Techniques for Estimation of Storm-Runoff Loads, Volumes, and Selected Constituent Concentrations in Urban Watersheds in the United States

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Techniques for Estimation of Storm-Runoff Loads, Volumes, and Selected Constituent Concentrations in Urban Watersheds in the United States

By NANCY E. DRIVER and GARY D. TASKER

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CONVERSION FACTORS

Readers who prefer metric (International System) units of measurement rather than the inch-pound units used in this report may use the following conversion factors:

Multiply inch-pound unit	By	To obtain metric unit
inch	25.40	millimeter
mile	1.609	kilometer
pound	0.4536	kilogram
pound per acre	544.75	kilogram per square kilometer
square mile	2.589	square kilometer
cubic foot	0.0283	cubic meter

Temperature can be converted to degree Celsius (°C) by the following equation:

$$°F = 9/5(°C) + 32$$

ABBREVIATIONS

$\hat{\beta}_0'$ Regression coefficient that is the intercept in the regression model, $\hat{\beta}_0' = 10^{\beta_0}$

BCF Bias correction factor. A factor that is included in the detransformed regression model to provide a consistent estimator of the mean response.

CD Total recoverable cadmium in storm-runoff load, in pounds, or in storm-runoff mean concentration, in micrograms per liter.

COD Chemical oxygen demand in storm-runoff load or mean seasonal or mean annual load, in pounds, or in storm-runoff mean concentration, in milligrams per liter.

CU Total recoverable copper in storm-runoff load or mean seasonal or mean annual load, in pounds, or in storm-runoff mean concentration, in micrograms per liter.

DA Total contributing drainage area, in square miles.

DP Dissolved phosphorus in storm-runoff load or mean seasonal or mean annual load, in pounds, or in storm-runoff mean concentration, in milligrams per liter.

DRN Duration of each storm, in minutes, for storm-runoff load and mean concentration models, and, in hours, for mean seasonal or mean annual load models.

DS Dissolved solids in storm-runoff load or mean seasonal or mean annual load, in pounds, or in storm-runoff mean concentration, in milligrams per liter.

IA Impervious area, as a percent of total contributing drainage area.

INT Maximum 24-hour precipitation intensity that has a 2-year recurrence interval, in inches.

LUC Commercial land use, as a percent of total contributing drainage area.

LUI Industrial land use, as a percent of total contributing drainage area.

LUN Nonurban land use, as a percent of total contributing drainage area.

LUR Residential land use, as a percent of total contributing drainage area.

MAR Mean annual rainfall, in inches.

MJT Mean minimum January temperature, in degrees Fahrenheit.

MNL Mean annual nitrogen load in precipitation, in pounds of nitrogen per acre.

PB Total recoverable lead in storm-runoff load or mean seasonal or mean annual load, in pounds, or in storm-runoff mean concentration, in micrograms per liter.

PD Population density, in people per square mile.

R^2 Coefficient of multiple determination; it measures the proportion of total variation about the mean $\overline{Y}$ explained by the regression.

RUN	Storm-runoff volume, in cubic feet.
SS	Suspended solids in storm-runoff load or mean seasonal or mean annual load, in pounds, or in storm-runoff mean concentration, in milligrams per liter.
TKN	Total ammonia plus organic nitrogen as nitrogen in storm-runoff load or mean seasonal or mean annual load, in pounds, or in storm-runoff mean concentration, in milligrams per liter.
TN	Total nitrogen in storm-runoff load or mean seasonal or mean annual load, in pounds, or in storm-runoff mean concentration, in milligrams per liter.
TP	Total phosphorus in storm-runoff load or mean seasonal or mean annual load, in pounds, or in storm-runoff mean concentration, in milligrams per liter.
TRN	Total storm rainfall, in inches.
ZN	Total recoverable zinc in storm-runoff load or mean seasonal or mean annual load, in pounds, or in storm-runoff mean concentration, in micrograms per liter.
I	Region I representing areas that have mean annual rainfall less than 20 inches.
II	Region II representing areas that have mean annual rainfall of 20 to less than 40 inches.
III	Region III representing areas that have mean annual rainfall equal to or greater than 40 inches.

Techniques for Estimation of Storm-Runoff Loads, Volumes, and Selected Constituent Concentrations in Urban Watersheds in the United States

By Nancy E. Driver *and* Gary D. Tasker

Abstract

Urban planners and managers need information on the quantity of precipitation and the quality and quantity of runoff in their cities and towns if they are to adequately plan for the effects of storm runoff from urban areas. As a result of this need, four sets of linear regression models were developed for estimating storm-runoff constituent loads, storm-runoff volumes, storm-runoff mean concentrations of constituents, and mean seasonal or mean annual constituent loads from physical, land-use, and climatic characteristics of urban watersheds in the United States. Thirty-four regression models of storm-runoff constituent loads and storm-runoff volumes were developed, and 31 models of storm-runoff mean concentrations were developed. Ten models of mean seasonal or mean annual constituent loads were developed by analyzing long-term storm-rainfall records using at-site linear regression models.

Three statistically different regions, delineated on the basis of mean annual rainfall, were used to improve linear regression models where adequate data were available. Multiple regression analyses, including ordinary least squares and generalized least squares, were used to determine the optimum linear regression models. These models can be used to estimate storm-runoff constituent loads, storm-runoff volumes, storm-runoff mean concentrations of constituents, and mean seasonal or mean annual constituent loads at gaged and ungaged urban watersheds.

The most significant explanatory variables in all linear regression models were total storm rainfall and total contributing drainage area. Impervious area, land-use, and mean annual climatic characteristics also were significant in some models. Models for estimating loads of dissolved solids, total nitrogen, and total ammonia plus organic nitrogen as nitrogen generally were the most accurate, whereas models for suspended solids were the least accurate. The most accurate models were those for application in the more arid Western States, and the least accurate models were those for areas that had large mean annual rainfall.

INTRODUCTION

The Clean Water Act of 1977 (PL 95–217) established the Nationwide Urban Runoff Program (NURP) to assess the nature and cause of urban runoff and its effects on surface and ground water. The goals of NURP were to develop information to determine whether urban runoff affects water quality and to provide the means to control nonpoint sources of pollution from urban areas. In response to this need, the U.S. Geological Survey and the U.S. Environmental Protection Agency in cooperation with State and local governments conducted programs to collect and analyze data on storm rainfall, runoff, and water quality in numerous cities throughout the United States. The objective was to provide needed data for cities to properly plan, zone, and design storm-runoff areas.

Urban storm runoff is becoming a substantial source of surface-water pollution in the United States. Because collection and analysis of urban-storm-runoff data are expensive and time consuming, city planners and engineers need techniques to make estimates where minimal or no data exist. Current (1988) and past storm-runoff data-collection and analysis projects are site-oriented and isolated cases. Pollutants need to be categorized and characterized on the basis of climatic properties, physical and land-use characteristics, and geographic locations. Colyer and Yen (1983) identified the need for a generalized pollution prediction method, based on a sufficient quantity of data, for use at ungaged watersheds or watersheds with future urbanization. To fulfill this need, we developed regression models based on a national urban water-quality data base to relate variables—(1) discharge-weighted storm-runoff constituent loads (hereinafter referred to as storm-runoff loads), (2) storm-runoff volumes, (3) mean concentrations of constituents during storm runoff (hereinafter referred to as storm-runoff mean concentrations), and (4) mean seasonal or

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annual constituent loads (hereinafter referred to as mean seasonal or annual loads)—to urban physical, land-use, and climatic characteristics so as to predict these variables at ungaged urban watersheds.

Previous studies about estimating storm-runoff loads and mean seasonal or annual loads have been done on a site-specific basis in metropolitan areas throughout the United States. Selected references for U.S. Geological Survey studies are listed in Driver and others (1985), and selected references for U.S. Environmental Protection Agency site-specific studies are described by the U.S. Environmental Protection Agency (1983). There are other generalized techniques to estimate pollutant loads at urban watersheds. Young and others (1979) devised a simplified method to evaluate the severity of nonpoint-source loads for urban watersheds. The U.S. Environmental Protection Agency (1983) provided a national summary of urban-runoff characteristics in a table for planning-level purposes. These characteristics were intended for use as estimates to be used in the absence of any local information. A derived distribution approach to identify the effects of urbanization on frequencies of overflows and pollutant loadings from storm sewer overflows was developed by Loganathan and Delleur (1984). Preliminary findings for the national estimation of urban storm-runoff loads were reported by Driver and Lystrom (1986, 1987).

A variety of deterministic urban water-quality models are available for estimating pollutant loadings. Huber and Heaney (1982), Kibler (1982), and Whipple and others (1984) reviewed available models. Huber (1986) reviewed deterministic urban-runoff-quality estimating procedures in detail.

Purpose and Scope

The purpose of this report is to describe the methods and models of three procedures for estimating (1) storm-runoff loads and storm-runoff volumes, (2) storm-runoff mean concentrations, and (3) mean seasonal or annual loads. The first phase involved the development of linear regression models (hereinafter referred to as regression models) to estimate selected storm-runoff loads and volumes for urban watersheds on a regional basis. For this analysis, the United States was divided into three regions on the basis of mean annual rainfall. For each region, a regression model was developed that related 11 storm-runoff loads and volumes to physical, land-use, and climatic characteristics. Coefficients of multiple determination (R^2) and standard errors of estimate presented here are indicators of adequacy of fit of the regression model to the data and of the accuracy of estimates. Storm-runoff loads for 11 constituents—including chemical oxygen demand, suspended solids, dissolved solids, total nitrogen, total ammonia plus organic nitrogen as nitrogen (total Kjeldahl nitrogen), total phosphorus, dissolved phosphorus, total recoverable cadmium, total recoverable copper, total recoverable lead, and total recoverable zinc—and storm-runoff volumes have been analyzed. Thirty-four models and corresponding statistics for storm-runoff loads and volumes are included in this report.

The second phase involved developing regression models to estimate storm-runoff mean concentrations, defined as the storm-runoff load divided by the storm-runoff volume. The same regions, water-quality constituents, and sets of explanatory variables for each storm-runoff-load model that was developed in the first phase of this report were used in the second phase. For each region, a regression model also was developed that related 11 storm-runoff mean concentrations to physical, land-use, and climatic characteristics. These regression models and corresponding statistics for the storm-runoff mean concentrations are presented.

The third phase involved determining values of mean seasonal or annual loads for selected watersheds and developing regional regression models to estimate mean seasonal or annual loads that enter receiving water in urban watersheds. The water-quality constituents for the mean seasonal or annual loads include chemical oxygen demand, suspended solids, dissolved solids, total nitrogen, total ammonia plus organic nitrogen as nitrogen (total Kjeldahl nitrogen), total phosphorus, dissolved phosphorus, total recoverable copper, total recoverable lead, and total recoverable zinc. The regression models were based on physical, land-use, and climatic characteristics of urban watersheds.

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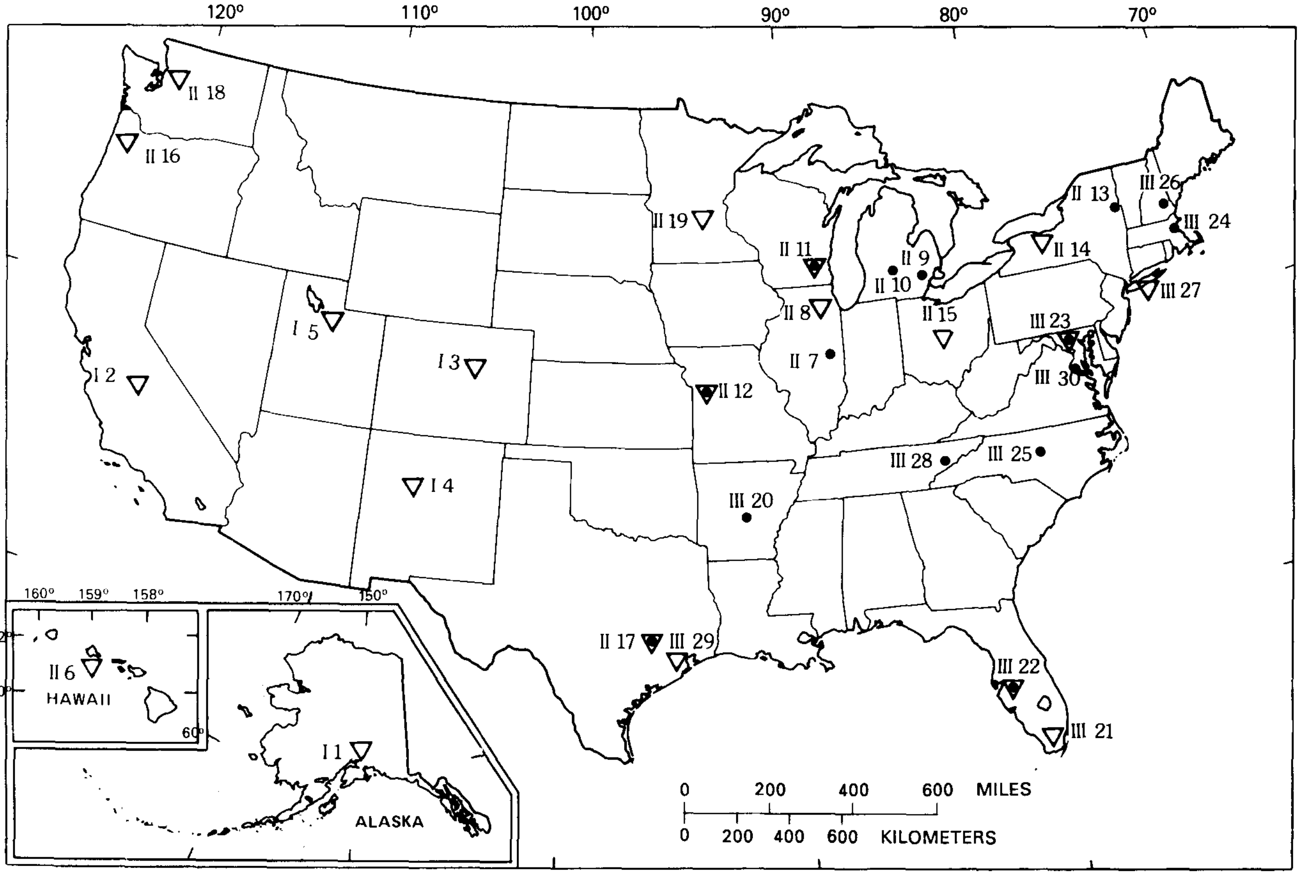
DATA BASE

The urban storm-runoff data base used for this report was developed by combining U.S. Geological Survey and U.S. Environmental Protection Agency urban storm-runoff data bases. The Survey data base consists of two complementary data bases. Driver and others (1985) compiled a national urban-storm-runoff data base that contains time-series values of rainfall and runoff, water-quality analyses, and physical and land-use characteristics for 99 watersheds monitored by the Survey. In a related effort, watershed maps that depict topographic, drainage, and land-use characteristics were compiled for most of the same urban watersheds (M.E. Jennings, U.S. Geological Survey, oral commun., 1987). The second data base, compiled by Mustard and others (1987), is composed of computed storm-runoff loads and characteristics of rainfall and runoff and includes physical, land-use, and antecedent conditions data for 98 of the 99 previously mentioned urban stations. The Survey data base used in this report includes data for 1,123 storms for 98 urban stations in 20 metropolitan areas (fig. 1).

The U.S. Environmental Protection Agency data base (U.S. Environmental Protection Agency, 1983) consists of similar data for 1,690 storms for 75 urban stations in 15 metropolitan areas (fig. 1). (The two agencies' data bases have five metropolitan areas in common.) Storm-runoff loads were computed by the Survey using published values of total storm runoff and storm-runoff mean concentrations. Information for a U.S. Environmental Protection Agency station was included in the combined data base if adequate data existed for one or more storms at each station. The minimal data included (1) storm-runoff mean concentration, (2) total rainfall and storm duration, and (3) total contributing drainage area, impervious area, and land use.

The U.S. Geological Survey and U.S. Environmental Protection Agency data bases were combined to create a common set of water-quality constituents—biochemical oxygen demand, chemical oxygen demand, total suspended solids, total nitrite plus nitrate, total ammonia plus organic nitrogen as nitrogen, fecal coliform bacteria, total phosphorus, dissolved phosphorus, total recoverable copper, total



EXPLANATION

STUDY AREA LOCATION—Roman numeral refers to region and number refers to metropolitan area listed below

I 4 ▽ U.S. Geological Survey study area

II 7 • U.S. Environmental Protection Agency study area

III 24 ▼ U.S. Environmental Protection Agency and U.S. Geological Survey study areas

REGION I—Mean annual rainfall less than 20 inches
1. Anchorage, Alaska
2. Fresno, California
3. Denver, Colorado
4. Albuquerque, New Mexico
5. Salt Lake City, Utah

REGION II—Mean annual rainfall 20 to less than 40 inches
6. Honolulu, Hawaii
7. Champaign-Urbana, Illinois
8. Glen Ellyn, Illinois
9. Ann Arbor, Michigan
10. Lansing, Michigan
11. St. Paul, Minnesota
12. Kansas City, Missouri
13. Lake George, New York
14. Rochester, New York
15. Columbus, Ohio
16. Portland, Oregon
17. Austin, Texas
18. Bellevue, Washington
19. Milwaukee, Wisconsin

REGION III—Mean annual rainfall equal to or greater than 40 inches
20. Little Rock, Arkansas
21. Miami, Florida
22. Tampa, Florida
23. Baltimore, Maryland
24. Boston, Massachusetts
25. Winston-Salem, North Carolina
26. Durham, New Hampshire
27. Long Island, New York
28. Knoxville, Tennessee
29. Houston, Texas
30. Washington, D.C.

Figure 1. Locations of urban-storm-runoff study areas and mean annual rainfall regions in the United States.

recoverable lead, and total recoverable zinc. Total nitrogen was calculated by adding total ammonia plus organic nitrogen as nitrogen and total nitrite plus nitrate. Common physical and land-use characteristics included total contributing drainage area, basin slope, percent of impervious area, five categories of land use—residential, commercial, industrial, open, and other—and population density. In the analyses, open and other land uses were combined to create a nonurban land-use category. Common storm characteristics included total storm rainfall, total storm runoff, and storm duration.

Data for the five stations common to both data bases were compared to indicate how well the data bases coincided. Runoff loads and characteristics for storms that were common to both data sets were compared, as were basin characteristics. Generally, there was little difference between the two data sets.

The values of storm-runoff mean concentrations for the Survey data were calculated by dividing the storm-runoff load, in pounds, by the average storm-runoff depth over the basin, in inches, and the total contributing drainage area, in square miles, multiplied by a conversion factor. The values of storm-runoff mean concentrations for the U.S. Environmental Protection Agency data were cited from the results of NURP (U.S. Environmental Protection Agency, 1983). In the U.S. Environmental Protection Agency study, the concentration of the flow-weighted composite sample was used to represent the storm-runoff mean concentration. Where sequential discrete samples were collected over the hydrograph, the storm-runoff mean concentration was determined by calculating the area under the curve of concentration multiplied by discharge rate over time and dividing it by the area of the curve of runoff volume over time. Again, when storms that were common to both data sets were compared, there was little difference found between the two data sets.

Mean seasonal and annual loads were based on storm-runoff loads obtained from the two data bases. Long-term rainfall characteristics, used to calculate long-term mean seasonal and annual loads, were obtained from National Oceanic and Atmospheric Administration weather tapes (Warren, 1983). Calculation procedures are discussed in the section entitled "Estimating Procedures for Mean Seasonal or Mean Annual Loads."

ESTIMATING PROCEDURES FOR STORM-RUNOFF LOADS AND STORM-RUNOFF VOLUMES

Methods

Storm-runoff loads or storm-runoff volumes can be estimated by either deterministic or statistical models. Because of the costs and uncertain accuracy of deterministic models for ungaged sites, statistical models, which should be sufficient for planning purposes at most ungaged sites, were selected to develop the relation of physical, land-use, and climatic characteristics to storm-runoff loads and volumes. Troutman (1985) stated that "a model, no matter how simple, complex, or physically based, becomes a statistical model simply by representing the errors in the model as random variables and imposing a probabilistic structure on them." A study comparing results of deterministic and regression models of storm-runoff loads and volumes in Denver, Colo., indicated that neither type of model consistently was more accurate than the other when applied to a particular basin (Lindner-Lunsford and Ellis, 1987). A study assessing commonly used flood-frequency methods compared deterministic and regression models for determining peak flood-flow frequencies for rural ungaged watersheds (Newton and Herrin, 1982). The study was based on information developed during a pilot test that evaluated the feasibility of a nationwide test to discriminate between procedures for estimating peak flood-flow frequencies for ungaged watersheds. The authors concluded that the most accurate and reproducible procedures evaluated were regression-based procedures in which estimating models are calibrated to flood-frequency determinations at gaged locations.

In this study, regional regression models were developed that related storm-runoff loads and volumes (response variables) to easily measured physical, land-use, and climatic characteristics (explanatory variables). Accuracy of the estimates of storm-runoff loads or volumes (standard error of estimate) is a function of the difference between measured and estimated storm-runoff loads or volumes.

In a simplistic assessment, storm-runoff loads or volumes could be estimated from their mean values for each region. However, more accurate estimates can result by using multiple-regression analysis to relate these response variables to physical, land-use, and climatic characteristics. Regional analyses account for spatial variations in storm-runoff loads or volumes that are caused by regional differences in characteristics directly or indirectly affecting storm-runoff loads or volumes.

Selection of Response and Explanatory Variables

Storms were selected from the data base according to certain assumptions and availability of specific variables. When a variable selected for a specific analysis was unavailable for a storm, that storm was omitted from the analysis. No attempts were made to estimate missing variables. Because of missing data, not all 2,813 storms in the data base were used for most analyses.

Regional regression models were developed for 11 storm-runoff loads plus storm-runoff volume. The 11 storm-runoff loads, expressed in pounds, are chemical oxygen demand (COD), suspended solids (SS), dissolved solids (DS), total nitrogen (TN), total ammonia plus organic nitrogen as nitrogen (TKN), total phosphorus (TP), dissolved phosphorus (DP), total recoverable cadmium (CD), total recoverable copper (CU), total recoverable lead (PB), and total recoverable zinc (ZN). Storm-runoff volumes (RUN) are expressed in inches. Storm-runoff loads of DS and CD are available only in the Survey data base. All abbreviations are described in the "Conversion Factors and Abbreviations" section of the table of contents and will be used throughout the report.

The response variables (storm-runoff loads and volumes) were selected according to the frequency of that variable in the data base and according to the general importance of the variable in urban planning. Although one of the assumptions of regression analysis is that the errors are uncorrelated in time, some storm-runoff loads and volumes may be slightly correlated because some storms were sampled consecutively in a watershed. This correlation in the response variable is negligible in this analysis because most storms were well separated in time.

Explanatory variables used in the regression models of storm-runoff loads and volumes include the following:

Physical and land-use characteristics:

1. Total contributing drainage area (DA), in square miles.
2. Impervious area (IA), as a percent of total contributing drainage area.
3. Industrial land use (LUI), as a percent of total contributing drainage area.
4. Commercial land use (LUC), as a percent of total contributing drainage area.
5. Residential land use (LUR), as a percent of total contributing drainage area.
6. Nonurban land use (LUN), as a percent of total contributing drainage area.
7. Population density (PD), in people per square mile.

Climatic characteristics:

1. Total storm rainfall (TRN), in inches.
2. Duration of each storm (DRN), in minutes.
3. Maximum 24-hour precipitation intensity that has a 2-year recurrence interval (INT), in inches.
4. Mean annual rainfall (MAR), in inches.
5. Mean annual nitrogen load in precipitation (MNL), in pounds of nitrogen per acre.
6. Mean minimum January temperature (MJT), in degrees Fahrenheit.

Highly correlated explanatory variables were identified so they would not be combined in the same model. Alley and Veenhuis (1979) reported a high correlation between land use and percent effective impervious area. In this report, because the correlation between land use and impervious area was high, the most significant of these explanatory variables was selected for each model. Explanatory variables also were selected on the basis of their frequency of availability in the data base, on their ease of measurement by urban planners, and on the basis that their various combinations were physically logical. For instance, mean annual climatic characteristics were not combined in a model because rainfall, temperature, and rainfall intensity all are highly related to one another. Also, impervious area and land uses were not combined in a model because the variables explain similar physical processes. Although storm-runoff volume generally fulfilled the selection criteria, storm-runoff loads (constituent concentration multiplied by storm-runoff volume) are not regressed against storm-runoff volume because storm-runoff data are more difficult and expensive to collect than physical, land-use, and storm characteristics.

Explanatory variables for each regression model were selected using stepwise regression procedures available through the Statistical Analysis System (SAS Institute, 1985). The primary criterion for selecting the most appropriate set of explanatory variables was that regression coefficients were significantly different from zero (Draper and Smith, 1981) at a 5-percent level. Several other criteria were applied to distinguish between explanatory variable sets that fulfilled the primary criterion. These were (1) the mean square error (δ^2), the variance about the regression, which represents a measure of error with which any observed value of Y could be predicted from a given value of X using the determined model; (2) the coefficient of multiple determination (R^2), which measures the proportion of total variation about the mean, $\overline{Y}$, explained by the regression; (3) Mallows' C_p statistic, a measure of the squared bias and variance of the error (Draper and Smith, 1981); (4) the signs on the coefficients of the explanatory variables; and (5) correlation among the explanatory variables, which was intended to decrease the multicollinearity among the explanatory variables.

Definition of Homogeneous Regions

Initially, all data were analyzed together, and the most accurate regression models were selected for each constituent. Then the data were analyzed on a regional/stratified basis to evaluate if the regression models could be improved. Regionalization on the basis of statistically aggregated patterns and physical settings has been beneficial in many hydrologic studies including those of Waylen and Woo (1984), Kircher and others (1985), and Schuster and Yakowitz (1985).

The optimum regional divisions were selected after testing seven possible bases for regionalization or stratification: physiographic divisions, geographic divisions, total contributing drainage areas, impervious areas, 2-year 24-hour rainfall, mean annual rainfall, and mean minimum January temperatures. The resultant regionalized models were compared with the regression models representing all the data. Regionalization improved the accuracy of the regression models. According to the smallest standard errors of estimate, the regional breakdown that provided the best regression results was based on mean annual rainfall.

Analysis of covariance was done on data in regions based on mean annual rainfall to determine if the regions were significantly different from one another. The three regions were different statistically from one another at a 1-percent or better significance level, according to an F-test. The F-test is used to test if the variation observed between the regions is greater than would be expected by chance in $100(1-\alpha)$ percent similar sets of data with the same values of n and X. The coefficients for each explanatory variable in the regression models differed significantly between regions. The F-test further verified that regionalization was appropriate.

The United States was divided into three geographically distinguishable regions (fig. 1) that represented areas that have mean annual rainfall less than 20 inches (region I), mean annual rainfall of 20 to less than 40 inches (region II), and mean annual rainfall equal to or greater than 40 inches (region III). Geographically, metropolitan areas in region I included the Western States, excluding Hawaii, Oregon, and Washington; metropolitan areas in region II included the Midwestern and Great Lakes States, the Pacific Northwest, and Hawaii; and metropolitan areas in region III included the Southern States and the coastal Northeastern States. Values of mean annual rainfall can be determined from data listed in the report by the National Oceanic and Atmospheric Administration (1980).

Selection of Model Form

Coinciding with selection of the best explanatory variables, the best transformations for each regression model were determined. Transformations are used to achieve linearity of the regression function, normality of residuals, and stability in the error variance. The Box and Cox maximum-likelihood method (Draper and Smith, 1981) was used for selecting the best transformation for the response variable. For all regression models of storm-runoff loads and volumes, the best transformation for the response variable was the logarithmic transformation. The logarithmic transformation is appropriate because there generally is more uncertainty associated with larger storm-runoff volumes and, therefore, with larger storm-runoff loads than with smaller storm-runoff loads or volumes (lack of homoscedasticity). Homoscedasticity, which is one of the standard assumptions of least-squares theory, infers constancy of error variance for all observations. The net effect of the transformation is to assign less weight to the more uncertain, large storm-runoff loads or volumes; as a result, during the calibration period, the fit will seem worse for larger storm-runoff loads or volumes than if the calibration had been done without transformation. However, estimates of regression coefficients probably are more accurate (Troutman, 1985).

Plots of residuals, which are the differences between the measured values and the regression predictions, were examined to determine the best transformation for the explanatory variables. On the basis of minimizing the standard error of estimate, logarithmic transformation also was found generally to be more suitable for the explanatory variables in all models of storm-runoff loads and volumes. Multiple regression models that use the power regression function, which is based on logarithmic transformations of the response and explanatory variables, are in the following form:

$$\log \hat{Y} = \hat{\beta}_0 + \hat{\beta}_1 \times \log X_1 + \hat{\beta}_2 \times \log X_2 + \ldots + \hat{\beta}_n \times \log X_n \qquad (1)$$

where

$\hat{Y}$ = estimated storm-runoff load or volume (response variable);
$\hat{\beta}_0, \hat{\beta}_1, \hat{\beta}_2, \hat{\beta}_n$ = regression coefficients;
$X_1, X_2 \ldots, X_n$ = physical, land-use, or climatic characteristics (explanatory variables); and
n = number of physical, land-use, and climatic characteristics in the regression model.

The most appropriate regression models were selected using stepwise regression and the criteria noted earlier. All models were tested further to ensure that they satisfied the assumptions of regression. One necessary assumption for obtaining accurate results from ordinary least-squares regression is that the random errors (residuals), which are the differences between the measured values and the regression predictions, have constant variance throughout the range of the explanatory variables (homoscedasticity). Some violations of the constant-variance assumption can be detected by plotting the residual values against the predicted values. This procedure indicated that the variance of the residuals seems to be reasonably constant throughout the entire range of prediction.

When equation 1 is detransformed it becomes

$$\hat{Y} = \hat{\beta}_0' \times X_1^{\hat{\beta}_1} \times X_2^{\hat{\beta}_2} \ldots X_n^{\hat{\beta}_n} \qquad (2)$$

where

$$\hat{\beta}_0' = 10^{\hat{\beta}_0} .$$

Miller (1984), Koch and Smillie (1986), and Ferguson (1986) reported that detransformation of a fitted regression model provides a consistent estimator of median response, but the detransformation systematically underestimates the mean response. Therefore, a bias-correction factor needs to be included in the detransformed regression model if an unbiased estimate of the mean is to be obtained. Bias-correction factors were estimated using a parametric method (Miller, 1984) and a nonparametric method (Duan, 1983). The values were similar, and the nonparametric method was used. A bias-correction factor (BCF) was calculated for each model by using a smearing estimate that is a nonparametric method based on the average residuals in original units according to suggestions in Duan (1983). As a result of this BCF, the form of the regression model that applies to all models of storm-runoff loads and volumes (equation 1) is

$$\hat{Y} = \hat{\beta}_0' \times X_1^{\hat{\beta}_1} \times X_2^{\hat{\beta}_2} \ldots X_n^{\hat{\beta}_n} \times \text{BCF} \ . \quad (3)$$

Models

Thirty-one storm-runoff-load models and three storm-runoff-volume models were developed for metropolitan areas throughout the United States. The models were developed using ordinary least-squares regression. Except for dissolved solids and cadmium, there was one regression model for each of the storm-runoff loads and volumes in each of the three mean annual rainfall regions. The regression models for dissolved solids and cadmium in region III were omitted because only one metropolitan area was represented. One metropolitan area in a region was not adequate for development of a regression model because four of the explanatory variables (INT, MAR, MNL, MJT) had only one common value for all watersheds in a metropolitan area.

The regression models and their corresponding BCF's are listed in table 1. Equation 3 defines the regression model used to compute these storm-runoff loads and volumes. The metropolitan areas, R^2, standard errors of estimate (expressed in percent and in logs), standard deviations of log of response variable, mean of log of response variable, average prediction errors, and number of storms and stations corresponding to each regression model are listed in table 2. R^2 indicates the proportion of the total variation of the response variable that is explained by the explanatory variables. Therefore, the value of R^2 is used as a summary measure to judge the fit of the regression model to the data. The standard error of estimate of the mean is an estimate of the standard deviation about the regression. The smaller the standard error of estimate, the more precise will be the predictions. The standard error of estimate, in percent, was calculated for all the regression models using the following equation:

$$SE = 100\ [e^{(\sigma^2 \times 5.302)} - 1]^{1/2} \quad (4)$$

where

SE = the standard error of estimate, in percent; and
σ^2 = the mean square error in log (base 10) units.

Average prediction errors are discussed in the section entitled "Validation, Testing, and Application of Regression Models."

The values of R^2 in the models that use ordinary least squares range from 0.35 to 0.95 (table 2). Standard errors of estimate range from 57 to 265 percent (table 2 and fig. 2). Accuracy of the models is discussed further in the section entitled "Comparisons of All Storm-Runoff Load and Storm-Runoff Volume Models."

Three-Variable Models

The three-variable models are simplified regression models for the 11 storm-runoff loads. The explanatory variables always are TRN, DA, and IA. The 31 three-variable models are listed in table 3. Equation 3 defines the regression model used to compute the storm-runoff loads listed in table 3. The BCF's, R^2, standard errors of estimate (expressed in percent and in logs), and number of storms also are listed.

These three-variable models are simplified alternatives to the regression models listed in table 1. City planners or engineers can use the three-variable models if they want an approximate estimate of the storm-runoff loads for urban watersheds. However, if more accurate estimates are desired, the regression models listed in table 1 need to be applied. The three-variable models were derived using ordinary least squares.

Comparisons of All Storm-Runoff-Load and Storm-Runoff-Volume Models

Many consistent patterns are apparent when all storm-runoff load models are compared. The two most significant explanatory variables in the 31 storm-runoff load models were TRN and DA. According to an *F*-test, the coefficients of these explanatory variables were significant at a 1-percent or better level for all models. These two explanatory variables always were the first to enter the model in a forward-stepwise regression.

In addition to these two explanatory variables, the 31 regression models in table 1 generally included a combination of land uses or impervious area. In regression models where a combination of land-use variables was significant, only three of the four land-use categories (industrial, commercial, and nonurban) generally were significant at a 15-percent or better level in a forward-stepwise regression, and the fourth, residential land use, generally was not significant. Although many urban studies have not reported land use to be significant in estimating storm-runoff loads, many of the regression models in this report include land-use variables that are significant at the 0.05 level. The U.S. Environmental Protection Agency nationwide urban study reported that land-use category does not provide a useful basis for predicting differences in values of storm-runoff mean concentrations at sites (U.S. Environmental Protection Agency, 1983). Lystrom and others (1978) reported that, in the Susquehanna River basin, land use had

Table 1. Summary of regression models for storm-runoff loads and volumes

[$\hat{\beta}_0$ is the regression coefficient that is the intercept in the regression model; TRN is total storm rainfall; DA is total contributing drainage area; IA is impervious area; LUI is industrial land use; LUC is commercial land use; LUR is residential land use; LUN is nonurban land use; PD is population density; DRN is duration of each storm; INT is maximum 24-hour precipitation intensity that has a 2-year recurrence interval; MAR is mean annual rainfall; MNL is mean annual nitrogen load in precipitation; MJT is mean minimum January temperature; BCF is bias correction factor; COD is chemical oxygen demand in storm-runoff load, in pounds; I is region I representing areas that have mean annual rainfall less than 20 inches; II is region II representing areas that have mean annual rainfall of 20 to less than 40 inches; III is region III representing areas that have mean annual rainfall equal to or greater than 40 inches; SS is suspended solids in storm-runoff load, in pounds; DS is dissolved solids in storm-runoff load, in pounds; TN is total nitrogen in storm-runoff load, in pounds; TKN is total ammonia plus organic nitrogen as nitrogen in storm-runoff load, in pounds; TP is total phosphorus in storm-runoff load, in pounds; DP is dissolved phosphorus in storm-runoff load, in pounds; CD is total recoverable cadmium in storm-runoff load, in pounds; CU is total recoverable copper in storm-runoff load, in pounds; ZN is total recoverable zinc in storm-runoff load, in pounds; RUN is storm-runoff volume, in cubic feet; dashes (--) indicate that the variable is not included in the model; equation form is:

$$\hat{Y} = \hat{\beta}_0' \times X_1^{\hat{\beta}_1} \times X_2^{\hat{\beta}_2} \ldots X_n^{\hat{\beta}_n} \times \text{BCF}]$$

Response variable and region	Regression coefficients														
	$\hat{\beta}_0'$	TRN (inches)	DA (square miles)	IA +1 (percent)	LUI +1 (percent)	LUC +1 (percent)	LUR +1 (percent)	LUN +2 (percent)	PD (people per square mile)	DRN (minutes)	INT (inches)	MAR (inches)	MNL (pounds of nitrogen per acre)	MJT (degrees Fahrenheit)	BCF
COD I	7,111	0.671	0.617	--	0.415	0.267	--	-0.156	--	--	--	-0.683	--	--	1.304
COD II	36.6	.878	.696	--	.072	.261	--	-.056	--	--	--	.866	--	--	1.389
COD III	479	.857	.634	--	.321	.217	--	-.111	--	--	--	--	--	--	1.865
SS I	1,518	1.211	.735	--	--	--	--	--	--	-0.463	--	--	--	--	2.112
SS II	2,032	1.233	.439	0.274	--	--	--	--	0.041	--	--	--	--	-0.590	1.841
SS III	1,990	1.017	.984	--	.226	.228	--	-.286	--	--	--	--	--	--	2.477
DS I	54.8	.585	1.356	1.383	--	--	--	--	--	--	--	-.718	--	--	1.239
DS II	2,308	1.076	1.285	1.348	--	--	--	--	--	--	--	--	--	-1.395	1.208
TN I	1,132	.798	.960	--	.462	.260	--	-.194	--	--	--	-.951	--	--	1.139
TN II	3.173	.935	.939	.672	--	--	--	--	--	--	--	--	0.196	--	1.372
TN III	.361	.776	.474	.611	--	--	--	--	--	--	--	--	.863	--	1.709
TKN I	18.9	.670	.831	--	.378	.258	--	-.219	--	--	--	--	1.350	--	1.206
TKN II	2.890	.906	.768	.545	--	--	--	--	--	--	--	--	.225	--	1.512
TKN III	199,572	.875	.393	--	--	--	--	.082	--	--	--	-2.643	--	--	1.736
TP I	262	.828	.645	--	.583	.181	--	-.235	--	--	--	-1.376	--	--	1.548
TP II	.153	.986	.649	.479	--	--	--	--	--	--	1.543	--	--	--	1.486
TP III	53.2	1.019	.846	--	--	.189	0.103	-.160	--	--	--	--	--	-0.754	2.059
DP I	588	.808	.726	--	.642	.096	--	-.238	--	--	--	-1.899	--	--	1.407
DP II	.025	.914	.699	.649	--	--	--	--	--	--	1.024	--	--	--	1.591
DP III	.369	.955	.471	--	--	--	--	.364	--	--	--	--	--	--	2.027
CD I	.039	.845	.753	--	.138	.248	--	-.374	--	--	--	--	--	--	1.244
CD II	.005	1.168	1.265	--	--	--	--	--	--	--	--	--	--	.965	1.212
CU I	.141	.807	.590	--	.424	.274	--	-.061*	--	--	.928	--	--	--	1.502
CU II	.013	.504	.585	.816	--	--	--	--	--	--	--	--	--	--	1.534
CU III	4.508	.896	.609	--	.648	.253	--	-.328	--	--	-2.071	--	--	--	2.149
PB I	478	.764	.918	--	-.161	.276	--	-.282	--	--	--	-1.829	--	--	1.588
PB II	.076	.833	.381	--	--	.243	.087	-.181	--	--	--	.574	--	--	1.587
PB III	.081	.852	.857	.999	--	--	--	--	--	--	--	--	--	--	2.314
ZN I	224	.745	.792	--	--	.172	-.195	-.142	--	--	--	-1.355	--	--	1.444
ZN II	.002	.796	.667	1.009	--	--	--	--	--	--	--	--	--	1.149	1.754
ZN III	4.355	.830	.555	--	.402	.287	-.191	--	--	--	--	--	--	-.500	1.942
RUN I	1,123,052	1.016	.916	.677	--	--	--	--	--	--	--	-1.312	--	--	1.299
RUN II	62,951	1.127	.809	.522	--	--	--	--	--	--	--	--	--	--	1.212
RUN III	32,196	1.042	.826	.669	--	--	--	--	--	--	--	--	--	--	1.525

a significant impact on some water-quality characteristics. In a Denver urban study, land use was not significant (Ellis and others, 1984). However, on a national basis, land use explained a significant quantity of variability in the storm-runoff loads for 18 of the 31 storm-runoff-load models. Impervious area was a significant explanatory variable in 12 storm-runoff-load models. Mean annual climatic variables also were significant in 25 regression models.

Signs of the coefficients for each of the regression models generally were hydrologically logical; however, signs sometimes are difficult to interpret in multiple regression models because some correlation between explanatory variables exists. Although regression models cannot directly define cause-effect relations, explanatory variables and regression coefficients of each regression model need to be evaluated from the standpoint of conceptual knowledge of the water-quality processes. If the sign of a regression coefficient is contrary to intuitive understanding of the process involved, the following causes are possible explanations:

1. Significant cross-correlation between explanatory variables causes multicollinearity problems in the regression models.
2. The process involving the effect of the explanatory variables on the water-quality constituents is not well understood.
3. The explanatory variable is a surrogate for another variable.

4. Large data-input errors occurred during compilation of the response or explanatory variables.
5. The apparent significance of an explanatory variable may be due to chance and, therefore, the relation would be spurious.

These causes were considered during the selection of variables and the analysis of the regression models.

The explanatory variables expected to have a positive sign were TRN, DA, IA, LUI, LUC, LUR, PD, and MNL. Explanatory variables expected to have a negative sign were LUN, DRN, INT, MAR, and MJT. The explanatory variables included in each regression model generally had the expected signs on the coefficients. However, because of the effects of multicollinearity, signs on individual terms in a regression model may seem counterintuitive while the regression model is still statistically correct. The reason is that the sign on an individual term indicates the direction of change in the prediction corresponding to a change in the individual explanatory variable with other explanatory variables held constant. However, in a natural setting, certain variables are never held constant; rather, changes in all the explanatory variables usually occur simultaneously. DRN has an inverse relation with storm-runoff loads in region I because the shorter storms in the West generally are more intense thunderstorms that have greater rainfall and result in larger storm-runoff loads. MAR generally has a negative relation to storm-runoff loads, which may indicate that longer periods between storms in drier climates enable more residue to build up on impervious surfaces; therefore, a smaller MAR would produce greater storm-runoff loads. Values of MJT are inversely related to storm-runoff loads of SS and DS for region II. This inverse relation may reflect the effects of salting the roads in this region.

Ranges of R^2 and standard errors of estimate indicate that all of the regression models have significant unexplained errors. However, because the coefficients of the regression models are significant at the 5-percent level, more variability is explained by the regression model than by the mean of the response variable. The significance of regression is determined by hypothesis testing on the slopes and intercept at some predetermined level. In this report we applied an α level of 0.05. Standard errors of estimate generally are less than 160 percent except for the models for storm-runoff loads of SS and several regression models in region III. In models where the standard errors of estimate are large, the BCF's are correspondingly large, which indicates that the mean is substantially larger than the median.

Values of R^2 and corresponding standard errors of estimate for the models of storm-runoff loads of SS indicate that these regression models have significant unexplained errors. The BCF's are significantly larger than the BCF's for all other models. In the U.S. Environmental Protection Agency national urban study, the values of storm-runoff mean concentrations of SS had coefficients of variation that ranged between 100 and 250 percent, and all other constituents had coefficients of variation that ranged between 50 and 100 percent (U.S. Environmental Protection Agency, 1983). SS values are difficult to estimate because sampling techniques are poor, and there is considerable variation in the composition of suspended-solids samples. Some of the unexplained error may be because samples collected from manmade and natural channels have been combined in this data base.

The values of R^2 for the two models of storm-runoff loads of DS, 0.92 and 0.93, indicate that most of the variability in the storm-runoff loads is explained by the regression model. A large value of R^2 simply may result because the explanatory variables have a large range; however, ranges of the explanatory variables in these regression models correspond with those in other models. Standard errors of estimate are relatively small for estimations of storm-runoff loads throughout large geographical areas.

Values of R^2 are small and corresponding standard errors of estimate generally are large for the models of storm-runoff loads of trace metals. These values indicate that there is much unexplained variability and error in these regression models, which may partly be a factor of the analytical technique. Varying analytical recovery of metals from water samples that contain different sediment mineralogy occurs because of differences in chemical digestion rates. This variation can cause differences in analytical results of trace-metal concentrations and cause problems in the interpretation of total-recoverable data. In addition, the trace-metal analyses lack any specific relation to biotic uptake because the total-recoverable method greatly overestimates the bioavailable concentrations. Therefore, Davies (1986) recommended that concentrations of trace metals be analyzed in effluent samples and in samples used to measure the effects of nonpoint sources of pollution based on the "potentially dissolved method." Future urban studies need to examine this analytical method.

Storm-Runoff-Load Models for Region I

In region I models, values of R^2 generally were larger and standard errors of estimate (table 2 and fig. 2) were smaller than those in the region II and region III models. As mean annual rainfall increased, the ability to estimate storm-runoff loads decreased. Therefore, the most accurate models for storm-runoff loads generally were those for the more western States, and the least accurate models were those for areas that had larger quantities of mean annual rainfall. A possible statistical explanation for the larger values of R^2 in region I is that the range of the explanatory variables is larger than the range in regions II and III. However, although TRN had the smallest range in region I and DA had the largest range in region I (figs. 3 and 4), most of the models for region I were developed from values of TRN and DA that were comparable to the other two regions (table 4). A plausible physically based explanation

Table 2. Summary of statistics and information for regression models of storm-runoff loads and volumes

[This table corresponds to models in table 1; COD is chemical oxygen demand in storm-runoff load, in pounds; I is region I representing areas that have mean annual rainfall less than 20 inches; II is region II representing areas that have mean annual rainfall of 20 to less than 40 inches; III is region III representing areas that have mean annual rainfall equal to or greater than 40 inches; SS is suspended solids in storm-runoff load, in pounds; DS is dissolved solids in storm-runoff load, in pounds; TN is total nitrogen in storm-runoff load, in pounds; TKN is total ammonia plus organic nitrogen as nitrogen in storm-runoff load, in pounds; TP is total phosphorus in storm-runoff load, in pounds; DP is dissolved phosphorus in storm-runoff load, in pounds; CD is total recoverable cadmium in storm-runoff load, in pounds; CU is total recoverable lead in storm-runoff load, in pounds; ZN is total recoverable zinc in storm-runoff load, in pounds; RUN is storm-runoff volume, in cubic feet]

Response variable and region	Metropolitan areas	R^2	Standard error of estimate (percent)	Standard error of estimate (log)	Standard deviation of log of response variable (pound)	Mean of log of response variable (pound)	Average prediction error (percent)	Number of storms	Number of stations
COD I	Fresno, Calif.; Denver, Colo.; Salt Lake City, Utah	0.76	86	0.324	0.653	2.479	104	216	21
COD II	Honolulu, Hawaii; Champaign-Urbana, Ill.; Ann Arbor, Mich.; Lansing, Mich.; St. Paul, Minn.; Kansas City, Mo.; Rochester, N.Y.; Columbus, Ohio; Portland, Oreg.; Bellevue, Wash.; Milwaukee, Wis.	.71	97	.355	.659	2.078	98	793	57
COD III	Washington, D.C.; Miami, Fla.; Tampa, Fla.; Boston, Mass.; Baltimore, Md.; Winston-Salem, N.C.; Durham, N.H.; Long Island, N.Y.; Knoxville, Tenn.	.51	169	.505	.723	1.695	150	567	33
SS I	Denver, Colo.; Salt Lake City, Utah	.55	230	.589	.876	2.659	334	176	19
SS II	Champaign-Urbana, Ill.; Glen Ellyn, Ill.; Ann Arbor, Mich.; Lansing, Mich.; St. Paul, Minn.; Kansas City, Mo.; Rochester, N.Y.; Austin, Tex.; Bellevue, Wash.; Milwaukee, Wis.	.62	165	.498	.807	2.303	327	964	44
SS III	Washington, D.C.; Tampa, Fla.; Boston, Mass.; Baltimore, Md.; Winston-Salem, N.C.; Durham, N.H.; Knoxville, Tenn.; Houston, Tex.	.56	265	.627	.943	1.708	269	528	29
DS I	Anchorage, Alaska; Fresno, Calif.; Denver, Colo.; Albuquerque, N. Mex.; Salt Lake City, Utah	.93	73	.285	1.096	2.346	152	175	17
DS II	Honolulu, Hawaii; Glen Ellyn, Ill.; Columbus, Ohio; Portland, Oreg.; Bellevue, Wash.; Milwaukee, Wis.	.92	69	.272	.993	2.260	77	281	21
TN I	Anchorage, Alaska; Fresno, Calif.; Denver, Colo.; Albuquerque, N. Mex.	.95	57	.230	1.020	.997	56	121	16
TN II	Honolulu, Hawaii; Glen Ellyn, Ill.; Ann Arbor, Mich.; Lansing, Mich.; St. Paul, Minn.; Lake George, N.Y.; Columbus, Ohio; Austin, Tex.; Milwaukee, Wis.	.77	97	.353	.741	.718	86	574	45
TN III	Washington, D.C.; Miami, Fla.; Tampa, Fla.; Boston, Mass.; Baltimore, Md.; Winston-Salem, N.C.; Durham, N.H.; Long Island, N.Y.; Knoxville, Tenn.	.35	165	.498	.617	.240	219	617	37
TKN I	Fresno, Calif.; Denver, Colo.; Salt Lake City, Utah	.86	71	.277	.723	.853	68	188	23
TKN II	Honolulu, Hawaii; Champaign-Urbana, Ill.; Ann Arbor, Mich.; Lansing, Mich.; St. Paul, Minn.; Lake George, N.Y.; Rochester, N.Y.; Columbus, Ohio; Portland, Oreg.; Austin, Tex.; Bellevue, Wash.; Milwaukee, Wis.	.75	106	.377	.751	.471	87	859	62
TKN III	Washington, D.C.; Miami, Fla.; Tampa, Fla.; Boston, Mass.; Winston-Salem, N.C.; Baltimore, Md.; Durham, N.H.; Long Island, N.Y.; Knoxville, Tenn.; Houston, Tex.	.40	165	.498	.639	.098	116	613	35
TP I	Anchorage, Alaska; Fresno, Calif.; Denver, Colo.; Salt Lake City, Utah	.72	128	.427	.794	-.086	131	186	19
TP II	Honolulu, Hawaii; Champaign-Urbana, Ill.; Ann Arbor, Mich.; Lansing, Mich.; Kansas City, Mo.; St. Paul, Minn.; Lake George, N.Y.; Rochester, N.Y.; Columbus, Ohio; Portland, Oreg.; Austin, Tex.; Bellevue, Wash.; Milwaukee, Wis.	.64	116	.401	.669	-.393	96	1,091	60
TP III	Washington, D.C.; Tampa, Fla.; Miami, Fla.; Boston, Mass.; Baltimore, Md.; Winston-Salem, N.C.; Durham, N.H.; Knoxville, Tenn.; Houston, Tex.	.54	192	.540	.795	-.604	203	639	35
DP I	Anchorage, Alaska; Fresno, Calif.; Denver, Colo.; Salt Lake City, Utah	.76	100	.363	.727	-.372	103	248	23
DP II	Ann Arbor, Mich.; Lansing, Mich.; St. Paul, Minn.; Kansas City, Mo.; Lake George, N.Y.; Bellevue, Wash.; Milwaukee, Wis.	.64	119	.408	.679	-1.035	169	469	31
DP III	Washington, D.C.; Boston, Mass.; Baltimore, Md.; Knoxville, Tenn.	.39	180	.523	.667	-1.020	171	247	16
CD I	Anchorage, Alaska; Fresno, Calif.; Denver, Colo.; Salt Lake City, Utah	.80	82	.311	.678	-2.648	85	65	15
CD II	Rochester, N.Y.; Columbus, Ohio	.65	105	.374	.608	-1.793	87	47	5
CU I	Anchorage, Alaska; Fresno, Calif.; Denver, Colo.; Salt Lake City, Utah	.67	110	.388	.672	-1.232	195	212	22
CU II	Champaign-Urbana, Ill.; Lansing, Mich.; Kansas City, Mo.; Rochester, N.Y.; Columbus, Ohio	.55	123	.417	.617	-1.324	117	298	17

Table 2. Summary of statistics and information for regression models of storm-runoff loads and volumes—Continued

Response variable and region	Metropolitan areas	R^2	Standard error of estimate (percent)	Standard error of estimate (log)	Standard deviation of log of response variable (pound)	Mean of log of response variable (pound)	Average prediction error (percent)	Number of storms	Number of stations
CU III	Washington, D.C.; Miami, Fla.; Tampa, Fla.; Boston, Mass.; Baltimore, Md.; Winston-Salem, N.C.; Durham, N.H.; Knoxville, Tenn.	0.56	175	0.515	0.774	-1.525	238	464	30
PB I	Anchorage, Alaska; Fresno, Calif.; Denver, Colo.; Salt Lake City, Utah	.66	141	.455	.773	-.585	211	239	23
PB II	Honolulu, Hawaii; Champaign-Urbana, Ill.; Ann Arbor, Mich.; Lansing, Mich.; St. Paul, Minn.; Kansas City, Mo.; Lake George, N.Y.; Rochester, N.Y.; Columbus, Ohio; Bellevue, Wash.; Milwaukee, Wis.	.45	131	.435	.586	-.751	126	943	54
PB III	Washington, D.C.; Tampa, Fla.; Boston, Mass.; Baltimore, Md.; Durham, N.H.; Long Island, N.Y.; Knoxville, Tenn.	.54	227	.586	.864	-.837	196	418	31
ZN I	Anchorage, Alaska; Fresno, Calif.; Denver, Colo.; Salt Lake City, Utah	.70	119	.407	.728	-.433	181	224	21
ZN II	Champaign-Urbana, Ill.; Ann Arbor, Mich.; Lansing, Mich.; Kansas City, Mo.; Rochester, N.Y.; Columbus, Ohio Milwaukee, Wis.	.53	160	.490	.709	-.367	138	357	31
ZN III	Washington, D.C.; Tampa, Fla.; Miami, Fla.; Boston, Mass.; Baltimore, Md.; Winston-Salem, N.C.; Durham, N.H.; Knoxville, Tenn.	.49	181	.523	.728	-.919	142	591	30
RUN I	Anchorage, Alaska; Fresno, Calif.; Denver, Colo.; Albuquerque, N. Mex.; Salt Lake City, Utah	.87	84	.316	.895	4.417	79	348	27
RUN II	Honolulu, Hawaii; Champaign-Urbana, Ill.; Glen Ellyn, Ill.; Ann Arbor, Mich.; Lansing, Mich.; St. Paul, Minn.; Kansas City, Mo.; Lake George, N.Y. Rochester, N.Y.; Columbus, Ohio; Portland, Oreg.; Austin, Tex.; Bellevue, Wash.; Milwaukee, Wis.	.88	69	.270	.789	4.468	69	1,353	69
RUN III	Washington, D.C.; Little Rock, Ark.; Miami, Fla.; Tampa, Fla.; Baltimore, Md.; Boston, Mass.; Durham, N.H.; Long Island, N.Y.; Winston-Salem, N.C.; Knoxville, Tenn.; Houston, Tex.	.70	118	.406	.740	4.239	119	690	46

for the larger values of R^2 in region I is that, in urban areas that have small mean annual rainfall, the pollutants accumulate and are never washed off completely during any storm. In areas that have larger mean annual rainfall, the pollutant accumulation can be washed off completely by more frequent storms. As a result, the succeeding storm may produce the same quantity of rainfall as the preceding storm but may produce considerably smaller storm-runoff loads. The variable, antecedent dry days, which is discussed in the section entitled "Storm-Runoff-Load Models for Region III," could explain some of this variability.

The most accurate models in region I were for storm-runoff loads of DS, TN, and TKN. The values of R^2 in these models ranged from 0.86 to 0.95, and standard errors of estimate ranged from 57 to 73 percent (table 2 and fig. 2). The least accurate model was for storm-runoff loads of SS. The other storm-runoff-load models produced values of R^2 and standard errors of estimate between these values.

TRN and DA are plotted in figure 4 to compare the range of these two explanatory variables and to show the lack of correlation between them. DA ranges from less than 1 to about 80 square miles; most of the observations plot in the range of less than 1 square mile. TRN ranges from less than 1 to 2 inches, but most TRN is less than 0.4 inch. Therefore, most urban watersheds in region I have small drainage areas, and the storms also are small.

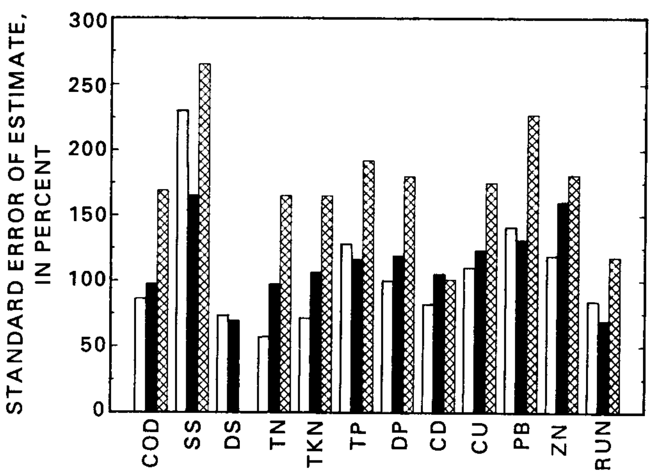
Storm-Runoff-Load Models for Region II

In region II, model values of R^2 were smaller than those in region I models, and standard errors of estimate (fig. 2) were comparable to those in region I models. The most accurate models in region II were those for storm-runoff loads of COD, DS, TN, and TKN. The values of R^2 ranged from 0.71 to 0.92, and standard errors of estimate ranged from 69 to 106 percent (table 2). The least accurate models were those for storm-runoff loads of SS, PB, and ZN. The value of R^2 was small for the storm-runoff load of PB. Standard errors of estimate were large for storm-runoff loads of SS and ZN. An explanation for the inaccuracy of the models for storm-runoff loads of SS were described in the previous section; however, the large standard error of estimate for ZN and the small value of R^2 for PB are difficult to explain. Several factors, including the following, were considered but deemed to be inconsequential. The range of the explanatory variables were compared with ranges for other storm-runoff-load models in region II and were not different. The number of storms, stations, and metropolitan areas were sufficient to explain the variability of the response variable throughout the region (table 2). The data of storm-runoff loads for PB before 1979, when laws were passed requiring unleaded fuel in automobiles, were deleted to eliminate major discrepancies in the PB data.

TRN and DA are plotted in figure 5 to compare the range of these two explanatory variables and to show the lack of correlation between them. TRN ranges from less than 0.1 to 5 inches, but most TRN is less than 1.5 inches. DA ranges from less than 1 to about 45 square miles; most of the observations plot in the range of less than 1 square mile. Therefore, most urban watersheds in region II have small drainage areas, and the average storms are larger than storms that occur in region I.

Storm-Runoff-Load Models for Region III

In region III, model values of R^2 were substantially smaller than those in regions I and II; standard errors of estimate (fig. 2) were either comparable or larger. The values of R^2 ranged from 0.35 to 0.58 (table 2). The standard errors of estimate ranged from 165 to 265 percent, which were the largest standard errors of estimate for the three regions. Because less variation is explained in areas of large mean annual rainfall, it is important to collect site-specific information to estimate storm-runoff loads. The magnitude of R^2 indicates predictive capability of use of the regression model over use of the mean of the response variable. Mean load per unit area represents the state of the art in estimating urban storm-runoff loads. Because R^2 values in region III tend to be low, use of the regression models for region III is not much improvement over use of the mean load per unit area. A reason for these poor relations could be that areas that have large quantities of precipitation generally have fewer dry days between storms, and pollutants accumulate at different rates depending on the number of days between storms. Antecedent dry days are not available in the data base, and there are conflicting views in the literature on the importance of dry days in predicting water quality. Miller and Mattraw (1982) reported that in a Florida study antecedent dry periods correlated highly with storm-runoff loads for the residential basin but not for the highway or commercial basins. Ellis, Harrop, and Revitt (1986) reported that in London, United Kingdom, antecedent dry days were not important in controlling the removal of particle-associated pollutants from a highway catchment. Halverson and others (1984) stated that antecedent conditions had little linear correlation with storm-runoff quality. Athayde, Healy, and Field (1982) suggested that antecedent dry periods were important regulators for pollutant concentrations. In Denver, Colo. (Ellis and others, 1984) and Portland, Ore. (Miller and McKenzie, 1978), antecedent dry days were apparently unimportant; but, in Missouri (Blevins, 1984), an extended dry period tended to increase the lead and zinc concentrations near the beginning of storm runoff. Although these findings are conflicting, the locality of the urban area may determine the importance of antecedent dry days, and in regions that have large mean annual rainfall these antecedent dry days may be important in explaining variations in storm-runoff loads.



EXPLANATION

REGION I—Mean annual rainfall less than 20 inches
REGION II—Mean annual rainfall 20 to less than 40 inches
REGION III—Mean annual rainfall equal to or greater than 40 inches
COD Chemical oxygen demand in storm-runoff load, in pounds
SS Suspended solids in storm-runoff load, in pounds
DS Dissolved solids in storm-runoff load, in pounds
TN Total nitrogen in storm-runoff load, in pounds
TKN Total ammonia plus organic nitrogen in storm-runoff load, in pounds
TP Total phosphorus in storm-runoff load, in pounds
DP Dissolved phosphorus in storm-runoff load, in pounds
CD Total recoverable cadmium in storm-runoff load, in pounds
CU Total recoverable copper in storm-runoff load, in pounds
PB Total recoverable lead in storm-runoff load, in pounds
ZN Total recoverable zinc in storm-runoff load, in pounds
RUN Storm-runoff volume, in cubic feet

Figure 2. Standard errors of estimate for regression models of water-quality constituents and total runoff in three mean annual rainfall regions.

TRN and DA are plotted in figure 6 to compare the range and relation of these two explanatory variables to one another and to show the lack of correlation between them. TRN ranges from less than 0.1 to 5.8 inches, but most TRN is less than 2.5 inches. DA ranges from less than 1 to 14 square miles; most of the observations plot in the range of less than 1 square mile. Therefore, most urban watersheds in region III have small drainage areas, and average storms generally are larger than storms in regions I and II.

Storm-Runoff-Volume Models

In storm-runoff-volume (RUN) models, values of R^2 generally are larger and standard errors of estimate generally are smaller than those for storm-runoff-load models. In the region I model for RUN, the value of R^2 is greater than in all the models of storm-runoff loads except for DS and TN, and the standard error of estimate is smaller than in all the models of storm-runoff loads except for TN and TKN. In the region II model for RUN, the value of R^2 is larger

Table 3. Summary of three-variable models for storm-runoff loads

[$\hat{\beta}_0$ is the regression coefficient that is the intercept in the regression model; TRN is total storm rainfall; DA is total contributing drainage area; IA is impervious area; BCF is bias correction factor; COD is chemical oxygen demand in storm-runoff load, in pounds; I is region I representing areas that have mean annual rainfall less than 20 inches; II is region II representing areas that have mean annual rainfall of 20 to less than 40 inches; III is region III representing areas that have mean annual rainfall equal to or greater than 40 inches; SS is suspended solids in storm-runoff load, in pounds; TN is total nitrogen in storm-runoff load, in pounds; TKN is total ammonia plus organic nitrogen as nitrogen in storm-runoff load, in pounds; TP is total phosphorus in storm-runoff load, in pounds; DP is dissolved phosphorus in storm-runoff load, in pounds; CD is total recoverable cadmium in storm-runoff load, in pounds; CU is total recoverable copper in storm-runoff load, in pounds; PB is total recoverable lead in storm-runoff load, in pounds; ZN is total recoverable zinc in storm-runoff load, in pounds; asterisk (*) indicates that the explanatory variable is not significant at the 5-percent level; equation form is:

$$Y = \hat{\beta}_0' \times X_1^{\hat{\beta}_1} \times X_2^{\hat{\beta}_2} \ldots X_n^{\hat{\beta}_n} \times \text{BCF}]$$

Response variable and region	Regression coefficients				BCF	R^2	Standard error of estimate		Number of storms
	$\hat{\beta}_0'$	TRN (inches)	DA (square miles)	IA +1 (percent)			(percent)	(log)	
COD I	407	0.626	0.710	0.379	1.518	0.62	116	0.403	216
COD II	151	.823	.726	.564	1.451	.67	106	.376	793
COD III	102	.851	.601	.528	1.978	.46	186	.531	567
SS I	1,778	.867	.728	.157*	2.367	.52	251	.613	176
SS II	812	1.236	.436	.202	1.938	.60	173	.512	964
SS III	97.7	1.002	1.009	.837	2.818	.53	290	.651	528
DS I	20.7	.637	1.311	1.180	1.249	.93	75	.293	175
DS II	3.26	1.251	1.218	1.964	1.434	.86	101	.367	281
TN I	20.2	.825	1.070	.479	1.258	.92	72	.286	121
TN II	4.04	.936	.937	.692	1.373	.77	97	.353	574
TN III	1.66	.703	.465	.521	1.845	.31	178	.518	617
TKN I	13.9	.722	.781	.328	1.722	.65	129	.431	188
TKN II	3.89	.944	.765	.556	1.524	.75	107	.381	858
TKN III	3.56	.808	.415	.199	1.841	.32	184	.529	613
TP I	1.725	.884	.826	.467	2.130	.56	184	.529	186
TP II	.697	1.008	.628	.469	1.790	.62	120	.411	1,091
TP III	1.618	.954	.789	.289	2.247	.50	210	.565	639
DP I	.540	.976	.795	.573	2.464	.55	161	.492	248
DP II	.060	.991	.718	.701	1.757	.63	121	.412	467
DP III	2.176	1.003	.280	-.448	2.254	.35	193	.542	247
CD I	.00001	.886	.821	2.033	1.425	.72	101	.365	65
CD II	.021	1.367	1.062	.328*	1.469	.62	109	.386	47
CU I	.072	.746	.797	.514	1.675	.58	134	.440	212
CU II	.013	.504	.585	.816	1.548	.55	123	.417	298
CU III	.026	.715	.609	.642	2.819	.35	263	.625	464
PB I	.162	.839	.808	.744	1.791	.59	166	.500	239
PB II	.150	.791	.426	.522	1.665	.43	135	.442	943
PB III	.080	.852	.857	.999	2.826	.54	228	.586	418
ZN I	.320	.811	.798	.627	1.639	.60	146	.465	224
ZN II	.046	.880	.808	1.108	1.813	.51	166	.500	357
ZN III	.024	.793	.628	1.104	2.533	.43	200	.551	591

than in all the models of storm-runoff loads except for DS, and the standard error of estimate is smaller than in all the models of storm-runoff loads. In the region III model for RUN, the value of R^2 is larger than in all the models of storm-runoff loads, and the standard error of estimate is smaller than in all the models of storm-runoff loads. Typically, storm-runoff volumes are more accurately estimated than water-quality constituents. A national urban study presented models for estimating flood-peak characteristics (Sauer and others, 1983), and the standard errors of estimate were much smaller than those for storm-runoff-load models in this report.

In models for RUN, regions I and II models are similar in accuracy, whereas the region III model is less accurate. Therefore, the most accurate models for RUN are those for the more arid Western States and for the Pacific Northwest and Midwestern and Great Lakes States, and the least accurate models are those for the wetter coastal Northeastern and Southern States. However, in other rainfall-runoff studies, such as Lichty and Liscum (1978), estimates of runoff generally improve as rainfall increases. This anomaly could be attributed to limitations in the data base. For instance, the data base for region III is less homogeneous than the data base for regions I and II because the number of storms measured per metropolitan area is smaller. Also, the explanatory variables to estimate runoff may be inadequate. For instance, in region III one might expect more pervious area runoff than in region I, but the antecedent conditions, which are unavailable in this data base, may strongly control the rainfall-runoff relations. Also, region III has significantly more pervious area than regions I or II.

TRN and DA are again the two most significant explanatory variables in the RUN models. Also, IA always was significant in explaining the variability of RUN.

Three-Variable Models for Storm-Runoff Loads

Generally, the values of R^2 are smaller and the standard errors of estimate are larger in the three-variable models (table 3) when compared with the more accurate models listed in table 1. In the three-variable models, the values of

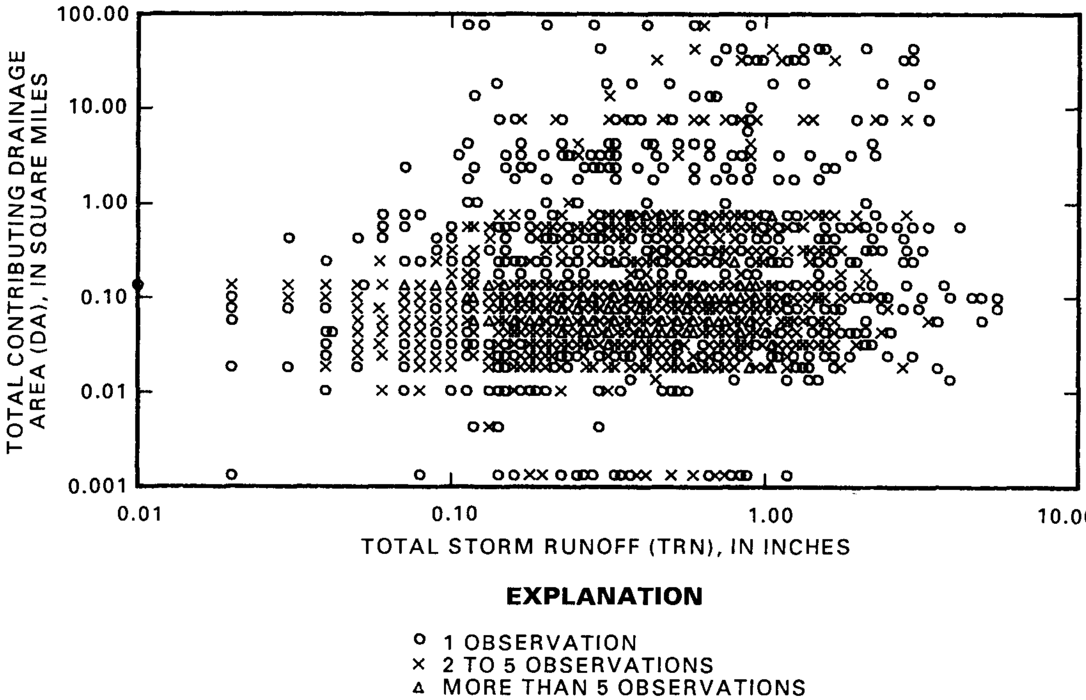


Figure 3. Relation between total storm rainfall and total contributing drainage area for storms in all three regions.

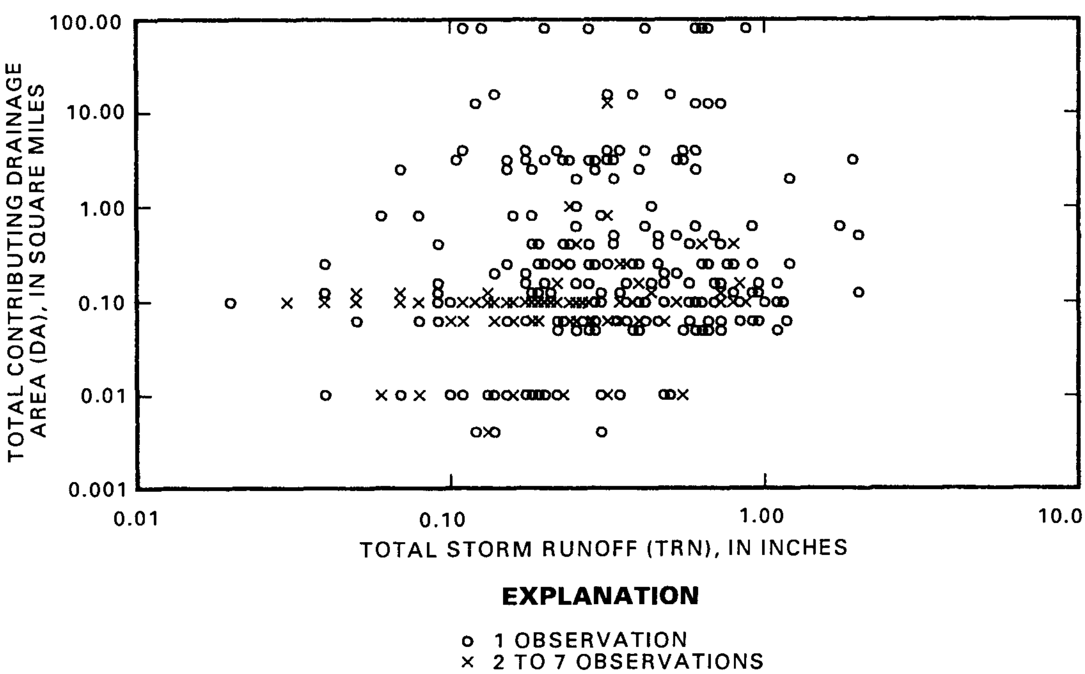


Figure 4. Relation between total storm rainfall and total contributing drainage area for storms in region I.

Table 4. Ranges of values, standardized beta coefficients, and standard deviations of log of each explanatory variable in regression models

[This table corresponds to models in table 1; COD is chemical oxygen demand in storm-runoff load, in pounds; I is region I representing areas that have mean annual rainfall less than 20 inches; II is region II representing areas that have mean annual rainfall of 20 to less than 40 inches; III is region III representing areas that have mean annual rainfall equal to or greater than 40 inches; SS is suspended solids in storm-runoff load, in pounds; DS is dissolved solids in storm-runoff load, in pounds; TKN is total ammonia plus organic nitrogen as nitrogen in storm-runoff load, in pounds; TP is total phosphorus in storm-runoff load, in pounds; DP is dissolved phosphorus in storm-runoff load, in pounds; CD is total recoverable cadmium in storm-runoff load, in pounds; CU is total recoverable copper in storm-runoff load, in pounds; PB is total recoverable lead in storm-runoff load, in pounds; ZN is total recoverable zinc in storm-runoff load, in pounds; RUN is storm-runoff volume, in cubic feet; TRN is total storm rainfall, in inches; DA is total contributing drainage area, in square miles; IA is impervious area, in percent; LUI is industrial land use, in percent; LUC is commercial land use, in percent; LUR is residential land use, in percent; LUN is nonurban land use, in percent; PD is population density, in people per square mile; DRN is duration of each storm, in minutes; INT is maximum 24-hour precipitation intensity that has a 2-year recurrence interval, in inches; MAR is mean annual rainfall, in inches; MNL is mean annual nitrogen load in precipitation, in pounds of nitrogen per acre; MJT is mean minimum January temperature, in degrees Fahrenheit]

Response variable and region	Explanatory variables	Minimum	Maximum	Mean	Median	Standardized beta coefficient	Standard deviation of log of explanatory variable
COD I	TRN	0.02	1.99	0.38	0.28	0.385	0.374
COD I	DA	.05	17.50	1.18	.12	.599	.634
COD I	LUI	0	65.80	4.32	0	.303	.477
COD I	LUC	0	100	28.55	10.40	.321	.785
COD I	LUN	0	100	14.89	9	-.128	.537
COD I	MAR	10.24	19.00	14.75	15.51	-.092	.088
COD II	TRN	.01	4.87	.59	.43	.538	.404
COD II	DA	.02	44.40	.91	.09	.636	.601
COD II	LUI	0	100	4.44	0	.054	.493
COD II	LUC	0	100	27.49	6.80	.303	.765
COD II	LUN	0	90.30	10.60	0	-.045	.532
COD II	MAR	26.69	37.61	32.72	30.50	.063	.048
COD III	TRN	.02	5.65	.66	.45	.464	.392
COD III	DA	.0012	2.64	.13	.06	.511	.583
COD III	LUI	0	10.70	.38	0	.259	.195
COD III	LUC	0	100	28.88	1.90	.087	.862
COD III	LUN	0	71.70	11.74	2.10	-.081	.529
SS I	TRN	.03	1.99	.39	.29	.546	.395
SS I	DA	.05	17.50	1.45	.12	.572	.681
SS I	DRN	10	2,220	358.39	231	-.264	.499
SS II	TRN	.01	4.87	.58	.43	.640	.419
SS II	DA	.02	44.40	.98	.09	.341	.628
SS II	IA	3.60	100	46	37.90	.100	.295
SS II	PD	1	13,889	5,302	5,001	.076	1.490
SS II	MJT	3.20	39.30	15.86	15.30	-.194	.279
SS III	TRN	.03	5.65	.65	.44	.420	.389
SS III	DA	.0012	.94	.14	.05	.641	.614
SS III	LUI	0	100	1.46	0	.069	.288
SS III	LUC	0	100	25.29	.95	.201	.829
SS III	LUN	0	52.20	8.04	1.80	-.143	.472
DS I	TRN	.02	1.23	.36	.28	.170	.318
DS I	DA	.01	80.54	4.92	.12	1.059	.856
DS I	IA	11	98.90	60.63	57	.235	.187
DS I	MAR	7.77	19.00	12.80	10.24	-.076	.117
DS II	TRN	.02	2.90	.48	.36	.428	.391
DS II	DA	.02	2.37	.35	.15	.741	.569
DS II	IA	19	99.40	50.25	36.10	.245	.178
DS II	MJT	11.40	67.60	23.68	20.40	-.289	.204
TN I	TRN	.03	1.99	.41	.29	.295	.378
TN I	DA	.01	80.54	6.37	.11	.843	.896
TN I	LUI	0	65.80	2.18	0	.148	.328
TN I	LUC	0	100	22.02	2	.201	.790
TN I	LUN	0	100	18.12	5	-.119	.625
TN I	MAR	7.77	15.51	14.53	15.51	-.082	.088
TN II	TRN	.01	4.87	.63	.47	.466	.369
TN II	DA	.02	12.30	.90	.22	.867	.684
TN II	IA	1.22	100	43.43	35.00	.408	.449
TN II	MNL	.39	6.10	5.11	5.60	.032	.121

Table 4. Ranges of values, standardized beta coefficients, and standard deviations of log of each explanatory variable in regression models—Continued

Response variable and region	Explanatory variables	Minimum	Maximum	Mean	Median	Standardized beta coefficient	Standard deviation of log of explanatory variable
TN III	TRN	0.03	5.65	0.67	0.46	0.484	0.385
TN III	DA	.0012	.94	.12	.06	.389	.506
TN III	IA	4.70	98.80	41.64	33.90	.273	.276
TN III	MNL	2.60	7.00	4.79	5.20	.244	.174
TKN I	TRN	.03	1.99	.37	.28	.343	.368
TKN I	DA	.05	80.54	4.79	.12	.734	.812
TKN I	LUI	0	65.80	5.56	0	.283	.530
TKN I	LUC	0	100	26.07	12.20	.271	.748
TKN I	LUN	0	100	17.54	9.00	-.163	.537
TKN I	MNL	1.00	4.00	1.90	1.80	.359	.188
TKN II	TRN	.01	4.87	.60	.43	.488	.404
TKN II	DA	.02	44.40	1.57	.12	.739	.723
TKN II	IA	1.22	100	40.79	36.10	.294	.406
TKN II	MNL	.39	6.10	4.40	4.50	.076	.253
TKN III	TRN	.04	5.65	.66	.46	.522	.381
TKN III	DA	.0012	2.64	.13	.06	.321	.522
TKN III	LUN	0	71.70	11.10	2.10	-.067	.522
TKN III	MAR	40.00	62.00	45.76	41.36	-.277	.067
TP I	TRN	.03	1.99	.38	.28	.401	.385
TP I	DA	.01	4.00	.49	.12	.450	.553
TP I	LUI	0	65.80	5.94	0	.399	.544
TP I	LUC	0	100	26.01	8	.182	.802
TP I	LUN	0	100	15.75	9	-.166	.561
TP I	MAR	10.24	19.00	15.05	15.51	-.130	.075
TP II	TRN	.01	3.66	.57	.43	.574	.389
TP II	DA	.02	8.34	.62	.10	.621	.643
TP II	IA	1.22	100	46.38	38.40	.294	.411
TP II	INT	2.00	5.00	2.67	2.60	.137	.059
TP III	TRN	.02	4.13	.65	.46	.487	.380
TP III	DA	.0012	1.79	.13	.06	.598	.562
TP III	LUC	0	100	28.17	2.90	.202	.850
TP III	LUR	0	100	60.00	85.00	.113	.872
TP III	LUN	0	60	12.67	2.1	-.104	.515
TP III	MJT	12.40	58.70	34.02	28.50	-.162	.171
DP I	TRN	.03	1.99	.39	.28	.397	.357
DP I	DA	.01	4.00	.50	.11	.522	.522
DP I	LUI	0	65.80	4.34	0	.423	.477
DP I	LUC	0	100	29.24	10.40	.110	.835
DP I	LUN	0	100	15.06	9	-.172	.527
DP I	MAR	10.24	19.00	13.88	15.51	-.252	.096
DP II	TRN	.03	3.31	.61	.46	.502	.372
DP II	DA	.02	8.34	1.03	.12	.731	.712
DP II	IA	1.22	99.40	40.53	36.10	.436	.457
DP II	INT	2.00	3.50	2.55	2.50	.099	.065
DP III	TRN	.04	2.34	.58	.41	.530	.370
DP III	DA	.03	2.64	.14	.06	.262	.371
DP III	LUN	0	71.70	9.07	7	.245	.449
CD I	TRN	.03	.93	.26	.22	.463	.372
CD I	DA	.01	3.03	.36	.12	.531	.478
CD I	LUI	0	37	17.79	0	.138	.675
CD I	LUC	0	100	39.16	30	.312	.854
CD I	LUN	0	65.8	10.44	13	-.325	.590
CD II	TRN	.03	3.08	1.03	.79	.708	.346
CD II	DA	.04	.60	.42	.36	.437	.177
CD II	MJT	3.2	33.90	17.80	16.70	.195	.105
CU I	TRN	.02	1.99	.37	.27	.447	.372
CU I	DA	.01	4.00	.55	.12	.471	.537
CU I	LUI	0	65.80	6.05	0	.346	.548
CU I	LUC	0	100	29.61	12.20	.329	.806
CU I	LUN	0	100	15.29	9.00	-.049	.542
CU I	INT	.15	.32	.22	.15	.121	.087
CU II	TRN	.02	4.08	.55	.43	.307	.377
CU II	DA	.03	.83	.26	.09	.502	.533
CU II	IA	17.50	97.10	42.15	36.50	.277	.209

Table 4. Ranges of values, standardized beta coefficients, and standard deviations of log of each explanatory variable in regression models—Continued

Response variable and region	Explanatory variables	Minimum	Maximum	Mean	Median	Standardized beta coefficient	Standard deviation of log of explanatory variable
CU III	TRN	0.02	4.13	0.69	0.50	0.456	0.394
CU III	DA	.001	.94	.14	.05	.512	.651
CU III	LUI	0	10.70	.58	0	.196	.232
CU III	LUC	0	100	38.78	16.40	.276	.839
CU III	LUN	0	60	11.51	1.8	-.228	.539
CU III	INT	.48	.76	.59	.56	-.272	.102
PB I	TRN	.02	1.99	.39	.28	.374	.378
PB I	DA	.004	4.00	.47	.11	.677	.896
PB I	LUI	0	65.8	5.92	0	-.113	.328
PB I	LUC	0	100	28.38	8	.295	.790
PB I	LUN	0	100	14.23	9	-.198	.625
PB I	MAR	10.24	19.00	14.36	15.51	-.214	.088
PB II	TRN	.01	4.87	.55	.41	.582	.409
PB II	DA	.02	8.34	.54	.09	.407	.625
PB II	LUC	0	100	28.69	6.8	.316	.760
PB II	LUR	0	100	52.88	53.2	.109	.731
PB II	LUN	0	98.2	15.00	0	-.187	.601
PB II	MAR	26.69	37.21	32.21	30.39	.043	.044
PB III	TRN	.02	5.65	.71	.50	.393	.399
PB III	DA	.001	1.79	.17	.06	.697	.702
PB III	IA	4.70	98.80	42.60	29.00	.372	.322
ZN I	TRN	.02	1.99	.39	.28	.387	.378
ZN I	DA	.01	4.00	.53	.12	.605	.556
ZN I	LUC	0	100	29.57	10.40	.191	.811
ZN I	LUR	0	100	50.74	44.00	-.220	.821
ZN I	LUN	0	100	16.95	9.00	-.107	.548
ZN I	MAR	10.24	19	14.36	15.51	-.162	.087
ZN II	TRN	.03	4.87	.70	.58	.388	.346
ZN II	DA	.02	4.49	.38	.10	.588	.626
ZN II	IA	3.60	100	59.03	51.40	.327	.230
ZN II	MJT	3.20	20.40	14.93	15.30	.178	.110
ZN III	TRN	.02	3.90	.65	.45	.443	.388
ZN III	DA	.001	.94	.13	.05	.452	.593
ZN III	LUI	0	10.7	.44	0	.339	.208
ZN III	LUC	0	100	30.81	1.90	.115	.858
ZN III	LUR	0	100	57.53	79.10	-.111	.885
ZN III	MJT	12.40	58.7	32.80	28.50	-.117	.170
RUN I	TRN	.02	1.99	.36	.26	.390	.356
RUN I	DA	.004	80.54	2.93	.11	.820	.831
RUN I	IA	0	98.90	58.68	57	.194	.266
RUN I	MAR	7.77	19.00	14.02	15.50	-.138	.098
RUN II	TRN	.01	4.87	.61	.43	.592	.417
RUN II	DA	.02	44.40	1.33	.10	.729	.714
RUN II	IA	1.22	100	44.54	37.50	.258	.392
RUN III	TRN	.02	5.65	.69	.48	.554	.395
RUN III	DA	.0012	15.74	.25	.06	.698	.623
RUN III	IA	3.50	98.80	42.09	33.90	.259	.288

R^2 range from 0.31 to 0.93 and the standard errors of estimate range from 72 to 290 percent, whereas in the more accurate models the values of R^2 range from 0.35 to 0.95 and the standard errors of estimate range from 57 to 265 percent.

TRN and DA always were significant at the 5-percent level. IA was significant at the 5-percent level for most of the models except those that have an asterisk next to IA in table 3.

Signs of the coefficients for each of the explanatory variables in the three-variable models generally were positive, which indicated an increase in storm-runoff loads resulting from an increase in the explanatory variables. However, the model for estimating storm-runoff loads of DP in region III had an unexpected negative sign on the coefficient for IA. Frequently, pervious land surface and its associated fertilizers can be a primary source for DP.

Limitations of Significant Explanatory Variables

For regression models listed in tables 1 and 3, the ranges for the physical, land-use, and climatic-characteristics (explanatory) variables are listed in table 4 for each model. If values outside these ranges are used in the regression models, the standard errors of estimate and the average prediction errors may be considerably larger than values reported in table 2. The graphs in figures 3 through 6 show the limited range of the data for the two most significant explanatory variables. As the user applies these regression models to larger drainage areas and larger storms, the accuracy of the estimated storm-runoff loads decreases.

Application of the regression models and interpretation of results are subject to a number of limitations. Each application needs to be evaluated on the basis of the following considerations:

1. The regression models developed in the study are limited to conditions in the 30 metropolitan areas within the three mean annual rainfall regions that have similar physiographic and hydrologic properties.
2. The regression models can only define the effects of the explanatory variables that are statistically significant for each regression model. Models do not include physical or land-use characteristics that define the effects of major industrial point sources, localized nonpoint sources, or atmospheric sources of pollution. Consequently, the possible effects of these variables on estimates from each model should be considered when applying the model.
3. Causal effects of the explanatory variable need to be interpreted carefully. Surrogate variables indirectly can explain the effect of another variable and, therefore, can be misleading. All explanatory variables in the models can be surrogates for another variable because a regression model does not account for all the physically based processes that explain the variation in the response variable. Therefore, each explanatory variable also may indirectly explain other processes in the model, and the limitations of such variables need to be known before applying the models for decision-making processes.
4. Expected errors in predicted storm-runoff loads or volumes are indicated by standard errors of estimate (table 2) for watersheds included in the calibration data set. For ungaged watersheds or watersheds not included in the calibration data set, average prediction errors (table 2) indicate the expected errors.

Other Potentially Useful Explanatory Variables

The explanatory variables of physical, land-use, and climatic characteristics used in the regional analyses were hydrologically relevant and statistically significant. Certain explanatory variables such as basin slope and other land uses were included in the analyses but failed to improve the accuracy of the regression model. Many explanatory variables such as street density, antecedent conditions, rainfall intensity, and main channel conveyance were limited in the number of observations in the data base. However, these explanatory variables are potentially significant and need to be considered in future studies.

In the Milwaukee, Wis., NURP project, street-refuse deposition, traffic emissions on roadways with a high traffic density, and urban erosion contributed the largest quantities of pollutants to urban storm runoff (Novotny and others, 1985). In Bellevue, Wash., the habitat adjacent to the streets and drainage channels were the major sources of sediment and pollutants to receiving water (Bissonnette,

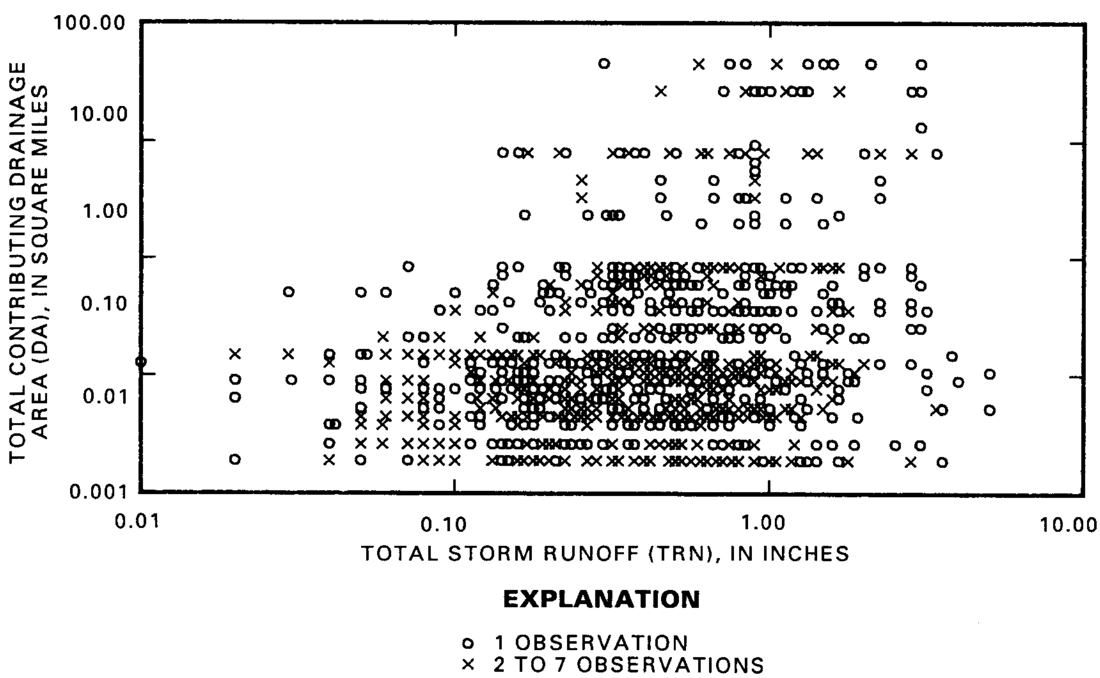


Figure 5. Relation between total storm rainfall and total contributing drainage area for storms in region II.

1986). Studies have indicated that the areas that contributed the largest loads of pollution were either highly erodible, such as plowed land or construction sites, or highly impervious, such as shopping malls (Randall, 1982). On the basis of these studies, perhaps more precisely defined land-use characteristics, such as area under construction, agricultural, or park, or other physical characteristics could explain more of the variation about the storm-runoff loads.

Regression models of urban storm-runoff quality need to include atmospheric contributions of ammonia and nitrate to more completely define the system (Halverson and others, 1984). Only extremely limited data were available on rainfall quality, but MNL was tested in all the nitrogen models as a means to define atmospheric contribution. Ellis, Harrop, and Revitt (1986) determined that storm duration was significant in explaining the observed variance in lead, cadmium, manganese, and sediment in storm-runoff loads. A variety of climatic characteristics would have been tested if the data base had had sufficient data for the intensity and duration of storms and for antecedent dry days. If the data for these limited explanatory variables become available nationally, many of these other physical, land-use, and climatic characteristics need to be tested to improve the models.

Validation, Testing, and Application of Regression Models

Several tests were made to determine the soundness of the most accurate models. These tests included split-sample analysis and standardized beta coefficients. The results of each of the tests are described briefly in the following sections; also, two examples of model application are described.

Split-Sample Analysis

The usefulness of the regression models may be assessed by comparing model results with observed storm-runoff loads or volumes for several independent watersheds not used in model calibration. However, all available data for the analysis were used in developing the models. Consequently, split-sample analyses were done on the 34 models of storm-runoff loads and volumes to assess their accuracy at ungaged watersheds and watersheds not included in the calibration data set. Model validation is important because, even though a model seems to perform well for a calibration data set, it may not perform well for a noncalibration data set and vice versa (Troutman, 1985).

The relative accuracy of the various models presented in this report is judged by the standard error of estimate, which is a measure of how well the regression models estimate the response variables at calibration stations. In contrast, the standard error of prediction is a measure of how well the regression models estimate the response variables at other than calibration stations. Standard error of prediction usually is larger than standard error of estimate because of parameter estimation error, which is a function of sample size. Because the estimation sample size is smaller in the split-sample procedure, the parameter esti-

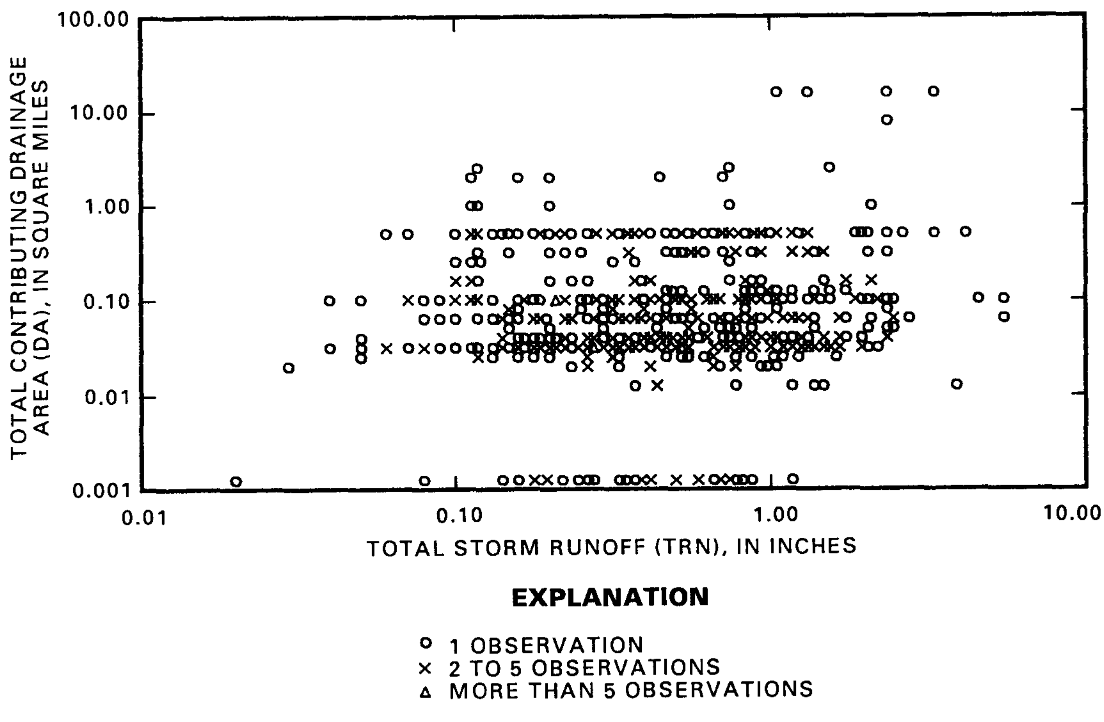


Figure 6. Relation between total storm rainfall and total contributing drainage area for storms in region III.