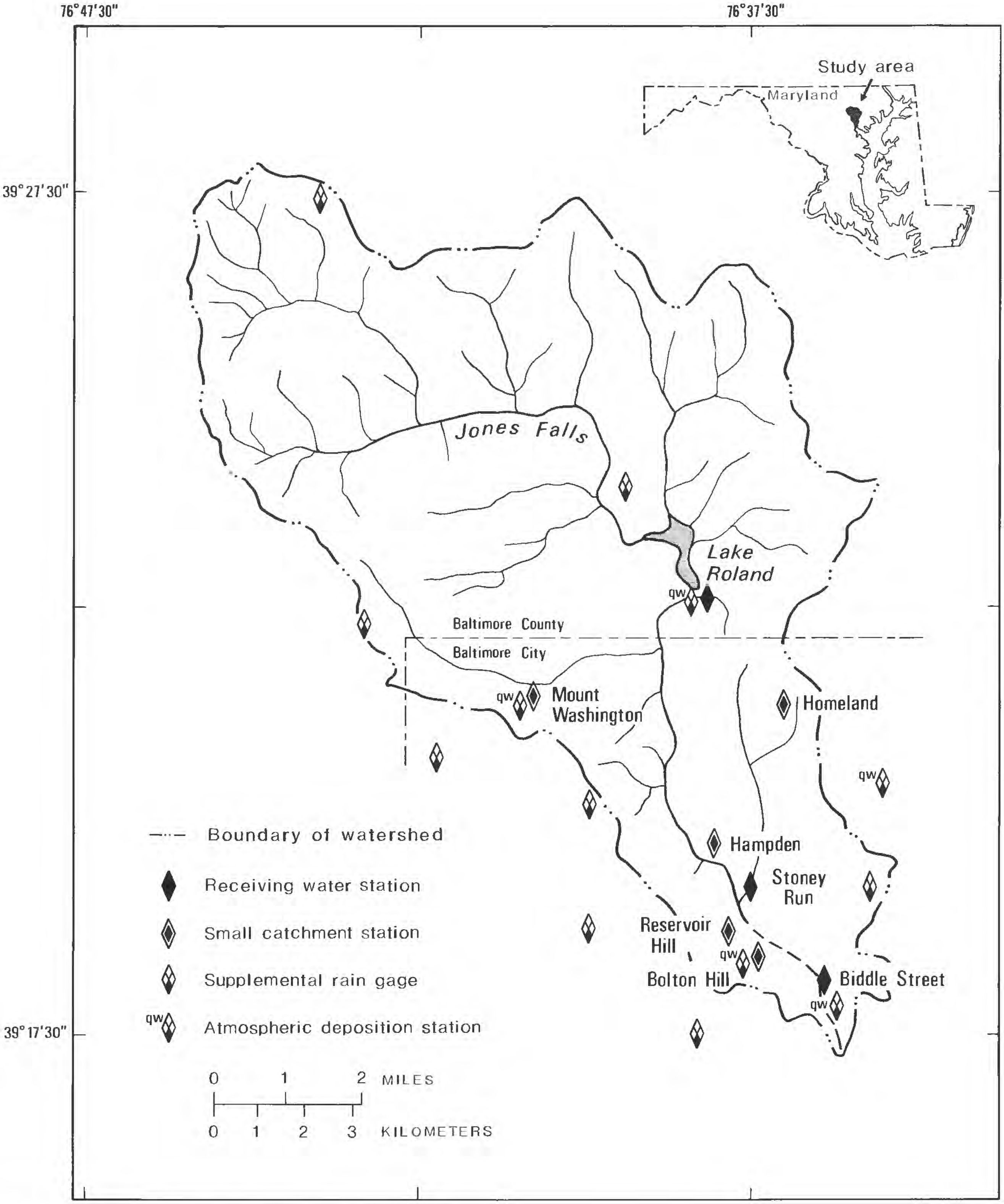

Figure 8. Data-collection sites in the Jones Falls watershed.

Table 4. Characteristics of drainage basins

[ft/mi^2 is feet per square mile; mi^2 is square miles; mi/mi^2 is miles per square mile; dashes indicate data not available]

Station name	Hampden	Reservoir Hill	Bolton Hill	Biddle Street (main stem)
Station number	01589460	01589470	01589475	01589480
Latitude/ longitude	39°19′42″ 76°37′52″	39°18′48″ 76°37′52″	39°18′29″ 76°37′31″	39°18′12″ 76°36′43″
Total drainage area (acres)	16.91	10.48	14.15	37,760
Impervious area (percentage of drainage area)	72	76	61	34
Effective impervious area (percentage of drainage area)	72	76	61	33
Average basin slope (ft/mi)	206	169	185	456
Main conveyance slope (ft/mi)	188	97	86	22
Population density (persons/mi^2)	35,800	47,300	17,800	3,640
Street density (lane mi/mi^2)	112	128	98	—
Land use (percentage of drainage area)				
Residential[1]	84	100	100	44
Commercial	16	0	0	4
Other	0	0	0	[2]52
Percentage of area drained by storm sewers	100	100	100	—
Percentage of streets with curb and gutter drainage	100	100	100	—

[1] Residential land use was all high density (more than eight dwelling units per acre) for Hampden, Reservoir Hill, and Bolton Hill.

[2] "Other" land use for Biddle Street included industrial (2 percent), institutional (4 percent), cemetery/recreational (6 percent), agricultural (12 percent), brush/grass (3 percent), woodland (23 percent), and miscellaneous (2 percent).

Data were collected, verified, and entered into WATSTORE for the events sampled during 36 separate storms. Table 5 indicates the storms for which data were collected.

Table 6 lists the water-quality constituents for which analyses were made. Eight of the sixteen constituents were selected for detailed data analysis. The eight constituents were chosen because they are representative of the types of potential contaminants of most interest in the study—total suspended solids is a measure of sediment, which is itself of concern, but also is a medium for constituent transport; total Kjeldahl nitrogen and total phosphorus are important nutrients; total organic carbon and chemical oxygen demand are measures of organic pollution; and total copper, total lead, and total zinc are potentially toxic metals.

It may be useful at this point to consider the meaning of these various measurements and determinations in more detail. The nutrients nitrogen and phosphorus are essential for the growth of all plants, including algae. However, nutrient concentrations in water in excess of those required to sustain an existing algal population lead to excessive propagation, or algal blooms. These blooms are unsightly; they can foul equipment and can block light penetration to flora and fauna at lower depths. When the blooms die off, at the least there will probably be an objectionable odor. Possibly, the consumption of dissolved oxygen required for decomposition of the dead algae will deplete that available for fish, and fish kills will occur.

Sediment, another pollutant, is indigenous to the environment. Sediment is a product of erosion, a natural process. However, man's activities often accelerate erosion. The sediment thus generated can, like algae, reduce light penetration in water. In sufficient quantities, it can bury submerged aquatic vegetation and bottom-dwelling animals as it drops out of suspension in a stream, lake, or estuary. Also, it is a medium for transport of other pollutants, including phosphorus, metals, and organic chemicals, such as pesticides.

Organic pollution, indicated by high chemical oxygen demand and concentrations of total organic carbon, in most cases causes a demand upon the aquatic system for oxygen to decompose organic materials. As discussed above, oxygen depletion can lead to odor problems and fish kills. Sources of organic pollution

Figure 9. Representative land uses and an alley in the Hampden commercial/high-density residential watershed.

include dead plant materials (such as algae), sewage, and anything that is biodegradable. Chemical oxygen demand is a measure of oxygen consumption when all materials in a sample are oxidized in a strong chemical reaction. Materials that would not normally be oxidized by biological decomposition are included, so it is used only as an index of organic pollution. However, it is a relatively simple and inexpensive procedure. Total organic carbon is a direct measurement of total organic material from both natural and synthetic sources. It is a more complex and more expensive procedure than the determination of chemical oxygen demand. Because it may include compounds that are not easily biodegradable, it also is only used as an index of organic pollution.

Metals are toxic to many organisms. Copper is an essential nutrient for both plants and animals at trace concentrations. However, at higher concentrations, copper is used as a herbicide, and, above 22 parts per billion, it is toxic to many fish. Zinc is also an essential nutrient at low concentrations. However, excessive amounts of zinc affect growth rates and decrease both the weight and fat content of the liver. Lead is not a nutrient and may be toxic even at trace concentrations.

Water-quality data were also collected during **base-flow** conditions at the Biddle Street site every 2 weeks, when possible. Data were collected to define water-quality conditions during nonstorm periods. Base-flow sampling included measurements of pH, specific conductance, dissolved oxygen, and temperature, as well as analysis for the constituents listed in table 6. Data for 29 base-flow samples have been entered into WATSTORE.

Table 7 lists and summarizes the rainfall and runoff characteristics of the sampled storms. Most of these characteristics were derived from 1-minute rainfall/runoff data at the small watersheds and 5-minute streamflow at Biddle Street. The supplemental rain-gage data were used to derive rainfall characteristics for the Biddle Street site (which represents the entire Jones Falls watershed) and to estimate missing data at the small watersheds. These results and their significance are discussed in the following section.

Table 5. Storms for which data were collected

[Storm data consist of streamflow and water-quality data for the Biddle Street site (main stem) and rainfall, runoff, and water-quality data for the other three sites (small watersheds)]

Storm no.	Date		Hampden	Reservoir Hill	Bolton Hill	Biddle Street
	Begin	End				
1	02/08/81	02/09/81				X
2	03/04/81	03/05/81		X	X	X
3	03/30/81	03/31/81				X
4	04/05/81	04/06/81				X
5	04/28/81	04/29/81				X
6	05/01/81	05/01/81			X	
7	05/15/81	05/15/81	X	X	X	
8	06/10/81	06/10/81				X
9	07/20/81	07/20/81			X	
10	07/25/81	07/25/81	X	X	X	
11	07/26/81	07/26/81	X	X	X	
12	07/28/81	07/28/81		X	X	
13	07/28/81	07/28/81		X	X	
14	08/06/81	08/06/81		X		
15	08/08/81	08/08/81		X		
16	08/11/81	08/11/81	X			
17	09/08/81	09/08/81	X			
18	09/15/81	09/16/81	X		X	
19	09/17/81	09/18/81	X			X
20	09/22/81	09/22/81	X			
21	09/27/81	09/27/81	X		X	X
22	10/01/81	10/02/81			X	X
23	10/06/81	10/06/81			X	
24	10/18/81	10/08/81		X	X	X
25	10/23/81	10/24/81		X	X	X
26	11/05/81	11/06/81			X	
27	12/01/81	12/02/81		X	X	X
28	12/14/81	[1]12/15/81	X		X	X
29	01/30/82	02/01/82				X
30	02/09/82	02/10/82				X
31	02/16/82	02/18/82				X
32	03/06/82	03/07/82	X	X		
33	03/16/82	03/17/82	X	X		
34	03/25/82	03/26/82		X		
35	04/03/82	04/03/82	X			X
36	04/26/82	[1]04/26/82	X			X

[1] Flow was sustained above base flow at Biddle Street until 12/19/81 and 04/29/82 for storms nos. 28 and 36, respectively.

Results of the Small Watershed Studies

Water-Quality Characteristics for Selected Constituents

Table 8 lists statistics for EMC's observed at the three small watershed sites. The standard deviation is high with respect to the mean (generally, about 100 percent of the mean), indicating that the data are widely dispersed. This means that additional observations can be expected to have a wide range of values; in other words, the EMC's do not remain constant between storms or over time. Percentiles are also listed in table 8. Note percentiles below 10 and above 90 are not given, because not enough data were collected to compute them. A percentile of 5 or 95, for example, requires at least 20 data points to compute.

Statistics can be used for data interpretation. For example, a comparison of means and standard deviations among several watersheds can reveal differences related to watershed characteristics. A mean value of a particular chemical constituent can be compared to a particular water-quality criterion, such as a drinking water standard. Also, a frequency analysis (percentiles) can be used to determine the percentage of data values that exceed the criterion. Such an analysis can be used to estimate the probability that the criterion will be exceeded in the future.

Figure 10. Representative land use and an alley in the Reservoir Hill high-density residential watershed.

Figure 11. Representative land use and an alley in the Bolton Hill high-density residential watershed.

Table 6. Selected chemical constituents analyzed in the water samples

Constituent	WATSTORE code[1]
Total Kjeldahl nitrogen[2]	00625
Ammonia	00610
Total phosphorus[2]	00665
Total orthophosphorus	70507
Total organic carbon[2]	00680
Total inorganic carbon	00685
Suspended solids[2]	00530
Dissolved solids	70300
Turbidity	00076
Chemical oxygen demand[2]	00335 or 00340
Cadmium	01027
Chromium	01034
Copper[2]	01042
Iron	01045
Lead[2]	01051
Zinc[2]	01092

[1] WATSTORE is the WATer STOrage and REtrieval system, the hydrologic data base of the U.S. Geological Survey.

[2] Detailed statistical analyses are for these constituents only.

Table 9 compares instantaneous concentrations (at a particular instant in time) and EMC's to selected water-quality criteria. Figures 12 through 15 present the comparisons graphically. Both instantaneous concentrations and EMC's must be considered in assessing water quality. Aquatic organisms can be affected by either a short-term exposure to a high concentration (acute) or by a prolonged lower concentration (chronic). High instantaneous concentrations, while important, may result from a transient condition or contamination of water samples. EMC's are more indicative of long-term conditions; thus, only EMC's are subjected to further detailed analysis.

As table 9 shows, the criteria considered are exceeded in most stormflow observations, particularly the EMC's. Most suspended solids EMC's exceed limits for secondary sewage effluent. EMC's for nutrients, total Kjeldahl nitrogen, and total phosphorus exceed concentrations observed in forest watersheds for 93 to 100 percent of all observations. Also, total phosphorus for all samples exceeds 0.04 mg/L, a general criterion

Table 7. *Summary of storm characteristics for sampled events*

DURRNF ..... Duration of rainfall, in minutes.
TRAINA ..... Average total rainfall for the basin, in inches.
MAXR1 ...... Maximum 1-minute rainfall rate, in inches.
MAXR5 ...... Maximum 5-minute rainfall rate, in inches.
MAXR15 ..... Maximum 15-minute rainfall rate, in inches.
MAX1H ...... Maximum 1-hour rainfall rate, in inches.
NDRD02 ..... Number of dry hours since storm with 0.2 inch or more rainfall.
NDR001 ...... Number of dry hours since storm with 0.01 inch or more rainfall.
DERNPD ..... Rainfall accumulation, in inches, during the 24 hours preceding beginning time of sampled storm.
DERNP3 ..... Rainfall accumulation, in inches, during the 72 hours preceding beginning time of sampled storm.
DERNP7 ..... Rainfall accumulation, in inches, during the 168 hours preceding beginning time of sampled storm.
DURSTO ..... Total duration of runoff, in minutes.
Q .... Total runoff for storm hydrograph, in inches.
PEAKQ ...... Peak discharge of event, in cubic feet per second.
TIMBPK ..... Time before peak, in minutes. Total elapsed time from the beginning of rainfall to the time of the occurrence of the peak discharge.
BFLOW ...... Base flow, in cubic feet per second. For the small watersheds, base flow is assumed to be zero; for Biddle Street, base flow is the mean daily discharge of the day prior to the beginning date of rainfall.
N .... The number of discrete samples analyzed.

Summary statistics format is: **maximum** (median);
minimum

[min is minutes; in. is inches; in/hr is inches per hour; hr is hours; ft^3/s is cubic feet per second; no. is number; dashes indicate data not available]

Characteristic	Hampden	Reservoir Hill	Bolton Hill	Main stem (Biddle Street)
DURRNF (min)	**943** (336) 8	**957** (179) 29	**996** (221) 29	**5735** (498) 110
TRAINA (in.)	**1.51** (0.45) 0.05	**1.02** (0.28) 0.03	**2.39** (0.60) 0.02	**1.74** (0.46) 0.07
MAXR1 (in/hr)	**22.2** (1.20) 0.60	**4.80** (1.20) 0.60	**10.2** (1.20) 0.60	–
MAXR5 (in/hr)	**5.64** (0.60) 0.12	**3.72** (0.30) 0.12	**5.04** (0.48) 0.12	**2.55** (0.42) 0.42
MAXR15 (in/hr)	**2.40** (0.48) 0.04	**2.28** (0.22) 0.04	**2.72** (0.34) 0.04	**1.13** (0.28) 0.14
MAX1H (in/hr)	**0.80** (0.25) 0.01	**0.93** (0.13) 0.01	**1.33** (0.22) 0.05	**0.32** (0.20) 0.04
NDRD02 (hr)	**747** (231) 13	**791** (290) 75	**791** (336) 58	**607** (187) 13
NDRD001 (hr)	**607** (101) 13	**343** (69) 6	**607** (101) 6	**607** (187) 13
DERNPD (in.)	**0.21** (0.00) 0.00	**0.07** (0.00) 0.00	**0.07** (0.00) 0.00	**0.21** (0.00) 0.00
DERNP3 (in.)	**1.52** (0.00) 0.00	**0.11** (0.04) 0.00	**0.57** (0.00) 0.00	**1.52** (0.00) 0.00
DERNP7 (in.)	**2.30** (0.15) 0.00	**1.13** (0.15) 0.00	**1.13** (0.15) 0.00	**1.52** (0.15) 0.00
DURSTO (min)	**1148** (323) 105	**958** (301) 101	**947** (321) 72	**6849** (365) 365
Q[1] (in.)	**1.15** (0.18) 0.01	**0.71** (0.10) 0.01	**1.89** (0.27) 0.00	**0.32** (0.08) 0.02
PEAKQ[1] (ft^3/s)	**67** (2.5) 0.17	**25** (0.91) 0.08	**46** (5.1) 0.05	**1700** (435) 100
TIMBPK (min)	**663** (65) 2	**363** (94) 9	**432** (47) 6	**1175** (230) 35
BFLOW (ft^3/s)	**0** (0) 0	**0** (0) 0	**0** (0) 0	**73** (41) 22
N (no.)	**11** (9) 4	**11** (8) 4	**10** (7) 3	**17** (9) 1

[1] Base flow has been subtracted from Q and PEAKQ to yield the volume of water that represents only stormwater runoff.

Table 8. Descriptive statistics for event-mean concentrations observed at the Hampden, Reservoir Hill, and Bolton Hill watersheds

[Items: TSS = total suspended solids; TKN = total Kjeldahl nitrogen; TP = total phosphorus; COD = chemical oxygen demand; TOC = total organic carbon; TCu = total copper; TPb = total lead; TZn = total zinc; No. obs. = Number of observations; Std. Dev. = Standard deviation. Sites: HA = Hampden, RH = Reservoir Hill, BH = Bolton Hill]

Item	Site	No. obs.	Mean	Std. Dev.	Percentiles 10	25	50	75	90
TSS	HA	17	77.6	66.3	12.1	35.3	60.7	114	206
(mg/l)	RH	12	136	96.4	25.3	42.8	127	180	318
	BH	16	92.4	122	11.7	27.9	59.9	114	263
TKN	HA	16	7.16	5.40	2.92	3.71	6.39	7.34	14.7
(mg/l	RH	12	11.0	5.42	3.99	8.20	10.0	13.3	21.8
as N)	BH	16	5.92	3.2	51.44	3.60	5.84	8.06	10.8
TP	HA	17	.663	.420	.193	.332	.619	1.01	1.24
(mg/l	RH	12	3.60	2.36	1.20	1.81	3.05	4.59	8.43
as P)	BH	17	1.02	1.05	.259	.371	.556	1.14	3.46
COD	HA	17	102	70.9	15.0	45.5	96.3	137	187
(mg/l)	RH	12	190	155	45.5	91.8	115	275	508
	BH	17	196	195	30.8	54.4	122	307	595
TOC	HA	17	22.4	16.1	3.83	13.0	17.4	24.8	54.0
(mg/l)	RH	12	40.3	33.8	6.79	14.6	36.0	53.5	109
	BH	17	25.3	29.0	3.80	4.85	11.7	39.7	78.4
TCu	HA	17	58.9	31.8	21.8	30.0	49.9	82.7	112
(μg/l)	RH	12	44.2	31.4	12.5	22.4	33.8	61.9	107
	BH	17	105	61.5	40.2	54.7	76.3	167	201
TPb	HA	17	247	169	55.0	114	200	373	513
(μg/l)	RH	12	395	363	43.0	120	292	608	1130
	BH	17	2590	5070	92.0	184	362	1660	10700
TZn	HA	17	332	177	112	195	280	461	649
(μg/l)	RH	12	514	468	95.0	262	422	546	1540
	BH	17	1580	3070	171	226	428	1020	6340

proposed by Lee and others (1981) for classifying lakes as **eutrophic**. Most EMC's for total organic carbon, an indicator of general organic contamination, are higher than those considered typical for nonpolluted streams in the United States. Except for total zinc at Reservoir Hill, all EMC's for metals exceed long-term exposure limits for freshwater aquatic life. Urban runoff is considered to be a primary source of some metals in receiving waters. In general, table 9 and figures 12 through 15 indicate that all the sampled urban stormwater runoff is significantly degraded with respect to the water-quality criteria considered.

Figures 14 and 15 show the distribution of EMC's observed for the three small watersheds. A visual comparison between plots reveals that the ranges of observations for the three sites generally have the same magnitudes. The only clear differences are that total phosphorus values tend to be higher at Reservoir Hill and total copper tends to be higher at Bolton Hill. Mean total lead and total zinc values are slightly higher at Bolton Hill, and total Kjeldahl nitrogen is slightly higher at Reservoir Hill. Statistical tests (analysis of variance, or ANOVA) verify these observations as being statistically significant differences. They reveal also that mean total lead and total zinc values are higher at Reservoir Hill. The importance of statistical significance is that the comparison is objective; the statement that a difference exists can be made with some certainty. It is associated with a significance level—in this case, greater than or equal to 0.95, which is actually the probability that the correct decision has been made. The implication of observed differences is that one particular watershed can be shown to contribute more to water-quality problems, suggesting that pollution abatement programs will be more effective if they are concentrated in that watershed.

Table 9. Comparison of observed data to selected water-quality criteria at the Hampden, Reservoir Hill, and Bolton Hill watersheds

Constituent	Criteria[1] (milli-grams/liter)	Percentage exceeding criteria: Hampden	Reservoir Hill	Bolton Hill
Instantaneous concentrations				
Total suspended solids	[2]30	53	65	43
Total Kjeldahl nitrogen	[3].074	100	100	100
Total phosphorus	[3].069	99	100	98
Total organic carbon	[4]10	78	81	54
Total copper	[5].022	88	70	100
Total lead	[5].17	39	48	49
Total zinc	[5].32	40	47	44
Event-mean concentrations				
Total suspended solids	[2]30	78	86	73
Total Kjeldahl nitrogen	[3].074	100	100	100
Total phosphorus	[3].069	93	100	100
Total organic carbon	[4]10	80	84	46
Total copper	[6].0056	100	100	100
Total lead	[6].0038	100	100	100
Total zinc	[6].047	100	93	100

[1] No criteria have been established for total Kjeldahl nitrogen, total phosphorus, chemical oxygen demand, or total organic carbon; the listed values have been selected from the cited literature for comparison, except for chemical oxygen demand, for which no comparisons were found.

[2] U.S. Environmental Protection Agency, 1976; secondary sewage effluent limitation, mean for 30 days of consecutive sampling.

[3] Sylvester, 1961; mean concentration for three streams draining forested watersheds.

[4] Malcolm and Durum, 1976; typical concentration for nonpolluted United States streams under normal flow conditions.

[5] U.S. Environmental Protection Agency, 1980; acute exposure limit for freshwater aquatic life assuming hardness of 100 mg/L as $CaCO_3$.

[6] U.S. Environmental Protection Agency, 1980; chronic exposure limit for freshwater aquatic life assuming hardness of 100 mg/L as $CaCO_3$.

Factors Influencing Water Quality

Storm Characteristics

An axiom accepted at the onset of the project was that storm characteristics play a key role in influencing the water quality of urban stormwater runoff. The relation between storm characteristics and water quality must be determined before a pollution-control strategy can be developed. If peak discharge is the principal factor affecting water quality, for example, then techniques to control the peak, such as stormwater detention ponds, can be considered. Statistical correlation analysis was used to search for possible relationships between EMC's and storm characteristics. Twelve storm characteristics were investigated. To simplify interpretation of the results, these characteristics were grouped into five classes of influencing factors: (1) volume, (2) duration, (3) intensity, (4) accumulation, and (5) timing. Table 10 indicates the grouping of the factors. Accumulation refers to material on the land surface and is directly related to the time period since the previous rainfall. It is inversely related to antecedent rainfall—with greater antecedent rainfall, less material accumulates on the land surface. Antecedent rainfall is used in this analysis as a measure of accumulation.

Table 10. Grouping of storm characteristics

Group	Characteristic	Description[1]
Volume	TRAINA	Total rainfall.
	Q	Total runoff.
Duration	DURRNF	Duration of rainfall.
	DURSTO	Duration of runoff.
Intensity	MAXR5	Maximum 5-minute rainfall.
	MAXR15	Maximum 15-minute rainfall.
	MAX1H	Maximum 1-hour rainfall.
	PEAKQ	Peak discharge.
Accumulation	DERNPD	Rainfall previous 24 hours.
	DERNP3	Rainfall previous 72 hours.
	DERNP7	Rainfall previous 168 hours.
Timing	TIMBPK	Time to peak discharge.

[1] More detailed descriptions are given in table 7.

Correlation analysis between selected water-quality constituents and storm characteristics was used to identify relations having significant correlation coefficients: that is, those greater than 0.50 with a significance level of 0.95 or better. Table 11 summarizes the significant relations determined for event-mean concentrations versus the grouped storm characteristics from table 10. The sign indicates whether the relation is directly (+) or inversely (−) proportional.

In evaluating the correlations, certain general results are expected: EMC's should increase with intensity and accumulation factors and decrease with volume and duration. Accumulation makes material available for washoff, and intensity provides the energy required to transport it. EMC's decrease with increased duration and generally with volume as the supply of available

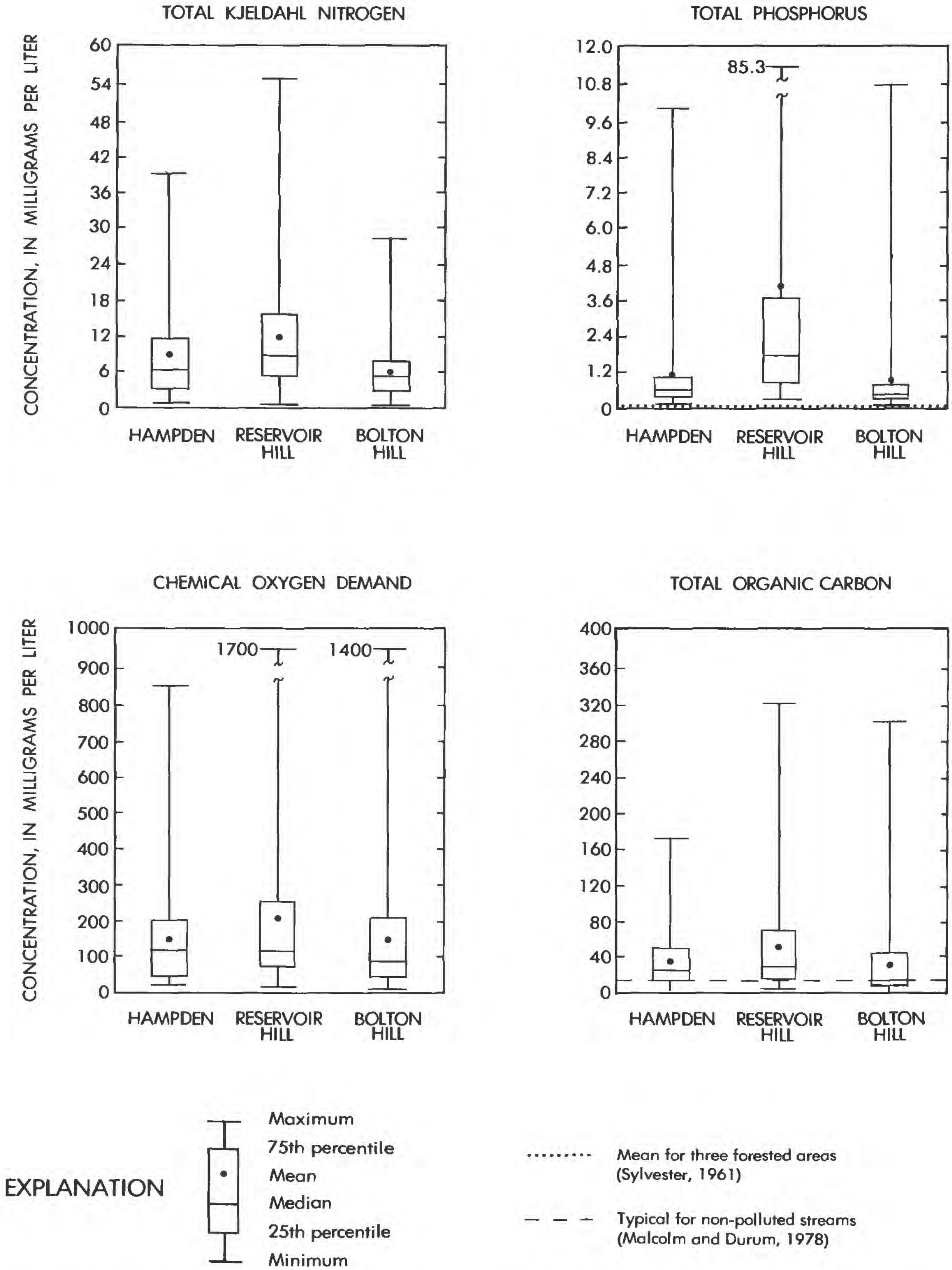

Figure 12. Comparison of instantaneous concentrations of total Kjeldahl nitrogen, total phosphorus, chemical oxygen demand, and total organic carbon at the Hampden, Reservoir Hill, and Bolton Hill watersheds.

Malcolm, R. L., and Durum, W. H., 1976, Organic carbon and nitrogen concentrations and annual organic carbon load of six selected rivers of the United States: U.S. Geological Survey Water-Supply Paper 1817-F, 21 p.

Martin, S. R., and Clayton, P. S., 1986, Jones Falls watershed urban storm-water runoff project, technical summary: Regional Planning Council, Baltimore, Md., 71 p.

McKee, J. E., and Wolf, H. W., 1963, Water quality criteria: California State Water Quality Control Board Publication 3-A, 548 p.

Mulvaney, T. J., 1851, On the use of self-registering rain and flood gauges in making observations of rainfall and flood discharges in a given catchment: Institution of Civil Engineers of Ireland, Transactions, v. 4, pt. 2, p. 18-31.

Nie, N. H., Hull, C. H., Jenkins, J. G., Steinbrenner, K., and Bent, D. H., 1975, Statistical package for the social sciences (2d ed): New York, McGraw-Hill, 675 p.

Rawls, W. J., Stricker, V. A., and Wilson, K. V., 1980, Review and evaluation of urban flood flow frequency procedures: U.S. Department of Agriculture, Science and Education Administration, Bibliographies and Literature of Agriculture No. 9, 63 p.

Riggs, H. C., 1968, Some statistical tools in hydrology: U.S. Geological Survey Techniques of Water-Resources Investigations, Book 4, Chapter A1, 39 p.

Savini, John, and Kammerer, J. C., 1961, Urban growth and the water regimen: U.S. Geological Survey Water-Supply Paper 1591-A, 43 p.

Shelley, P. E., and Driscoll, E. D., 1979, Evaluation of urban runoff studies conducted under the 208 program: EG & G Consultants, Rockville, Md., Report No. D460-101, 115 p.

Sherman, L. K., 1932, Stream flow from rainfall by the unit-graph method: Engineering News-Record, v. 108, p. 501-505.

Sylvester, R. O., 1961, Nutrient content of drainage water from forested, urban, and agricultural areas, *in* Algae and metropolitan wastes: U.S. Public Health Service, SEC TR W61-3, p. 80-87.

UNESCO, 1977, Research on urban hydrology, 1. State-of-the-art reports from Australia, Canada, USSR, United Kingdom, and USA: Technical Papers in Hydrology, no. 15, 185 p.

——1978, Research on urban hydrology, 2. State-of-the-art reports from Federal Republic of Germany, Sweden, France, Norway, Netherlands, Poland, and India: Technical Papers in Hydrology, no. 16, 265 p.

U.S. Environmental Protection Agency, 1976, Secondary treatment information, biochemical oxygen demand, suspended solids, and pH: Federal Register, v. 41, no. 144, Monday, July 26, 1976, p. 30788.

——1980, Water quality criteria documents; availability (Appendix A—Summary of water quality criteria): Federal Register, v. 45, no. 231, Friday, November 28, 1980, p. 79324-79341.

——1983, Results of the Nationwide Urban Runoff Program: Water Planning Division, Washington, D.C., 3 volumes plus Executive Summary.

U.S. Geological Survey, 1982-83, Water resources data for Maryland and Delaware, water years 1981-82: U.S. Geological Survey Water-Data Reports MD-DE-81-1 to MD-DE-82-1 (published annually).

U.S. Soil Conservation Service, 1975, Urban hydrology of small watersheds: Technical Release 55, 91 p.

Urban Hydrology Research Council, 1965, Report of conference, Engineering Foundation Research Conference: Andover, N.H., 1965, 25 p.

Viessman, Warren, Jr., 1966, The hydrology of small impervious areas: Water Resources Research, v. 2, p. 405-412.

——1968, Runoff estimation for very small drainage areas: Water Resources Research, v. 4, p. 87-93.

SELECTED SERIES OF U.S. GEOLOGICAL SURVEY PUBLICATIONS

Periodicals

Earthquakes & Volcanoes (issued bimonthly).
Preliminary Determination of Epicenters (issued monthly).

Technical Books and Reports

Professional Papers are mainly comprehensive scientific reports of wide and lasting interest and importance to professional scientists and engineers. Included are reports on the results of resource studies and of topographic, hydrologic, and geologic investigations. They also include collections of related papers addressing different aspects of a single scientific topic.

Bulletins contain significant data and interpretations that are of lasting scientific interest but are generally more limited in scope or geographic coverage than Professional Papers. They include the results of resource studies and of geologic and topographic investigations; as well as collections of short papers related to a specific topic.

Water-Supply Papers are comprehensive reports that present significant interpretive results of hydrologic investigations of wide interest to professional geologists, hydrologists, and engineers. The series covers investigations in all phases of hydrology, including hydrogeology, availability of water, quality of water, and use of water.

Circulars present administrative information or important scientific information of wide popular interest in a format designed for distribution at no cost to the public. Information is usually of short-term interest.

Water-Resources Investigations Reports are papers of an interpretive nature made available to the public outside the formal USGS publications series. Copies are reproduced on request unlike formal USGS publications, and they are also available for public inspection at depositories indicated in USGS catalogs.

Open-File Reports include unpublished manuscript reports, maps, and other material that are made available for public consultation at depositories. They are a nonpermanent form of publication that may be cited in other publications as sources of information.

Maps

Geologic Quadrangle Maps are multicolor geologic maps on topographic bases in 7 1/2- or 15-minute quadrangle formats (scales mainly 1:24,000 or 1:62,500) showing bedrock, surficial, or engineering geology. Maps generally include brief texts; some maps include structure and columnar sections only.

Geophysical Investigations Maps are on topographic or planimetric bases at various scales; they show results of surveys using geophysical techniques, such as gravity, magnetic, seismic, or radioactivity, which reflect subsurface structures that are of economic or geologic significance. Many maps include correlations with the geology.

Miscellaneous Investigations Series Maps are on planimetric or topographic bases of regular and irregular areas at various scales; they present a wide variety of format and subject matter. The series also includes 7 1/2-minute quadrangle photogeologic maps on planimetric bases which show geology as interpreted from aerial photographs. Series also includes maps of Mars and the Moon.

Coal Investigations Maps are geologic maps on topographic or planimetric bases at various scales showing bedrock or surficial geology, stratigraphy, and structural relations in certain coal-resource areas.

Oil and Gas Investigations Charts show stratigraphic information for certain oil and gas fields and other areas having petroleum potential.

Miscellaneous Field Studies Maps are multicolor or black-and-white maps on topographic or planimetric bases on quadrangle or irregular areas at various scales. Pre-1971 maps show bedrock geology in relation to specific mining or mineral-deposit problems; post-1971 maps are primarily black-and-white maps on various subjects such as environmental studies or wilderness mineral investigations.

Hydrologic Investigations Atlases are multicolored or black-and-white maps on topographic or planimetric bases presenting a wide range of geohydrologic data of both regular and irregular areas; principal scale is 1:24,000 and regional studies are at 1:250,000 scale or smaller.

Catalogs

Permanent catalogs, as well as some others, giving comprehensive listings of U.S. Geological Survey publications are available under the conditions indicated below from the U.S. Geological Survey, Books and Open-File Reports Section, Federal Center, Box 25425, Denver, CO 80225. (See latest Price and Availability List.)

"Publications of the Geological Survey, 1879-1961" may be purchased by mail and over the counter in paperback book form and as a set of microfiche.

"Publications of the Geological Survey, 1962-1970" may be purchased by mail and over the counter in paperback book form and as a set of microfiche.

"Publications of the U.S. Geological Survey, 1971-1981" may be purchased by mail and over the counter in paperback book form (two volumes, publications listing and index) and as a set of microfiche.

Supplements for 1982, 1983, 1984, 1985, 1986, and for subsequent years since the last permanent catalog may be purchased by mail and over the counter in paperback book form.

State catalogs, "List of U.S. Geological Survey Geologic and Water-Supply Reports and Maps For (State)," may be purchased by mail and over the counter in paperback booklet form only.

"Price and Availability List of U.S. Geological Survey Publications," issued annually, is available free of charge in paperback booklet form only.

Selected copies of a monthly catalog "New Publications of the U.S. Geological Survey" available free of charge by mail or may be obtained over the counter in paperback booklet form only. Those wishing a free subscription to the monthly catalog "New Publications of the U.S. Geological Survey" should write to the U.S. Geological Survey, 582 National Center, Reston, VA 22092.

Note.--Prices of Government publications listed in older catalogs, announcements, and publications may be incorrect. Therefore, the prices charged may differ from the prices in catalogs, announcements, and publications.