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QUANTITY AND QUALITY OF STORM RUNOFF FROM THREE URBAN CATCHMENTS IN BELLEVUE, WASHINGTON

By Edmund A. Prych and J. C. Ebbert

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(Plates in back cover pocket)

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METRIC CONVERSION FACTORS

Multiply	By	To obtain
inches (in.)	25.4	millimeters (mm)
	2.540	centimeters (cm)
	0.0254	meters (m)
feet (ft)	0.3048	meters (m)
miles (mi)	1.609	kilometers (km)
square miles (mi^2)	2.590	square kilometers (km^2)
cubic feet (ft^3)	0.02872	cubic meters (m^3)
inches per hour (in./hr)	25.4	millimeters per hour (mm/hr)
acres	0.4047	hectares
cubic feet per second (ft^3/s)	0.02832	cubic meters per second (m^3/s)
	28.32	liters per second (L/s)
degrees Celsius (°C)	1.8, then add 32	degrees Fahrenheit (°F)

National Geodetic Vertical Datum of 1929 (NGVD of 1929): A geodetic datum derived from a general adjustment of the first-order level nets of both the United States and Canada, formerly called "mean saa level." NGVD of 1929 is referred to as sea level in this report.

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ABSTRACT

Data on the quantity and quality of urban runoff were collected, analyzed, and used to evaluate the effects of street sweeping and of storm-water detention on quality of runoff. The data included rainfall, runoff discharge, concentrations of selected constituents in discrete samples of runoff, and chemical characteristics of wet- and-dry atmospheric deposition. The City of Bellevue, in a companion study, collected data on the amounts, particle-size distributions, and chemical characteristics of street dirt.

To investigate the effects of street sweeping, streets were swept about three times a week for 5-month periods in one or the other of two catchments that are single-family residential areas of about 100 acres each. Statistical analyses of runoff loads and of discharge-weighted constituent concentrations in runoff for about 25 different storms showed that, for most constituents, street sweeping had little effect on water quality. One possible reason for this is that much of the suspended material in runoff consisted of silt- and clay-size particles, the size classes least affected by street sweeping. The data also show that rainfall is often the source of approximately one-third of the total nitrogen in storm-water runoff.

Incorporated in the storm-sewer network of the third catchment is a storm-water detention system consisting of an oversize pipe and a grassy depression. Comparison of discharge-weighted average concentrations in the inflow and outflow of the detention system for four to seven storms indicated that the detention system did not have a large effect on the average concentrations of constituents in runoff. Typically, average concentrations of suspended constituents in the outflow were slightly lower than in the inflow, and average concentrations of dissolved constituents were slightly higher.

Regression equations for predicting runoff volumes and peak discharges for individual storms were derived separately for each catchment using data from nearly all storms. Standard errors of estimate for these storms were 21 to 28 percent for runoff volume and 22 to 40 percent for peak discharge. The independent variables in the equations for volume were quantities of total rainfall and 3-day antecedent rainfall. For peak discharge the independent variables were maximum 15-minute rainfall rate and the 3-day antecedent rainfall amount.

Runoff volumes simulated by a calibrated deterministic numerical model for each catchment had standard errors of estimate of 25 to 34 percent for a verification period that was different than the calibration period. Similarly, standard errors of estimate for peak flows were 23 to 37 percent.

Regression analyses and graphs of constituent concentrations and water discharge as functions of time indicate that when discharge is high, concentrations of constituents in suspended form tend to be higher and concentrations of constituents in dissolved form tend to be lower than when discharge is low.

INTRODUCTION

From late 1979 to early 1982 the U.S. Geological Survey, in cooperation with the City of Bellevue, Wash., conducted an investigation of the quantity and quality of urban runoff from three catchment areas in Bellevue. The purpose of the study was to collect and analyze data on the quantity and quality of urban runoff, on wet- and dry-atmospheric deposition, and on street dirt; and to evaluate the effects of street sweeping and of storm-water detention on the quality of runoff.

This report describes and presents the results of the various analyses performed on the data and the evaluation of the effects of street sweeping and detention on runoff quality.

The data collected during this study have been previously published by Ebbert, Poole, and Payne (1985) and are stored in WATSTORE, the U.S. Geological Survey's computerized data storage and retrieval system. These data are also stored in a special data-management system for urban-hydrology studies (Doyle and Lorens, 1982), along with basin characteristics, such as the amount of impervious area in a catchment, and storm characteristics, such as maximum rainfall intensity.

During the period of this study, the City of Bellevue, the Municipality of Metropolitan Seattle, and the University of Washington also conducted related studies in Bellevue. The Geological Survey's study and parts of the other studies were part of the U.S. Environmental Protection Agency's Nationwide Urban Runoff Program. These other investigations are described separately by Pitt, 1983; Galvin and Moore, 1982; Dally and others, 1983; and Perkins, 1982. Pitt and Bissonnette (1983) published a summary of the results of all investigations.

Data Collection

Data were collected in three urban-catchment areas (pls. 1-3). The 148th Avenue SE catchment, consisting of a four-lane arterial street and adjacent properties, was used to investigate the effects of detention on water quality. The other two catchments, Surrey Downs and Lake Hills, are single-family residential areas, and were used to evaluate the effects of street sweeping on runoff water quality. During the study one or the other of these two catchments was swept while the other was unswept for use as a control.

The data collected by the Survey included discharge at the outlet of each catchment and rainfall at two to three locations in each catchment. Storage volume in the 148th Avenue SE detention system and discharge at its outlet were also gaged during the period when the detention system was used. All these data were collected at 5-minute intervals. Quality of runoff water was typically determined by analyzing five to eight discrete samples taken with automatic samplers during 23 to 37 storms in each catchment. Samples were also collected manually at the inlet and outlet of the detention system. The chemical characteristics of wet-atmospheric deposition and the chemical characteristics and amounts of dry-atmospheric deposition were determined from samples collected at one site in each catchment. Typical collection periods were about 1 month long; however, some collection periods for wet-atmospheric deposition were as short as 1 day. The amounts, size distributions, and chemical characteristics of street dirt were collected and reported by the City of Bellevue (Pitt, 1983).

Methods of Data Analyses

This section describes briefly the different methods of data analyses used in this study. More detailed descriptions of the methods are given in the sections where they are used.

Concentrations in wet- and dry-atmospheric deposition samples were used in correlation analyses to determine if there were any correlations between the concentrations of different constituents at a site. Student's t tests were used to determine if there were significant differences between the concentrations at the different sites.

Student's t tests were also used on street-dirt data to test if the amounts and chemical characteristics of street dirt in the Lake Hills and Surrey Downs catchments were different and to test if street sweeping affected either the street-dirt amounts or their chemical characteristics.

Regression analysis was used to obtain empirical equations for runoff volume and peak discharge for individual storms in each catchment as functions of rainfall characteristics. Deterministic rainfall-runoff models of each catchment for computing runoff discharges were constructed, calibrated, and verified. The effect of the detention system on peak discharge was evaluated by using linear regression analysis with a dummy variable to compare peak discharges with and without the detention system.

The effect of street sweeping on runoff water quality was evaluated by using linear regression analyses with dummy variables to compare loads and discharge-weighted average concentrations for individual storms from swept catchments with similar data from unswept catchments. The effect of storm-water detention on water quality was evaluated by comparing discharge-weighted average concentrations in the inflow with those in the outflow of the detention system.

Regression analyses of constituent concentrations in discrete samples were performed to obtain some general information on the variation of concentrations during storms and to determine the applicability of equations used in many models for simulating the temporal variations of constituent concentrations during storms.

DESCRIPTION OF THE STUDY AREA

Bellevue, Wash., is located in the Puget Sound lowlands on the west side of the Cascade Range. The western edge of Bellevue is along the shore of Lake Washington, and the city of Seattle is located to the west on the opposite side of the lake (fig. 1).

Bellevue is a middle-to-upper class suburban community, and as such the city is decentralized, having residential areas served by shopping malls and numerous businesses located along arterial streets. The growth of Bellevue has been rapid in the last decade, and in 1980 the population was about 74,000 (Washington State Office of Financial Management, 1981). Although the growth of Bellevue has centered around residential development, recent development has included construction of additional office buildings and hotels. The city has no heavy industry.

The climate, which is influenced by the proximity of Bellevue to Puget Sound, is moderate. The mean annual precipitation is about 40 inches (U.S. Soil Conservation Service, 1965), which occurs mostly as rainfall during the months of October through May. Most of the rainfall results from frontal storm systems formed over the Pacific Ocean during the autumn and winter months. Rainfall is usually of low to moderate intensity and high intensity storms are infrequent.

Description of the Catchments

The locations of the three study catchments within the city of Bellevue are shown in figure 1. The Surrey Downs and Lake Hills catchments are residential areas with single-family homes; 148th Avenue SE catchment consists primarily of an arterial street. Plates 1-3 present detailed maps of each catchment showing streets, buildings, land-surface elevations, the storm-drainage system, data-collection sites, soil types, and segmentation of the catchment for representation in a numerical model for simulating storm-water runoff. Supplementary tables giving details of the storm-drainage system and a classification of catchment areas also appear on the plates. Additional data on land use within catchments are given in the data report (Ebbert, Poole, and Payne, 1985).

Areas within the catchments were classified as either pervious--lawns, gardens, and areas of natural vegetal cover, or impervious--all roofs, driveways, streets, parking lots, and other paved surfaces. The impervious classification was subdivided into (1) "effective impervious areas" that drain to other impervious areas or directly to the storm-drainage system; (2) "noneffective impervious areas" that drain onto the surface of pervious areas, such as roof-gutter downspouts that discharge onto lawns; and (3) "roofs draining to drywells" that contribute no surface runoff.

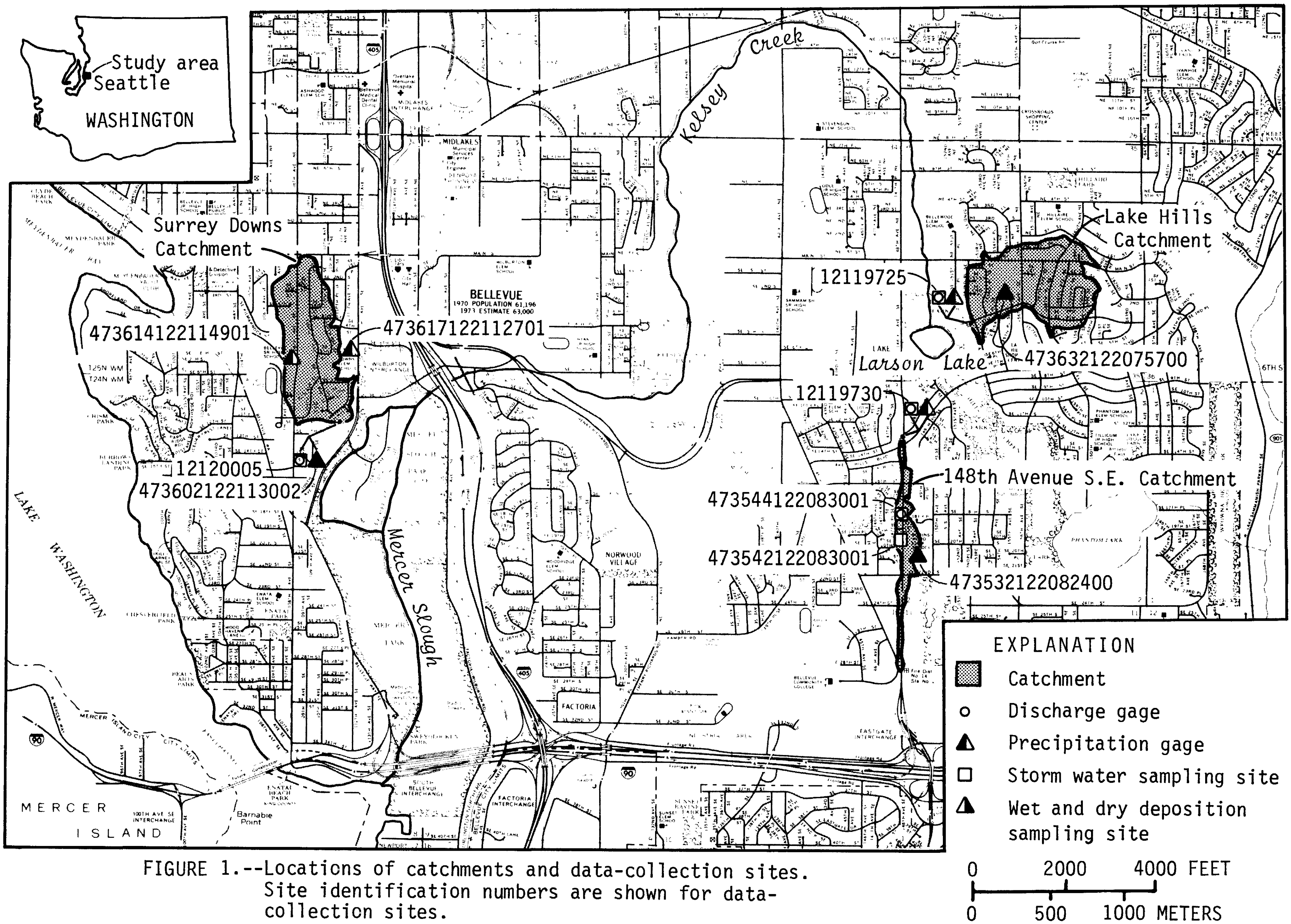


FIGURE 1.--Locations of catchments and data-collection sites. Site identification numbers are shown for data-collection sites.

Lake Hills Catchment

Lake Hills (pl. 1), one of the catchments used to study effects of street sweeping on storm-runoff quality, is a single-family residential area developed in the late 1950's. The St. Louise Parish grounds, with school, church, and convent, are in this catchment. The total catchment area is 101.7 acres; slopes are moderate, and altitudes range from 260 to 406 feet. The area is isolated from through traffic except for Main Street and 156th Avenue SE, which carry more traffic than average residential streets. Average total traffic volume is 6,490 vehicle miles per day. The structural storm-drainage system, streets, curbs and gutters, storm inlets, catch basins, and culverts are in good condition. All streets have curbs and some have gutters. The discharge from the catchment's storm sewer flows into an open channel that joins Kelsey Creek just downstream from Larson Lake (fig. 1). Kelsey Creek discharges through Mercer Slough into Lake Washington.

148th Avenue SE Catchment

The 148th Avenue SE catchment (pl. 2) was used to investigate effects of detention on storm runoff quality. This catchment consists primarily of a four-lane arterial street, 148th Avenue SE, plus adjacent areas consisting of parks, a school, an office building, apartments, a convalescent home, and parking lots. The catchment covers 24 acres, and slightly more than one-fourth of this area is the street surface of 148th Avenue SE. The average total traffic volume is 20,700 vehicle miles per day.

A storm-water detention system is located in a small park adjacent to 148th Avenue SE. The park, approximately 1,000 feet long and 100 feet wide, was constructed with five depressions that could serve as basins for detaining storm runoff. A 27-inch trunkline of the 148th Avenue SE storm-drainage system runs under the park. This pipe is oversized, and thus provides a storage volume that is about equal to that of the depressions. Flow-control structures that regulate flow in the system are located along the trunkline. An 8-inch line, parallel to the trunkline, connects control structures with the detention basins. During this study only the farthest basin downstream (No. 5) was used. The gates in the control structures for all the other basins were removed or opened wide. The control structure for basin No. 5 was modified as shown in figure 2.

On September 1, 1981, near the end of the study, the storm-sewer system for Robinswood Park was connected to the 148th Avenue SE storm-drainage system, adding another 37.5 acres to the drainage area (see pl. 2).

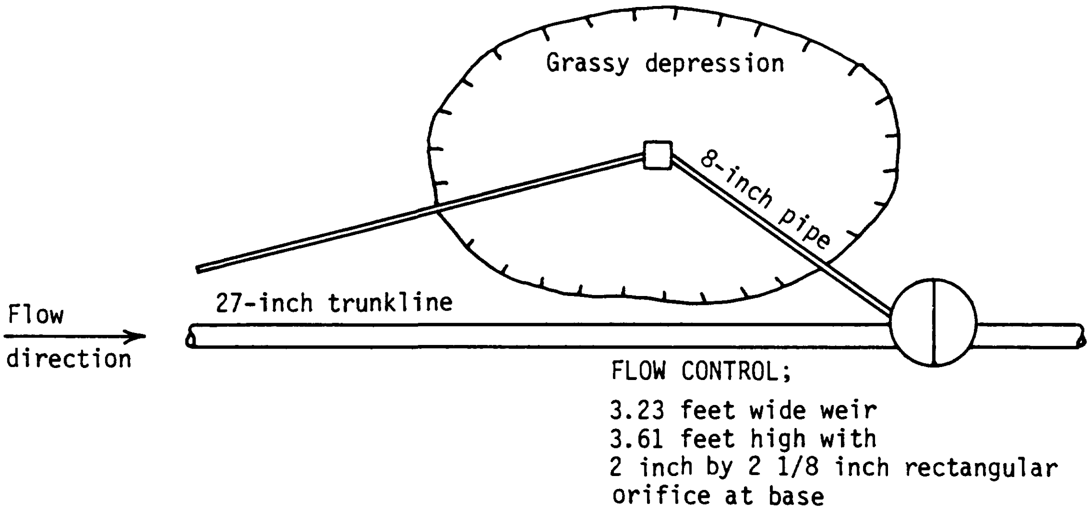


FIGURE 2.--Schematic plan drawing of basin No. 5 of the storm-water detention system in the 148th Avenue SE catchment. Flow control was modified as shown for this study.

Surrey Downs Catchment

Surrey Downs (pl. 3), the other catchment used to study effects of street sweeping on storm-runoff quality, is predominately a single-family residential area which was developed in the late 1950's. It contains Bellevue Senior High School and a few multifamily residences. The total area of the catchment is 95.1 acres, altitudes range from 40 to 176 feet, and slopes in the basin are moderate east of 109th Avenue SE but steep on the west side. Traffic volume is less than in Lake Hills (3,660 vehicle miles per day) and 108th Avenue SE is the only through street. The structural storm-drainage system is in good condition. Nearly all streets have curbs or gutters except 108th Avenue SE and Westwood Homes Road. The discharge from the storm-drainage system eventually flows through Mercer Slough to Lake Washington.

WET- AND DRY-ATMOSPHERIC DEPOSITION

Because of their probable influence on runoff quality, samples of wet- and dry-atmospheric deposition were collected at one site in each of the study catchments (see fig. 1 and pls. 1-3) and were analyzed to determine their chemical characteristics. Wet-atmospheric deposition was mostly rain, with little snow, whereas dry-atmospheric deposition appeared to be mostly dust and other windblown matter. Ebbert, Poole, and Payne (1985) published the data and described the methods used to obtain them.

The types of data collected, and the medians and ranges of observed values appear on table 1. Typical collection periods were about 1 month long; however, some wet-atmospheric-deposition collection periods were less than 1 day. The samples from the short periods were collected to obtain data for specific storms during which runoff was sampled. These data were used to estimate the percentages of constituents in the sampled runoff that originated in the rainfall. These percentages are presented in the section Quality of Runoff.

This section describes and presents the results of statistical analyses that were performed to determine if there are correlations between different chemical characteristics at a given site, and if the characteristics at the different sites were different. The statistical tests showed that at a given site only a few of the characteristics of wet-atmospheric deposition correlated with each other. Better correlation was found between the different characteristics of dry deposition. Most of the characteristics of wet-atmospheric deposition were similar at the different sites. However, statistically significant differences were found between a number of the characteristics of dry-atmospheric deposition. Because differences in the chemical characteristics of wet- or dry-atmospheric deposition could affect the quality of runoff, the statistical method used to evaluate the effects of street sweeping on runoff quality (see section on Quality of Runoff) is not dependent on the characteristics being the same in the two catchments used in this evaluation.

TABLE 1.--Maximum, minimum, and median concentrations of constituents in wet- and dry-atmospheric deposition. All concentrations in wet-atmospheric deposition are in milligrams per liter, and all dry-atmospheric-deposition concentrations are in grams per kilogram of total solids, except as noted below. (From Ebbert, Poole, and Payne, 1985)

Surrey Downs

Constituent	Wet deposition Max.	Wet deposition Min.	Wet deposition Median	Wet deposition Samples	Dry deposition Max.	Dry deposition Min.	Dry deposition Median	Dry deposition Samples
Specific conductance (uS/cm)[1]	52	8	18	47				
pH (units)	5.1	2.8	4.4	48				
Dissolved solids	44	0	7	20				
Suspended solids	21	0	3	27				
Total solids (lbs/acre)[2]					23	2	6	31
Dissolved organic carbon	12.3	0.0	1.7	44				
Suspended organic carbon	1.6	0.0	0.3	42				
Total organic carbon					680	22	22	25
Chemical oxygen demand	113	2	12	44	3,500	130	940	29
Dissolved nitrite plus nitrate (as N)	2.7	.00	.13	45				
Total nitrite plus nitrate (as N)					32	0.02	5.7	24
Dissolved ammonia (as N)	.308	.000	.092	44				
Total ammonia (as N)					34	0.00	5.6	22
Dissolved ammonia plus organic nitrogen (as N)	1.20	.02	.36	42				
Total ammonia plus organic nitrogen (as N)	1.6	.12	.47	48	66	2.1	27	29
Dissolved phosphorus (as P)	0.13	.000	.008	48				
Total phosphorus (as P)	0.16	.000	.008	48	17	0.19	1.1	28
Dissolved lead	0.011	.000	.004	8				
Total recoverable lead	2.3	.000	.012	47	17	0.27	1.6	31

Lake Hills

Constituent	Wet deposition Max.	Wet deposition Min.	Wet deposition Median	Wet deposition Samples	Dry deposition Max.	Dry deposition Min.	Dry deposition Median	Dry deposition Samples
Specific conductance (uS/cm)[1]	76	8	17	34				
pH (units)	5.2	3.8	4.4	33				
Dissolved solids	16	0	2	13				
Suspended solids	5	0	3	24				
Total solids (lbs/acre)[2]					45	2	5	19
Dissolved organic carbon	9.0	0.0	1.7	30				
Suspended organic carbon	0.8	0.0	0.2	26				
Total organic carbon					400	14	14	14
Chemical oxygen demand	111	1	10	28	3,111	50	730	16
Dissolved nitrite plus nitrate (as N)	3.0	.00	.12	32				
Total nitrite plus nitrate (as N)					83	0.01	8.9	14
Dissolved ammonia (as N)	.342	.023	.085	32				
Total ammonia (as N)					36	0.15	7.0	14
Dissolved ammonia plus organic nitrogen (as N)	.95	.05	.33	28				
Total ammonia plus organic nitrogen (as N)	1.8	.14	.42	33	53	3.3	35	16
Dissolved phosphorus (as P)	.063	.000	.008	33				
Total phosphorus (as P)	.042	.000	.008	33	27	0.16	1.3	15
Dissolved lead	.008	.000	.003	5				
Total recoverable lead	.102	.002	.011	34	3.8	0.14	1.5	19

148th Avenue SE

Constituent	Wet deposition Max.	Wet deposition Min.	Wet deposition Median	Wet deposition Samples	Dry deposition Max.	Dry deposition Min.	Dry deposition Median	Dry deposition Samples
Specific conductance (uS/cm)[1]	68	6	19	35				
pH (units)	5.4	3.8	4.4	35				
Dissolved solids	12	0	0	13				
Suspended solids	13	0	3	27				
Total solids (lbs/acre)[2]					22	2	6	20
Dissolved organic carbon	7.5	0.0	1.7	31				
Suspended organic carbon	1.1	0.1	0.2	32				
Total organic carbon					330	16	16	19
Chemical oxygen demand	101	1	11	31	1,900	100	690	20
Dissolved nitrite plus nitrate (as N)	3.6	.00	.13	34				
Total nitrite plus nitrate (as N)					26	0.03	6.5	18
Dissolved ammonia (as N)	.320	.020	.093	34				
Total ammonia (as N)					30	0.12	4.9	18
Dissolved ammonia plus organic nitrogen (as N)	1.1	.08	.30	28				
Total ammonia plus organic nitrogen (as N)	1.1	.18	.45	35	52	1.9	20	20
Dissolved phosphorus (as P)	.053	.000	.008	35				
Total phosphorus (as P)	.065	.000	.008	35	8.4	0.17	0.91	19
Dissolved lead	.008	.002	.003	6				
Total recoverable lead	.132	.003	.010	34	4.2	0.10	1.8	20

[1] Microsiemens per centimeter at 25°C.

[2] Pounds per acre.

Correlations Between Variables at a Site

Pearson product-moment correlations between variables consisting of logarithms of chemical and physical characteristics of wet-atmospheric deposition, precipitation amount, and collector exposure time were performed on the data collected at each sampling site. The r-square values (squares of the correlation coefficients) between most variables were less than 0.25; therefore, individual values of r-square are not reported here. Instead, table 2 shows which pairs of variables tend to be more closely correlated than others by indicating between which pairs of variables and at which sites the r-square values equal or exceed 0.25 and 0.5. Although the lower value represents a low degree of correlation, the confidence at which one can reject the hypothesis that the variables are uncorrelated exceeds 99 percent for these data where r-square equals or exceeds 0.25. Table 3 summarizes the results of similar analyses performed on dry-atmospheric deposition data. No attempt was made to correlate wet- with dry-deposition data.

Before the correlation analyses were performed, data that may have been affected by the August 7, 1980, eruption of Mount St. Helens were deleted. The wet-atmospheric-deposition data set was modified by replacing all zero values and values given as less than the analyzing laboratory's detection limit with values equal to one-half the detection limit. Logarithms were taken of the data before performing the correlations to make the data more nearly normally distributed.

Wet-Atmospheric Deposition

Table 2 shows that there is little correlation between different chemical constituent concentrations and properties at a given site except for pH and specific conductance, which are negatively correlated, and between different forms of the same element, such as total and dissolved organic carbon. Consequently, these data show that, with the exception of the few cases mentioned above, it is not feasible to deduce one chemical characteristic of wet-atmospheric deposition from the measurement of another.

The value of r-square between precipitation amount and each of the chemical characteristics was less than 0.25 at all sites. Also, the computed probability that precipitation amount correlated with a chemical characteristic was low in many cases. Nevertheless, in nearly every case the correlation coefficient was negative, suggesting that average concentrations were slightly lower during periods when there was more rainfall. This was also found to be true when correlation coefficients (not shown) were computed using only data from samples collected over a period of 15 days or more. These negative correlations imply that concentrations in rainfall were slightly less during the rainy season than during the dry season. This seems plausible if during the rainy season the supply of constituents in the atmosphere becomes depleted.

TABLE 2.--Matrix showing which pairs of wet-atmospheric-deposition variables at a sampling site are correlated. Upper case (L, A, S) and lower case (l, a, s) letters denote correlations within the Lake Hills, 148th Avenue SE, and Surrey Downs catchments, respectively. An upper-case letter signifies that the square of the correlation coefficient, R-square, is 0.5 or larger; a lower-case letter signifies that R-square is equal to or greater than 0.25 but less than 0.5. A negative sign signifies that the pair of variables are negatively correlated

1. Collector exposure time	1																		
2. Precipitation amount	L A S	2																	
3. Specific conductance, in uS/cm	. . .	. . .	3																
4. pH, in units	. . .	. . .	-L-A -s	4															
5. Suspended solids	. . .	. . .	. . .	. . .	5														
6. Dissolved organic carbon	. . .	-l . .	. . .	. . .	. . .	6													
7. Suspended organic carbon	. . .	. . .	. . .	. . .	. a .	. . .	7												
8. Total organic carbon[1]	. . .	-l . .	. . .	. . .	. a .	L A S	. . s	8											
9. Chemical oxygen demand	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	9										
10. Total recoverable lead	. . .	. . .	l . .	. . .	. . .	. . .	. . .	. . .	. . .	10									
11. Dissolved ammonia	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	11								
12. Dissolved ammonia plus organic nitrogen	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . s	. . .	. . .	. . .	12							
13. Suspended ammonia plus organic nitrogen[2]	. . .	. . .	. . .	. . .	. -a .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	13						
14. Total ammonia plus plus organic nitrogen	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. a s	l . .	14					
15. Dissolved nitrate plus nitrite	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	15				
16. Total nitrogen[3]	. . .	-l . s	l . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. a s	l . .	L A S	. . .	16			
17. Dissolved phosphorous[2]	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	17		
18. Suspended phosphorous[2]	. . .	. . .	. . .	. . .	. a .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	l . .	. . .	. . .	. . .	. . .	18	
19. Total phosphorous	. . .	. . .	. . .	. . .	. a .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . s	. . .	L . .	. a s	19
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	

[1] Concentrations computed as sum of dissolved plus suspended concentrations.
[2] Concentrations computed as difference between total and dissolved concentrations.
[3] Concentrations computed as sum of total ammonia plus organic nitrogen and dissolved nitrite plus nitrate concentrations.

Notes - Concentrations of dissolved lead in a few samples were determined; however, the data were too few to be included in this analysis.

Concentrations of dissolved solids were determined for many samples; however, because the precision of these data were poor the data were not included in this analysis. Use specific conductance as an indicator of dissolved-solids concentration.

Data for samples collected during the period August 18-September 17, 1980, were not included in the analyses because some of the data are suspect and may have been affected by the August 7, 1980, eruption of Mount St. Helens.

Logarithms were taken of all data except pH before computing correlation coefficients. Unless otherwise indicated original quality data were in terms of concentrations. Concentrations that were zero or were indicated as being less than the analyzing laboratory's detection limit were replaced with values equal to one-half the detection limit before taking logarithms.

Dry-Atmospheric Deposition

Correlations between constituent concentrations in dry-atmospheric deposition tended to be better than those in wet-atmospheric deposition. Table 3 shows that the value of r-square between logarithms of concentrations of organic carbon, lead, and the different forms of nitrogen (except ammonia) equals or exceeds 0.25 in most instances, and in some cases equals or exceeds 0.5. However, the value of r-square between phosphorous, ammonia, or chemical-oxygen demand and another constituent seldom equals or exceeds 0.25.

The r-square value between logarithms of the amount of dry-atmospheric deposition collected and the collector exposure time is also less than 0.25 at all three sites (table 3). The low degree of correlation between collection time and collected mass suggests that the dry-atmospheric deposition collectors may not have been efficient in retaining materials that were deposited into them. It is possible that after some period the rate of deposition into a collector was balanced by the rate of removal by wind. A balance between deposition and removal is probably achieved on the streets also; however, the equilibrium amounts of dry deposition per unit area for the streets and the collectors could be different.

TABLE 3--Matrix showing which pairs of dry-atmospheric-deposition variables at a sampling site are correlated. Upper case (L, A, S) and lower case (l, a, s) letters denote correlations of data from sampling sites within the Lake Hills, 148th Avenue SE, and Surrey Downs catchments, respectively. An upper-case letter signifies that the square of the correlation coefficient, R-square, is 0.5 or higher, a lower case letter signifies that R-square is equal to or greater than 0.25 but less than 0.5. A negative sign indicates that the variables are negatively correlated.

1. Collector exposure time	1									
2. Amount of dry solids	. . .	2								
3. Total organic carbon	. . .	-l-A -s	3							
4. Chemical oxygen demand	. . .	. . -s	. . .	4						
5. Total recoverable lead	. . .	-l-a -s	l . s	. . .	5					
6. Total ammonia	. . .	-l-a -s	. . .	. . .	l . .	6				
7. Total ammonia plus organic nitrogen	. . s	-l-A -S	L A s	. . .	. a s	. . .	7			
8. Total nitrate plus nitrate	. . .	.-a -s	. . .	. . .	. . S	. . s	. a s	8		
9. Total nitrogen[1]	. . s	-l-A -S	l A s	. . .	. a s	. . .	l A S	L A S	9	
10. Total phosphorous	. . .	. . .	. . .	. . s	. . .	. . .	. . .	. . .	. . .	10

[1] Computed value, sum of total ammonia plus organic nitrogen and total nitrate plus nitrate.

Note: Logarithms were taken of all data prior to computing the correlation coefficients. The original chemical data were expressed in units of mass of constituent per unit mass of dry solids.

The r-square values between the logarithms of the amounts of dry solids and the concentrations of all constituents except phosphorous equal or exceed 0.25 or 0.50 at one or more sites (table 3). In each of these cases the correlation coefficient is negative. The reason for the high degree of negative correlation between dry-atmospheric deposition amount and constituent concentrations is unknown.

Differences Between Sites

Statistical analyses were made in order to compute the probabilities that concentrations in wet- or dry-atmospheric deposition at the different collection sites were different. A Student's t test on paired data was used for each constituent to compute the confidence with which one can reject the null hypothesis that the mean of the differences between logarithms of concentrations in samples collected during the same periods at different sites was zero. This confidence level, expressed in percent, can be interpreted as the probability that the geometric mean of the ratio of concentrations is not unity, or, in less mathematically rigorous terminology, the probability that concentrations at different sites are different. These probabilities and the geometric means of the ratios are given in tables 4 and 5 for wet- and dry-atmospheric deposition, respectively.

Wet-Atmospheric Deposition

The data in table 4 show that differences in physical and chemical characteristics of wet-atmospheric deposition at the different collection sites were small. Most of the geometric mean ratios of observed data are between 0.8 and 1.2 and half are between 0.9 and 1.1. The average differences between pH values are all less than 0.1 pH unit. In only a few cases is the probability greater than 75 percent that the characteristics at the different sites are different.

The only characteristics for which the geometric mean ratio of observed data differs from unity by more than 15 percent are the concentration of suspended ammonia plus organic nitrogen for the comparison between Lake Hills and the other two sites, the concentration of dissolved phosphorous for the comparison between all sites, and the concentration of suspended phosphorous for the comparison between Lake Hills and 148th Avenue SE. The reasons for the differences in concentrations of suspended ammonia plus organic nitrogen are unknown. However, an examination of the dissolved phosphorous data for Lake Hills and 148th Avenue SE (not shown) reveals that concentrations were nearly identical at the two sites for more than half of the sample pairs. The difference in dissolved phosphorous concentration indicated in table 4 was caused mostly by three pairs of samples which biased the statistical analysis.

TABLE 4.--Probabilities that wet-atmospheric deposition at different sampling sites is different, and geometric means of ratios of observed data. Probabilities were computed using two-tailed Student's t-tests on differences between logarithms (paired-data tests) of all data except pH, logarithms were not taken of pH. Numbers of pairs ranged from 17 to 32

	Sampling sites					
	Surrey Downs/Lake Hills		Lake Hills/148th Ave. SE		148th Ave. SE/Surrey Downs	
Variables	Probability (pct)	Ratio[1]	Probability (pct)	Ratio[1]	Probability (pct)	Ratio[1]
Collector exposure time	31	0.98	89	0.87	96	1.11
Precipitation amount	93	.95	33	1.02	84	1.06
Specific conductance, in uS/cm	44	1.03	21	1.02	4	1.00
pH, in units	68	.03	81	.04	96	-.08
Suspended solids	59	1.14	65	.84	5	1.01
Dissolved organic carbon	45	.94	61	1.05	26	1.02
Suspended organic carbon	4	1.01	22	1.03	75	1.17
Total organic carbon[2]	47	.94	32	1.03	34	1.05
Chemical oxygen demand	5	1.01	45	1.13	48	.89
Total recoverable lead	68	1.10	18	.97	29	1.04
Dissolved ammonia	28	.96	86	1.09	34	.95
Dissolved ammonia plus organic nitrogen	80	1.12	17	.97	31	.94
Suspended ammonia plus organic nitrogen[3]	74	1.52	75	.52	11	.92
Total ammonia plus organic nitrogen	69	1.12	47	.95	60	.92
Dissolved nitrate plus nitrite	91	1.14	35	1.11	62	.83
Total nitrogen[4]	58	1.06	30	.97	33	.97
Dissolved phosphorous	55	1.19	97	.54	69	1.29
Suspended phosphorous[3]	33	.91	49	1.19	37	1.11
Total phosphorous	32	1.04	27	1.08	13	1.03

[1] The number in this column for pH is the mean difference rather than the geometric mean of the ratios.
[2] Concentrations computed as sum of dissolved plus suspended concentrations.
[3] Concentrations computed as difference between total and dissolved concentrations.
[4] Concentrations computed as sum of total ammonia plus organic nitrogen and dissolved nitrite plus nitrate concentrations.

Notes - Concentrations of dissolved lead in a few samples were determined; however, the data were too few to be included in this analysis.

Concentrations of dissolved solids were determined for many samples; however, because the precision of these data were poor the data were not included in this analysis. Use specific conductance as an indicator of dissolved-solids concentration.

Data for samples collected during the period August 18-September 17, 1980, were not included in the analyses because some of the data are suspect and may have been affected by the August 7, 1980, eruption of Mount St. Helens.

Unless otherwise indicated original quality data were in terms of concentration. Concentrations that were zero or were indicated as being less than the laboratory's detection limit were replaced with values equal to one-half the detection limit before taking logarithms.

Dry-Atmospheric Deposition

Table 5 summarizes the results of statistical analyses performed to determine if the characteristics of dry-atmospheric deposition are different at the different sampling sites. The data in this table indicate that the geometric mean ratio of concentrations at the different sites differs from unity by more than 15 percent in numerous cases. The probabilities are greater than 75 percent that concentrations of nitrite-plus-nitrate, total nitrogen, and phosphorous at Lake Hills are different than at either of the other two sites, and that concentrations of organic carbon and chemical oxygen demand at 148th Avenue SE are different than at either the Lake Hills or Surrey Downs sites.

Higher lead concentrations were expected in the samples from the 148th Avenue SE catchment than from either Lake Hills or Surrey Downs because the collector was approximately 200 feet from the four-lane arterial street. However, the probability is 74 percent or less that lead concentration at any one site is different from that of any other. The reason for the absence of high lead concentrations at the 148th Avenue SE site is unknown, but it could be that the collector was too far from the street to be directly influenced by traffic emissions.

Although not all probabilities in table 5 associated with the Lake Hills collection site are high, the data are consistent in that mean concentrations of all constituents at Lake Hills are higher than at either Surrey Downs or 148th Avenue SE. The reasons for the higher concentrations at Lake Hills are unknown. Among the various possible causes is the location of the Lake Hills collector. At all sites, samples in collectors occasionally had large pieces of organic detritus, such as pieces of leaves or evergreen needles, which were removed from the samples before chemical analysis. However, large particles of detritus were found more often in samples from the Lake Hills site than in samples from the other two sites, possibly because there were more trees in the vicinity of the Lake Hills collector. Therefore, it is probable that there were also more small particles of detritus in the Lake Hills samples that were not removed before analyses. Because the concentrations of most of the constituents in table 5 are probably higher in organic detritus than in other types of dry deposition, a larger fraction of this type of material in dry deposition would cause the concentrations of these constituents to be higher.

The table also shows that there is a relatively high probability (greater than 90 percent) that the amounts of deposition in the Lake Hills collector were different than at either of the other two sites. The geometric mean ratios indicate that the amounts were less at Lake Hills. However, as was mentioned earlier in this section, there is considerable doubt that the amounts of material collected are reliable indicators of actual deposition amounts; therefore, the differences in the amount of solids collected may not be indicative of differences in actual deposition amounts or rates between different sites.

In summary, a comparison between concentrations in dry-atmospheric deposition from different collection sites shows that for some constituents there is a high probability that the concentrations are different at the different sites. For other constituents the probabilities are low. It is possible that some of the observed differences in concentrations between sampling sites are due more to the natural variability in the data and to deficiencies in the data-collection methods than to actual differences in dry-atmospheric deposition on the different catchments. The deficiencies in data collection include the probable removal of material from the collectors by wind, and the possibility that the deposition of a collector site was not representative of the average deposition over the entire catchment area.

TABLE 5.--Probabilities that dry-atmospheric deposition at different sampling sites is different, and geometric means of ratios of observed data. Probabilities were computed using two-tailed Student's t-tests on differences between logarithms of data (paired-data tests). Number of data pairs ranged from 10 to 16

Variable	Sampling sites					
	Surrey Downs/Lake Hills		Lake Hills/148th Ave. SE		148th Ave. SE/Surrey Downs	
	Probability (pct)	Ratio	Probability (pct)	Ratio	Probability (pct)	Ratio
Collector exposure time	66	1.01	91	1.02	96	0.97
Amount of dry solids	91	1.24	>99	.67	68	1.15
Total organic carbon	45	.88	99	1.49	94	.70
Chemical oxygen demand	9	.98	90	1.31	85	.79
Total recoverable lead	29	.94	40	1.13	74	1.18
Total ammonia	42	.80	15	1.07	54	1.26
Total ammonia plus organic nitrogen	57	.85	98	1.52	60	.86
Nitrate plus nitrite	96	.52	98	1.36	79	1.34
Total nitrogen[1]	78	.73	98	1.47	4	.99
Total phosphorous	88	.76	75	1.52	7	1.02

[1]Concentrations computed as sum of "total ammonia plus organic nitrogen" and "total nitrate plus nitrite" concentrations.

Notes: The original chemical data were in terms of mass of constituent per unit mass of dry solids.

Data from the samples collected during the period August 6-18, 1980, were not included in this statistical analysis because the samples contained material from the August 7, 1980, eruption of Mount Saint Helens.

STREET DIRT

Data on the amount, the particle-size distribution, and the chemical characteristics of street dirt in the three study catchments were collected by the City of Bellevue. These data are in the computer data base STORET, which is maintained by the U.S. Environmental Protection Agency. The data include mass of dirt per unit length of curb; fraction of mass in each of eight size classes; and concentrations of five constituents for each of the eight size classes, in units of mass of constituent per unit mass of dirt. Table 6 gives the size range for each class, and table 7 lists the constituents. These data have been described and analyzed in considerable detail by Pitt (1983). However, because the complete results of these analyses were not yet available for use in the work described in that report, statistical analyses were performed on some of these data to determine (1) if street sweeping affected the amounts or chemical characteristics of street dirt; and (2) if the amounts or chemical characteristics of street dirt differed between the Lake Hills and Surrey Downs catchments.

Street Sweeping

To investigate the effects of street sweeping on runoff water quality, either all the streets in the Lake Hills catchment or a large fraction of the streets in the Surrey Downs catchment were swept about three times per week for 5-month periods. This schedule was followed for 2 years. The swept part of Surrey Downs included all streets east of 108th Avenue SE, with the exception of Westwood Homes Road (pl. 3). A list of days on which streets were swept is given in Ebbert, Poole, and Payne (1985, table 5, page 12). The sweeping periods were chosen so that both catchments were swept during the same seasons but in different years. When the swept catchment was changed, a 2-month equalization period without sweeping in either catchment was allowed in order that street dirt could accumulate in the previously swept catchment.

TABLE 6.--Particle-size classes used in analyses of street dirt

Range of sizes, in microns	Class names[1]
less than 63	silt and clay
63-125	very fine sand
125-250	fine sand
250-500	medium sand
500-1,000	coarse sand
1,000-2,000	very coarse sand
2,000-6,400	very fine gravel
greater than 6,400	fine gravel and larger

[1]Names from Lane and others (1947).

TABLE 7.--Constituents for which street dirt was analyzed

Chemical oxygen demand
Ammonia plus organic nitrogen
Total phosphorous
Recoverable lead
*Recoverable zinc

*Not included in the statistical analyses of this report because samples of rainfall, dry atmospheric deposition, or runoff collected by the USGS were not analyzed for this constituent.

Sample Collection and Analysis

The City of Bellevue periodically collected samples of street dirt throughout each catchment by vacuuming randomly chosen 6-inch-wide strips from one side of the street to another. These random samples were combined to form a composite sample that was assumed to be representative of street dirt of that area. Composite samples were formed for the entire 148th Avenue SE catchment, the entire Lake Hills catchment, 108th Avenue SE in the Surrey Downs catchment, Westwood Homes Road in the Surrey Downs catchment, and the part of the Surrey Downs catchment that was swept during scheduled periods. The latter area is referred to in this report as the main area of Surrey Downs. Westwood Homes Road is a narrow cul-de-sac and receives little automobile traffic; 108th Avenue is a minor arterial street that carries considerably more traffic than the typical residential street.

In Lake Hills and Surrey Downs, the swept streets were sampled before and after every sweeping, unless rain prevented the sampling. The unswept streets were sampled about once a week. These catchments were sampled over a period of about 20 months. The 148th Avenue SE catchment was sampled once a week, but only during the final 8 months of the project.

Each of the composite samples was dried, weighed, and analyzed for particle size. Table 8 shows the number of these composite samples collected from each area. Although the sampling efficiency is known to be a function of particle size and the amount of moisture on the street, not enough is known to permit correcting the data for variations in sampling efficiency.

TABLE 8.--Numbers of street-dirt samples analyzed for particle size, and for chemical characteristics during swept and unswept periods

	Particle-size			Chemical characteristics		
Area	Swept	Unswept	Total	Swept	Unswept	Total
Lake Hills Catchment	159	61	220	4	6	10
148th Avenue SE Catchment	--	--	21	--	--	4
Surrey Downs Catchment						
Main area[1]	102	95	197	4	6	10
108th Avenue SE	0	97	97	0	10	10
Westwood Homes Road	0	52	52	0	8	8

[1]Refers to that area that was swept during scheduled periods.

Chemical analyses were performed on sets of samples that were created by additional compositing, for each particle-size class, of equal masses from all previously composited samples collected from an area during approximately 2-month periods. The number of sets of samples for which chemical analyses were obtained is also shown in table 8. Minimum, medium, and maximum concentrations for each size class are given in table 9. A comparison of the data in table 9 with concentrations in dry-atmospheric deposition (table 1) shows that concentrations of chemical oxygen demand and ammonia plus organic nitrogen are an order of magnitude less in street dirt. However, concentrations of phosphorous and lead are the same order of magnitude.

TABLE 9.--Maximum, minimum, and median concentrations of constituents in samples of street dirt from different areas in Bellevue, Washington. Concentrations are in grams of constituent per kilogram of dry street dirt. (Data collected by City of Bellevue.)

		Lake Hills			148th Ave. SE			Surrey Downs								
								Main area[1]			108th Ave. SE			Westwood Homes Road		
Chemical constituent	Size class (micrometers)	Maximum	Minimum	Median	Maximum	Minimum	Median	Maximum	Minimum	Median	Maximum	Minimum	Median	Maximum	Minimum	Median
Chemical oxygen demand	< 63	310	180	240	200	130	160	240	120	180	190	120	140	250	130	170
	63-125	320	100	160	120	68	93	220	110	140	260	21	89	270	140	170
	125-250	150	79	110	63	40	47	180	77	91	100	35	50	230	87	150
	250-500	150	58	99	48	36	41	180	41	92	63	26	31	190	80	170
	500-1000	320	100	200	140	67	91	200	44	120	85	16	29	220	150	160
	1000-2000	380	150	210	210	77	170	280	55	190	86	12	24	370	170	270
	2000-6400	460	23	220	270	98	190	260	65	170	200	14	36	390	120	340
	>6400	900	120	290	480	160	290	620	85	240	620	14	49	730	120	400
Ammonia plus organic nitrogen as N	< 63	4.4	2.6	3.5	1.9	.63	1.6	4.6	.60	3.0	2.7	.30	1.7	4.9	2.1	3.1
	63-125	5.0	1.6	3.2	1.4	.65	.97	5.4	1.6	2.2	2.1	.66	1.1	6.0	1.7	3.1
	125-250	3.1	.97	1.9	.70	.18	.52	3.8	.20	1.3	2.6	.32	.59	4.8	1.2	1.9
	250-500	2.8	.81	1.6	.52	.26	.43	3.0	.18	1.2	.71	.24	.35	3.2	.57	1.4
	500-1000	4.2	1.1	2.3	1.0	.55	.89	3.1	.18	1.4	.83	.21	.36	2.6	1.5	1.8
	1000-2000	3.6	.83	2.1	1.3	.73	1.1	2.7	.91	1.6	.87	.10	.23	3.5	1.8	2.3
	2000-6400	4.0	.50	2.1	1.1	.36	.92	1.8	.19	1.3	.72	.07	.22	6.2	.65	1.9
	>6400	8.3	.04	1.9	1.3	.41	.50	3.9	.15	1.3	.53	.10	.23	4.8	.41	1.6
Phosphorous	< 63	1.4	.61	.93	.88	.60	.75	1.1	.29	.89	.97	.42	.67	1.1	.49	.83
	63-125	1.4	.44	.69	.61	.32	.49	.89	.27	.63	1.1	.36	.46	.99	.36	.70
	125-250	.80	.39	.52	.43	.30	.30	.70	.32	.47	.41	.24	.33	.58	.37	.46
	250-500	.65	.22	.45	.38	.24	.33	.60	.31	.42	.39	.18	.31	1.2	.34	.40
	500-1000	.91	.14	.58	.46	.32	.41	.67	.35	.46	.46	.19	.40	.77	.40	.48
	1000-2000	1.2	.61	.72	.64	.50	.60	.98	.55	.64	.77	.36	.64	.64	.52	.58
	2000-6400	1.2	.61	.70	.76	.49	.54	1.1	.62	.72	.88	.33	.65	.74	.55	.66
	>6400	1.2	.49	.66	.58	.47	.52	.97	.60	.71	.79	.18	.68	.83	.45	.62
Recoverable lead	< 63	2.6	1.4	1.9	4.4	1.2	3.0	1.8	1.1	1.5	2.2	.23	1.5	.60	.34	.41
	63-225	2.3	1.3	1.9	4.1	1.1	2.7	1.6	.68	1.2	2.1	.85	1.4	.40	.25	.34
	125-250	2.2	1.1	1.8	3.3	.86	2.2	1.4	.72	.99	2.1	.84	1:3	.37	.16	.24
	250-500	1.8	.67	1.4	3.0	.82	2.2	1.1	.47	.86	1.2	.57	.91	.22	.14	.18
	500-1000	1.6	.53	.80	2.0	.41	1.4	1.2	.36	.54	1.0	.26	.54	.58	.08	.09
	1000-2000	.87	.24	.70	.66	.25	.43	.79	.22	.34	.40	.14	.20	1.9	.05	.08
	2000-6400	1.1	.15	.26	.18	.13	.17	.58	.13	.20	.23	.08	.11	.16	.03	.04
	>6400	.51	.10	.14	.54	.09	.26	.90	.06	.18	.90	.03	.05	.36	.02	.05

[1]Refers to that area in Surrey Downs that was swept during scheduled periods.

Differences Between Lake Hills and Areas in Surrey Downs

Surrey Downs and Lake Hills served alternately as experimental and control areas for evaluating the effects of street sweeping on storm-runoff quality. These catchments were chosen because of their similarity, and it was inferred that the amounts of street dirt and their chemical characteristics were similar in the two areas. The validity of this assumption was checked by using statistical tests.

Amounts of Street Dirt

All statistical analyses of street dirt amounts were performed on logarithms of 10-day averages of the data. These were computed by dividing the entire study period into consecutive 10-day subperiods and averaging the data within each subperiod. There were two reasons for taking 10-day averages. One was to create data sets in which the data were more nearly evenly distributed over the year. The original data sets contain more data from dry periods than from wet periods because the streets could not always be sampled when they were wet. The second reason was to create data sets for the different areas that contained data for the same periods and could be paired with each other. This was because different areas were often sampled on different days, and because swept and unswept streets were sampled at different frequencies.

In one set of analyses, two-tailed Student's t tests on unpaired data were used to compute the probabilities that the means of logarithms of 10-day averages of amounts of street dirt in each of the three areas of Surrey Downs were different from those in Lake Hills. The probabilities and the ratios of the geometric means are given in table 10 for comparisons between amounts of street dirt in the main area of Surrey Downs with Lake Hills for swept conditions and between data from all three areas in Surrey Downs with data from Lake Hills for unswept conditions.

For unswept conditions, there is little probability that the amounts of street dirt in the main part of Surrey Downs differ from those in Lake Hills. The probability is greater than 99 percent that for some size classes, amounts of street dirt in Lake Hills differ from those in Westwood Homes Road and 108th Avenue SE. For swept conditions, there is a high probability that amounts of street dirt for size classes greater than 250 um (micrometer) differ for these two areas, but less than a 70-percent probability for size classes finer than 250 um. In some cases, the probability exceeds 99 percent that Lake Hills is the cleaner of the two areas.

In another series of analyses, two-tailed Student's t tests with paired logarithms of 10-day averages of amounts of street dirt were used to compare amounts of street dirt in the three areas of Surrey Downs with those from Lake Hills. These tests could be performed only for unswept conditions because Lake Hills and the main area in Surrey Downs were never swept at the same time and 108th Avenue SE and Westwood Homes Road were never swept. The results of these tests (not shown) were similar to those for tests with unpaired data (table 10) and lead to the same conclusions.

TABLE 10.--Probabilities that the amounts of street dirt, expressed in masses per unit length of curb, in three different areas of the Surrey Downs catchment are different from those in the Lake Hills catchment, and ratios (Surrey Downs/Lake Hills) of the geometric means of street dirt amounts. The probabilities and ratios were computed using two-tailed unpaired Student's t-tests on logarithms of 10-day averages of data

Size class (micrometers)	Area in Surrey Downs that is compared with Lake hills							
	Streets swept		Streets unswept					
	Main area[1]		Main area[1]		Westwood Homes Rd		108th Avenue SE	
	Probability (pct)	Ratio	Probability (pct)	Ratio	Probability (pct)	Ratio	Probability (pct)	Ratio
<63	49	0.85	3	1.00	87	0.70	>99	0.24
63-125	19	1.04	27	.94	99	.60	>99	.29
125-250	68	1.15	8	1.01	99	.69	>99	.38
250-500	94	1.24	40	1.05	>99	.71	>99	.57
500-1000	>99	1.48	70	1.09	>99	.66	46	.94
1000-2000	>99	1.80	85	1.18	99	.67	99	1.39
2000-6400	>99	1.47	59	1.12	36	.94	>99	1.54
>6400	86	.79	18	.96	98	1.55	99	1.63
all sizes	95	1.26	28	1.03	98	.77	89	.84

[1]Refers to that area that was swept during scheduled sweeping periods.

Chemical Characteristics of Street Dirt

To investigate differences between chemical characteristics of street dirt from Lake Hills and from areas in Surrey Downs, two-tailed Student's t tests were used to compute the probabilities that the means of logarithms of concentrations in street dirt from the areas are different. Table 11 gives the computed probabilities and the ratios between the geometric means of observed concentrations in street dirt from Lake Hills and those in the three sampled areas in Surrey Downs.

TABLE 11.--Probabilities that constituent concentrations in different size classes of street dirt from three different areas in the Surrey Downs catchment are different from those in the Lake Hills catchment, and ratios (Surrey Downs/Lake Hills) of the geometric means of observed concentrations. The probabilities were computed using two-tailed, unpaired Student's t-tests on logarithms of concentrations in samples that were composited over about 2-month-long periods

		Area in Surrey Downs that is compared with Lake Hills							
		Streets swept		Streets unswept					
		Main area[1]		Main area[1]		Westwood Homes Road		108th Avenue SE	
Constituent	Size class (micrometers)	Probability (pct)	Ratio	Probability (pct)	Ratio	Probability (pct)	Ratio	Probability (pct)	Ratio
Chemical oxygen demand	<63	92	0.78	99	0.76	98	0.77	>99	0.59
	63-125	26	.95	83	.79	24	.96	99	.46
	125-250	65	.89	50	.91	76	1.19	>99	.13
	250-500	89	.66	31	1.07	90	1.39	>99	.33
	1000-2000	53	.76	75	.79	9	1.06	>99	.12
	2000-6400	6	.95	95	.69	20	.94	>99	.13
	>6400	52	.71	73	.62	43	.79	>99	.11
Ammonia plus organic nitrogen	<63	68	.65	75	.87	74	.86	99	.73
	63-125	26	.95	83	.79	24	.96	>99	.46
	125-250	80	.49	1	1.00	4	.99	99	.36
	250-500	85	.47	48	.87	51	.84	>99	.21
	500-1000	94	.36	97	.66	99	.69	>99	.13
	1000-2000	98	.55	9	.98	63	1.21	>99	.14
	2000-6400	90	.38	52	.80	27	1.13	>99	.13
	>6400	31	.78	53	.50	5	.95	97	.18
Phosphorous	<63	84	1.12	83	.68	85	.82	99	.69
	63-125	4	1.00	82	.72	59	.85	98	.63
	125-250	81	.85	79	.83	98	.78	>99	.56
	250-500	25	.94	9	1.02	29	1.09	98	.67
	500-1000	99	.74	4	1.02	5	1.02	80	.73
	1000-2000	95	.87	4	.93	>99	.73	97	.77
	2000-6400	7	.99	22	1.04	88	.85	80	.83
	>6400	28	1.04	1	1.00	9	.81	76	.77
Recoverable lead	<63	60	.91	99	.68	>99	.22	91	.79
	63-125	97	.97	99	.63	>99	.17	98	.67
	125-250	95	.71	99	.60	>99	.14	93	.75
	250-500	60	.83	99	.55	99	.12	99	.61
	500-1000	61	.83	77	.71	99	.14	96	.60
	1000-2000	87	.59	79	.68	99	.22	>99	.39
	2000-6400	82	.79	63	.71	>99	.13	>99	.36
	>6400	8	.95	29	1.20	98	.31	98	.39

[1]Refers to that area in Surrey Downs that was swept during scheduled street-sweeping periods.

When comparing concentrations in street dirt from the main area of Surrey Downs with those from Lake Hills, separate analyses were made with data from swept and unswept periods because, as explained in the following section, concentrations in street dirt appear to have been different during swept and unswept periods. Because Westwood Homes Road and 108th Avenue SE in Surrey Downs were never swept, concentrations in street dirt from these areas were compared with those from Lake Hills only for unswept periods.

In most cases the ratios of geometric means of observed concentrations (Surrey Downs/Lake Hills) were less than one, indicating higher concentrations in the street dirt from Lake Hills. Although the probabilities associated with the ratios that are less than unity vary over a wide range, some consistency is evident in the data. The probabilities that concentrations in dirt from 108th Avenue SE differ from those from Lake Hills are consistently high for all constituents and nearly all size classes. The statistics also show that for periods with no street sweeping, concentrations of lead in street dirt from all three areas of Surrey Downs are lower than those in Lake Hills, except for the larger size classes in the main area of Surrey Downs. For periods with sweeping, probabilities are also high that concentrations of lead in a number of size classes are different for the main part of Surrey Downs and for Lake Hills.

In only a few instances were the ratios (Surrey Downs/Lake Hills) of geometric means of concentrations in street dirt greater than one. Generally, the probabilities that the concentrations were different are low. Consequently, it is improbable that concentrations in street dirt from any of the three areas in Surrey Downs were greater than in Lake Hills.

Effects of Street Sweeping

Amounts of Street Dirt

The effect of street sweeping on the amount of street dirt in Lake Hills and the main area of Surrey Downs was tested using two methods. In one method, using unpaired data, amounts of street dirt in an area during periods of street sweeping were compared with amounts during periods when the area was not swept. In the other method, using paired data, amounts of street dirt in two different areas were compared during times when one area was being swept and the other was not. Both methods led to the same conclusion: street sweeping reduces the amount of street dirt, and the percent reduction increases with increasing particle size.

In the tests with unpaired data, two-tailed Student's t tests were used to compute the probabilities that the means of the logarithms of 10-day averages of the amounts of street dirt during periods when a basin was being swept were different from when it was not being swept. Table 12 shows that for sizes larger than 125 um and for both catchments the probabilities that the means are different exceed 90 percent, and that there was less street dirt during periods of sweeping than nonsweeping in all size classes. For sizes larger than 125 um the relative differences in the amounts of street dirt increased with increasing particle size.

TABLE 12.--Probabilities that the masses of street dirt per unit length of curb are different during periods of sweeping than during periods without sweeping, and ratios (swept/unswept) of geometric means of street-dirt amounts. The probabilities and ratios were computed using two-tailed Student's t-tests on unpaired data consisting of logarithms of 10-day averages of observed data

Area	Size class (micrometers)	Probability, in percent	Ratio
Lake Hills catchment	<63	85	0.72
	63-125	93	.72
	125-250	>99	.66
	250-500	>99	.58
	500-1000	>99	.45
	1000-2000	>99	.34
	2000-6400	>99	.28
	>6400	>99	.27
	all sizes	>99	.48
Main area of Surrey Downs catchment	<63	96	.63
	63-125	74	.82
	125-250	92	.79
	250-500	>99	.69
	500-1000	>99	.59
	1000-2000	>99	.48
	2000-6400	>99	.34
	>6400	>99	.21
	all sizes	>99	.57

The results of the analyses for paired data appear in table 13. For particle sizes coarser than 125 um and for the total amount of street dirt, regardless of which area was swept, the probabilities that the amounts of street dirt on swept streets are different from those on unswept streets equal or exceed 98 percent, and the amounts of street dirt are less on swept streets. With one exception the relative difference between amounts of street dirt increases with increasing particle size. However, for sizes less than 63 um, either the difference in amounts of street dirt between swept and unswept streets is statistically insignificant or the swept streets are dirtier than the unswept streets.

TABLE 13.--Probabilities that street-dirt amounts, expressed in masses per unit length of curb, in the main area of the Surrey Downs catchment are different from those in the Lake Hills catchment when one of the areas is swept and the other is not, and geometric means of the ratios (swept/unswept) of street-dirt amounts. The probabilities and ratios were computed by using two-tailed Student's t-tests on differences between logarithms of 10-day averages of observed data (paired-data tests)

	Lake Hills swept		Surrey Downs swept	
Size class (micrometers)	Probability, in percent	Ratio	Probability, in percent	Ratio
<63	94	1.17	11	1.02
63-125	28	1.03	83	.91
125-250	98	.83	>99	.83
250-500	>99	.62	>99	.71
500-1000	>99	.40	>99	.61
1000-2000	>99	.24	>99	.50
2000-6400	>99	.20	>99	.34
>6400	>99	.23	>99	.14
all sizes	>99	.48	>99	.57

Chemical Characteristics of Street Dirt

To investigate the effects of street sweeping on chemical characteristics of street dirt, two-tailed Student's t tests were used to compare the logarithms of concentrations in street dirt during periods when streets were swept with those for the same areas during periods when streets were not swept. Table 14 summarizes the results of analyses of data from the Lake Hills and the Surrey Downs catchments by giving the probabilities and the ratios of the geometric means that were computed with data.

The ratios of geometric means of concentrations (swept/unswept) are almost always less than unity, and in many of these cases the probabilities are high, suggesting that the concentrations in street dirt on swept streets are less than on unswept streets. For instance, chemical-oxygen demand and ammonia plus organic nitrogen in many of the size classes of street dirt from Surrey Downs and Lake Hills display these characteristics. The statistics for phosphorus and for lead also show the same tendency, but the data are not as consistent. In those cases where the ratio exceeds unity, the probabilities that differences exist are less than 75 percent.

TABLE 14.--Probabilities that the constituent concentrations in different size classes of street dirt during periods of sweeping are different from those during periods without sweeping, and ratios (swept/unswept) of the geometric means of observed concentrations. Analyses of data from the Surrey Downs catchment were limited to data from the area that was swept during scheduled street-sweeping periods. The probabilities were computed using two-tailed, unpaired Student's t-tests on logarithms of concentrations in samples that were composited over about 2-month long periods

Chemical Constituent	Size class (micrometers)	Surrey Downs Probability (pct)	Surrey Downs Ratio	Lake Hills Probability (pct)	Lake Hills Ratio
Chemical oxygen demand	<63	86	0.83	92	0.83
	63-125	74	.87	89	.71
	125-250	94	.74	97	.74
	250-500	99	.50	65	.81
	500-1000	>99	.44	95	.62
	1000-2000	84	.66	87	.69
	2000-6400	94	.50	95	.36
	>6400	22	.87	45	.76
Ammonia plus organic nitrogen	<63	79	.63	87	.85
	63-125	53	.87	95	.65
	125-250	96	.35	81	.72
	250-500	97	.35	91	.66
	500-1000	99	.30	99	.56
	1000-2000	>99	.54	15	.95
	2000-6400	92	.47	1	1.00
	>6400	70	2.19	27	1.41
Phosphorous	<63	71	1.41	69	.85
	63-125	43	1.15	66	.81
	125-250	86	.79	94	.78
	250-500	95	.81	40	.87
	500-1000	84	.79	21	.91
	1000-2000	97	.79	74	.85
	2000-6400	72	.89	40	.93
	>6400	43	.93	37	.91
Recoverable lead	<63	67	1.12	80	.81
	63-125	9	1.00	92	.79
	125-250	15	.98	72	.83
	250-500	22	1.05	93	.69
	500-1000	10	1.05	38	.89
	1000-2000	21	.91	16	1.07
	2000-6400	69	.72	72	.65
	>6400	11	.91	29	1.15

RUNOFF AND RAINFALL

Relations between rainfall and runoff for the catchments were obtained in two different ways. One was the development of regression equations for each catchment for runoff volume and peak discharge during a storm as functions of rainfall characteristics. The other was the development of deterministic rainfall-runoff models for each of the catchments. Although not done in this study, the regression equations could be used with precipitation records to synthesize storm peaks and volumes, and the models could be used in conjunction with precipitation records to synthesize runoff hydrographs for the catchments. These volumes or hydrographs, with estimated average constituent concentrations, could be used to estimate seasonal or annual constituent runoff loads.

Data

Water discharge and rainfall data were collected in each of the three catchments. Water discharge was monitored by automatically recording water level at the outlet of each catchment. During the period when the detention basin in the 148th Avenue SE catchment was used, the water level behind the weir that controlled the outflow was also monitored. Storage volumes in and discharge rates from the basin were computed from these water levels. Inflow rates to the basin were obtained by adding the rate of change of storage in the basin to the outflow discharge. Rainfall was monitored at two or three locations in or near each catchment. Water levels and rainfall amounts were automatically recorded every 5 minutes whenever water levels exceeded predetermined thresholds or whenever 0.01 inch was accumulated.

For most storms that occurred during the study, discharge and rainfall data at 5-minute intervals for each catchment have been stored in WATSTORE, the U.S. Geological Survey's computerized data storage and retrieval system, and in the Survey's urban hydrology data base (Doyle and Lorens, 1982). The number of storms in the data file that were used in the analyses for each basin is given in table 15. Only storms for which the rainfall equaled or exceeded 0.10 inch were used. These data were used in the calibration and verification of rainfall-runoff models that are discussed later in this section. Total runoff and rainfall amounts and other storm characteristics listed in table 16 were computed for these storms. These data have also been stored in the urban hydrology data base and were published by Ebbert, Poole, and Payne (1985). They were used in regression analyses to derive empirical equations for predicting runoff volume and peak discharge.

TABLE 15.--Number of storms included in statistical analyses of catchment discharge characteristics and periods from which data were taken. Total rainfall for each storm equals or exceeds 0.1 inch

Catchment name and station number	Start date	End date	Number of storms
Lake Hills (12119725)	Feb. 18, 1980	Jan. 30, 1982	163
Surrey Downs (12120005)	Dec. 30, 1979	Jan. 30, 1982	185
148th Avenue SE (12119730):			
without detention	July 8, 1980	Mar. 5, 1981	59
with detention	Apr. 8, 1981	Aug. 31, 1981	21

TABLE 16.--Characteristics of storms. (Modified from Ebbert, Pool, and Payne, 1985)

Variable name	Variable identification
Independent variables:	
BDATE	Storm begin data; year, month, day
BTIME	Storm begin time
EDATE	Storm end data; year, month, day
ETIME	Storm end time
TRAINA	Total rainfall, average for the catchment, in inches
MAXR5	Maximum 5-minute rainfall rate, in inches/hour
MAXR15	Maximum 15-minute rainfall rate, in inches/hour
MAX1H	Maximum 1-hour rainfall rate, in inches/hour
NDRDO2	Number of hours prior to storm, counting backwards to storm event with rainfall greater than 0.2 inches.
DERNPD	Depth of rainfall accumulated during the previous 24 hours (1 day), in inches
DERNP3	Depth of rainfall accumulated during the previous 72 hours (3 days), in inches
DERNP7	Depth of rainfall accumulated during the previous 168 hours (7 days), in inches
DURRNF	Duration of rainfall, in minutes
Dependent variables:	
TOTRUN	Total runoff, not including base flow, in inches
PEAKQ	Peak discharge, not including base flow, in cubic feet per second
BFLOW	Base flow prior to storm, in cubic feet per second
TIMBPK	Approximate response time of catchment, in minutes

Note: Variables TRAINA, MAXR5, MAXR15 and MAX1H were computed from Theisen-weighted average rainfall data (see, for example, Linsley, Kohler, and Paulhus, 1975, p. 82) for each catchment.
Variables NDRDO2, DERNPD, DERNP3, and DERNP7 were computed from rainfall data collected at the mouth of each catchment.

Regression Analyses

Correlations

Regression analyses were used to obtain expressions for runoff volume and peak discharge for each catchment as functions of the rainfall characteristics. As an aid in choosing the independent variables to be included in the analyses, correlation coefficients between logarithms of storm characteristics were computed for each catchment.

Table 17 presents matrices that identify for each catchment which pairs of variables have r-squares equal to or greater than 0.25 and 0.50. In each of these cases the probability that the variables are uncorrelated is less than 1 percent. As shown in table 17, the matrices for all catchments are similar, and those variables that one would expect to be correlated (such as runoff volume and total average rainfall amount) typically have r-square values greater than 0.5.

Pairs of independent variables between which the values of r-square are high include all combinations of the three maximum rainfall rates. They equal or exceed 0.5 for all three catchments. Also, the value of r-square between the total average rainfall for a storm and each of the maximum rainfall rates equals or exceeds 0.25 for all three catchments, and r-square between the total average rainfall and rainfall duration equals or exceeds 0.25 for two of the catchments. Values of r-square between the amount of rain during 1 and 3 days prior to a storm are equal to or greater than 0.25 for all three catchments, and between the amount of rain during 3 and 7 days prior to a storm are equal to or greater than 0.5. Also, the r-square values between each of the antecedent rainfall amounts and the length of time to a prior storm with 0.2 inch or more of rain equals or exceeds 0.25 in most cases. As to be expected, these correlations were negative.

The volume of runoff from a storm correlates best with rainfall amounts; r-square values exceeded 0.90 for all three catchments. Values of r-square between runoff volume and each of the maximum rainfall rates and the duration of rainfall also equal or exceed 0.25, possibly more the result of the independent variables being correlated with total average rainfall than a physical cause-and-effect relationship.

Values of r-square between peak discharge rate (PEAKQ) and each maximum rainfall rate exceed 0.5 for all three catchments. Values of r-square between peak discharge rate and the maximum 15-minute rainfall rate (MAXR15) ranged from 0.74 to 0.86. For Surrey Downs and Lake Hills, peak discharge rate correlated best with MAXR15; however, for 148th Avenue SE the best correlation was with the maximum 1-hour rate (r-square = 0.79). For all sites, correlations with the maximum 5-minute rainfall rate was poorest (r-square = 0.51 to 0.76). Peak discharge also correlates with total average rainfall, but probably because of correlations between this variable and the maximum rainfall rates.

For the Surrey Downs and Lake Hills catchments the value of r-square between base-flow discharge and the amount of rain during the 1 and 3 days prior to a storm and the number of days since the previous storm with 0.2 inch or more of rain equals or exceeds 0.25. These correlations are negative, as would be expected. The lack of correlation of base-flow discharge with these parameters for the 148th Avenue SE catchment is suspected to be due to poor resolution of the discharge data at low flows at this site.

Values of r-square between TIMBPK, the response time of the catchment, and all other variables were less than 0.25 for all catchments. TIMBPK was computed as the time between the peak discharge and the start of the rainfall that caused the peak discharge.

TABLE 17.--Matrix showing which pairs of storm-characteristic variables for a catchment are correlated. Upper case (L, A, S) and lower-case (l, a, s) letters denote correlations for the Lake Hills, 148th Avenue SE, and Surrey Downs catchments, respectively. An upper-case letter signifies that the square of the correlation coefficient, R-square, is 0.5 or higher, a lower case letter signifies that R-square is equal to or greater than 0.25 but less than 0.5. A negative sign indicates that the variables are negatively correlated. Variable defined in table 15

1.	TRAINA	1												
2.	MAXR5	l a s	2											
3.	MAXR15	l a s	L A S	3										
4.	MAX1H	L a S	L A S	L A S	4									
5.	NDRDO2	. . .	. . .	. . .	. . .	5								
6.	DERNPD+1	. . .	. . .	. . .	. . .	-l -a -s	6							
7.	DERNP3+1	. . .	. . .	. . .	. . .	-l -A -s	l a s	7						
8.	DERNP7+1	. . .	. . .	. . .	. . .	-l -a .	. a .	L A S	8					
9.	DURRNF	l a .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	9				
10.	TOTRUN	L A S	l . s	l a s	l a s	. . .	. . .	. . .	. . .	l a .	10			
11.	PEAKQ	l a s	L A S	L A S	L A S	. . .	. . .	. . .	. . .	. . .	L A s	11		
12.	BFLOW+1	. . .	. . .	. . .	. . .	-l . -s	l . s	l . s	. . .	. . .	. . .	. . .	12	
13.	TIMBPK	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .	13

Note: Logarithms were taken of all data before computing correlation coefficients.

Data for the variables DERNPD, DERNP3, DERNP7 and BFLOW had 1.0 added to them before taking logarithms because some of the values were zero.

Analyses for 148th Avenue South catchment used only data collected during period without detention.

Regression Equations

The regression equations for runoff volume and peak discharge, as functions of rainfall characteristics, together with values of r-square for the regressions (the fraction of the variance in the dependent data that can be accounted for by the regression relationship) and standard errors of estimate for the equations, are given in table 18. The mean values of base flow and the response time for each catchment also appear in the table. Regression equations for these two variables were derived, but are not given here because the r-square values for these equations were small (0.37 to less than 0.1). By contrast, the r-square values for the equations for total runoff and peak discharge ranged from 0.75 to 0.94.

Preliminary lists of independent variables included in the regression equation for TOTRUN and PEAKQ were chosen using stepwise multiple regression. The lists were truncated when the addition of another variable made little improvement in the regression. Some of the variables in this list were then replaced by correlated variables (selected from table 17) in order to obtain a standard set of independent variables for all catchments.

TABLE 18.--Regression equations for total runoff and peak-discharge rate, and average values of base flow, and response time for three urban catchments in Bellevue, Washington. Variables are defined in table 15. Equations for TOTRUN and PEAKQ obtained by linear regressions of logarithms of data; values of R-square are for logarithms of data, and standard error of estimate are for logarithms of data and approximate percent

Equation	R-square	Standard error of estimate
Lake Hills (Sta. No. 12119725)		
$TOTRUN = 0.282\ TRAINA^{1.35}\ (DERNP3 + 1.0)^{0.60}$	0.94	0.11 (25 pct)
$PEAKQ = 26.2\ MAXR15^{1.23}\ (DERNP3 + 1.0)^{0.40}$	0.86	0.13 (32 pct)
BFLOW = 0.04	--	0.05 ft^3/s
TIMBPK = 20	--	4 min.
148th Avenue SE (without detention and without Robinswood Park) (Sta. No. 12119730)		
$TOTRUN = 0.469\ TRAINA^{1.31}(DERNP3 + 1.0)^{0.40}$	0.92	0.12 (28 pct)
$PEAKQ = 8.05\ MAXR15^{1.05}(DERNP3 + 1.0)^{0.24}$	0.74	0.17 (40 pct)
BFLOW = 0.02	--	0.03 ft^3/s
TIMBPK = 20	--	5 min.
Surrey Downs (Sta. No. 12120005)		
$TOTRUN = 0.196\ TRAINA^{1.18}(DERNP3 + 1.0)^{0.35}$	0.94	0.09 (21 pct)
$PEAKQ = 10.6\ MAXR15^{0.96}(DERNP3 + 1.0)^{0.18}$	0.88	0.09 (22 pct)
BFLOW = 0.06	--	0.09 ft^3/s
TIMBPK = 19	--	4 min.

In the equations for total runoff the total rainfall (TRAINA) accounts for more than 90 percent of the maximum r-squares attainable using all nine independent variables. The same is true for the variable MAXR15 in the equations for peak discharge rate. The addition of the second variable, DERNP3, which is the amount of rainfall during the 3 days prior to a storm, in the equations for TOTRUN and PEAKQ increases r-square by less than 0.06.

Differences between the coefficients in the equations for the different catchments are most likely due to differences between the geometries of the catchments and of the storm sewer systems, and between total and impervious areas of the catchments. Because only three catchments were investigated in this study, no attempt was made to relate the coefficients to catchment characteristics through regression analysis. However, catchment characteristics were used as data for the numerical rainfall-runoff model described later in this report. The only apparent anomaly in the coefficients in table 18 is that the exponent of the variable MAXR15 is less than unity in the equation for peak discharge at Surrey Downs. This exponent would normally be expected to be greater than unity because the fraction of rainfall that runs off of pervious surfaces normally increases with rainfall intensity. Also, the depth of overland flow on pervious and impervious surfaces would tend to increase with rainfall intensity, which would shorten the response time of the catchment and consequently make the runoff more sensitive to short periods of high intensity rainfall.

Effects of Detention

The effects of the detention system in the 148th Avenue SE catchment on peak discharge rate and response time were evaluated by using regression analyses with dummy variables (see, for example, Draper and Smith, 1966, p. 134-142). A regression analysis for peak discharge was performed using as independent variables those in table 18 plus a dummy variable, D, which was assigned a value of 0 when the detention system was not used and 1 when it was. Therefore, the probability that detention affected peak discharge equals the level of significance with which one can reject the null hypothesis that c, the regression coefficient of D, is zero. Because this regression analysis was performed on base 10 logarithms of the data, the ratio of peak discharge rates with and without detention equals 10^c. The effect of detention on response time was evaluated by using D as the only independent variable. This is equivalent to performing a Student's t test to determine the differences between means of the data. Because storm runoff from Robinswood Park may have affected peak discharge rates and response times of the 148th Avenue SE catchment, the analyses were performed only on data collected prior to the addition of Robinswood Park to the catchment.

The result of the analyses indicate a greater than 99-percent probability that detention affected peak discharge rate and that the average ratio of peak discharge rates with detention to those without detention was 0.63. The results also indicate only a 51-percent probability that detention affected response time of the catchment, and that the effect was to decrease the response time by less than 1 minute, which is less than the resolution of the data (5 minutes).

Numerical Simulation

Description of the Model

A numerical model was used to simulate the rainfall-runoff processes for each of the three study catchments. The 148th Avenue SE catchment was modeled with and without detention, but without the drainage from Robinswood Park. The following paragraphs give a brief description of the model (for a detailed description and a listing of the computer program see Alley and Smith, 1982a).

The general model that was used was designed to simulate runoff from urban drainage basins ranging in size from tens of acres to several square miles; therefore, it is suitable for use in modeling runoff from the three study catchments. The model provides detailed simulation of individual storms and a daily soil-moisture accounting between storms. The model can be used to compute runoff volumes only or to simulate runoff hydrographs.

The drainage features of a catchment are represented in the model by a set of rectangular overland-flow segments, a network of converging open-channel flow segments, and reservoirs. Table 19 lists model parameters that were used to define the geometry and hydraulic characteristics of a catchment. In addition to the model parameters, rainfall and pan evaporation are necessary model input data. For days that contain modeled storms, rainfall data at short-time intervals are required (5-minute data were used in this study). For other days, daily rainfall amounts are required; all pan evaporation data are daily amounts.

The amount of detail used to represent the catchment geometry in the model segments depends on the application. When the model is used to simulate the runoff hydrograph, relatively detailed segmentation of the catchment geometry is necessary. When only runoff volumes are computed, the segmentation may be simplified. In both cases total catchment area and the relative amounts of pervious and impervious surfaces must be represented accurately.

In the model the impervious areas of an overland-flow segment are further subdivided into effective impervious surfaces, those that are hydraulically connected to a drainage channel, and ineffective impervious surfaces, those that drain to pervious surfaces. The model computes the volume of runoff from an effective impervious surface by subtracting surface retention and evaporation from the volume of rainfall on the surface. Runoff from an ineffective impervious surface is distributed evenly over the pervious area of the segment as additional rain falling on the pervious area. The volume of runoff from a pervious surface is computed as the amount of rainfall, less losses due to evaporation and infiltration. The latter is a function of rainfall intensity, soil moisture, and physical properties of the soil. Runoff from all overland-flow segments is assumed to discharge uniformly along the length of the adjacent channel segment.

TABLE 19.--Parameters used to describe catchment geometry and hydraulic characteristics

Symbol [1]	Description
	Soil-Moisture Accounting and Infiltration Parameters
EVC	A pan coefficient for converting measured pan evaporation to potential evapotranspiration.
RR	The proportion of daily rainfall that infiltrates into the soil on days when storm runoff is not simulated.
BMSN	Available soil water at field capacity, in inches.
KSAT	The effective saturated value of hydraulic conductivity, in inches per hour.
RGF	Ratio of suction at the wetting front for soil moisture at wilting point to that at field capacity.
PSP	Suction at wetting front for soil moisture at field capacity, in inches.
	Parameters that Describe Overland-Flow Segments
Parameters that vary by segment:	
ISEG	Name of segment.
FLGTH	Length of segment along flow direction, in feet. The width perpendicular to the flow direction equals the length of the adjacent channel segment.
SLOPE	Slope of segment, in feet per foot.
eff. imp.	Percent effective impervious area.
FRN	Roughness coefficient for segment.
RCOEF	Theissen coefficients for segment.
Parameters with the same value for all segments:	
EAC	A factor to adjust the initial value of percent effective impervious area.
IMP	Maximum impervious retention, in inches.
	Parameters that Describe Channel Segments
ISEG	Name of segment.
FLGTH	Length of segment, in feet
SLOPE	Slope of segment, in feet per foot.
FRN	Roughness coefficient for segment.
diam	Pipe diameter or channel dimensions, in feet.
IUP	Upstream channel segment names (3 or less).
ILAT	Lateral-inflow overland-flow segment names (4 or less).

[1]Uppercase symbols are the same as those used in the model documentation (Alley and Smith, 1982a). Lowercase symbols are unique to this report.

The model contains an automatic optimization procedure to calibrate for runoff volume. During calibration the soil moisture and infiltration parameters or EAC, a factor to adjust the initial estimate of the percentage of effective impervious area, are automatically adjusted to minimize the sum of the squares of the differences between logarithms of observed and computed runoff volumes.

The flow-routing algorithm of the model can be used to simulate the runoff hydrograph from any segment; however, hydrographs are usually displayed only for the catchment outlet or other locations where discharge is measured. Discharge across overland-flow segments and in channels is simulated using kinematic-wave equations. The routing model can be calibrated by varying a factor, ALPADJ, which is a multiplier applied to all kinematic-wave celerities, to obtain the best agreement between observed and model peak discharge rates. Calibration of the routing model is not automatic and must be done by trial and error.

The rainfall-runoff model of each catchment was developed in two phases. The first phase consisted of constructing, calibrating, and verifying a model that computed only runoff volumes, and the second phase consisted of doing the same for a routing model that also computed discharge hydrographs for the storms. Values of selected soil moisture and infiltration parameters, and the effective impervious area of a catchment, were determined by calibrating the runoff-volume model. These calibrated parameters were then used in the routing model.

Runoff-Volume Model

Estimation of model parameters

The runoff-volume model of each catchment was represented very simply by one channel that received runoff from two identical overland-flow segments. The total area of each catchment was determined by planimetering the area within drainage boundaries drawn on a 1-to-1,200-scale orthophoto map with 2-foot contour intervals. The boundaries were drawn in the office and then checked and modified in the field. The impervious area was determined by planimetering impervious surfaces, including streets, parking lots, roofs, driveways, and walkways. The planimetered total and impervious areas in the Lake Hills and Surrey Downs catchments were then corrected by subtracting from them the areas of residential roofs whose gutters drained into drywells, calculated as a percentage of the total roof areas. The percentage was determined by field inspection of a random sample at about 20 percent of the residences in each catchment.

The effective impervious areas in Surrey Downs and Lake Hills were estimated by summing the areas of all streets and parking lots and a percentage of the residential roofs, walks, and driveways. These percentages were also determined from a field inspection of about 20 percent of the residences in each catchment. The entire impervious area of the 148th Avenue SE catchment was estimated to be effective. Numerical data on areas for each catchment are given in tables on plates 1, 2, and 3.

Values of the soil-moisture and infiltration parameters were obtained or estimated from data in Snyder and others (1973) and from recommendations given by Alley and Smith (1982a). The values of impervious retention were obtained from the horizontal-axis intercepts of lines drawn through plots of runoff as a function of rainfall. The estimates for these parameters appear in table 20.

Calibration and verification

The runoff-volume model for each catchment area was calibrated by allowing the optimization feature to adjust initial estimates of soil-hydraulic conductivity (KSAT), soil-water capacity (BMSN), and the effective impervious area so as to minimize the error in computed runoff volumes. The values of the other soil-moisture and infiltration parameters were not allowed to vary because they are highly correlated with the chosen calibration parameters.

After calibration, the models were verified by using them to simulate runoff volumes during a different period. Runoff volumes were also simulated for these periods using an uncalibrated model for which the initial estimates of model parameters were used. Table 20 summarizes the results of the simulations by giving model parameters and standard errors of estimate for the different models and simulation periods. The table gives similar data for a few simulations that were made to examine the sensitivity of the model to some of the parameters. Figure 3 compares simulated and observed runoff volumes for both the calibration and verification periods.

The data in table 20 show that the standard errors of estimate of the calibrated models ranged from 15 to 23 percent for the calibration periods but were almost twice as large, 25 to 34 percent, for the verification period. The percentages for the verification period are the better indicators of the errors of the models when used for prediction purposes. The differences between the standard errors for the two periods for both the Lake Hills and Surrey Downs models are probably caused by apparent biases in the calibrated models for small storms during the verification periods. For the 148th Avenue SE catchment there appears to be a bias for the larger storms. No explanations are offered for these apparent biases.

TABLE 20.--Summary of calibration, verification, and sensitivity testing of runoff-volume models of three urban catchments in Bellevue, Washington

Catchment, period modeled[1], and comments	Standard error of estimate (pct)*	Model calibration parameters eff. imp. (pct)	KSAT (in./hr)	BMSN (in.)
Lake Hills				
C, calibrate parameters	15	28.0	0.116	2.6
V, verify calibrated model	34	28.0	.116	2.6
V, test uncalibrated model	34	29.0	2.00	2.7
C, test sensitivity to KSAT	23	28.0	.058	2.6
C, test sensitivity to KSAT	20	28.0	.232	2.6
C, test sensitivity to BMSN	18	28.0	.116	1.3
C, test sensitivity to BMSN	18	28.0	.116	5.2
[1] C: 28 storms during the period Aug. 15, 1980, to Dec. 31, 1980. V: 71 storms during the periods Feb. 18, 1980, to July 15, 1980, and Jan. 1, 1981, to Jan. 31, 1982.				
148th Avenue SE				
C, calibrate parameters	23	40.7	1.90	2.6
V, verify calibrated model	33	40.7	1.90	2.6
V, test uncalibrated model	32	56.7	2.00	2.7
[1] C: 27 storms during the period Aug. 15, 1980, to Dec. 5, 1980. V: 19 storms during the periods July 8, 1980, to July 15, 1980, and Dec. 24, 1980, to Mar. 5, 1981.				
Surrey Downs				
C, calibrate parameters	15	22.1	0.98	2.6
V, verify calibrated model	25	22.1	.98	2.6
V, test uncalibrated model	41	27.5	2.00	2.7
[1] C: 25 storms during the period Aug. 15, 1980, to Dec. 31, 1980. V: 85 storms during the periods Dec. 31, 1979, to July 15, 1980, and Jan. 1, 1982, to Jan. 31, 1982.				

Note: The following parameter values were the same for all three catchments.

EVC = 0.70	RGF = 10.0	IMP = 0.05 inch
RR = 0.95	PSP = 1.00 inch	

*Calculated by method given by Hardison (1971).

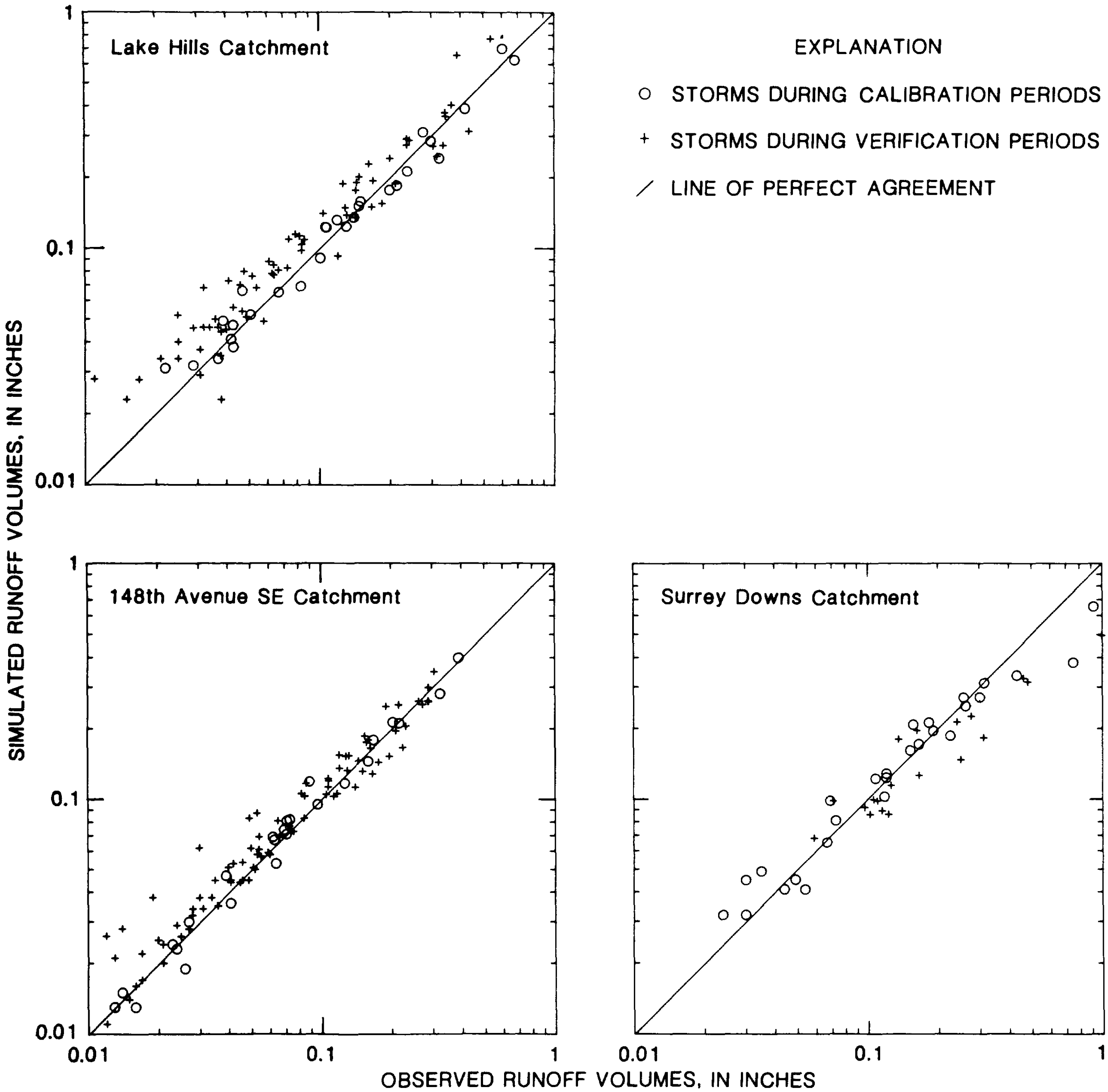


FIGURE 3.--Comparison of simulated and observed runoff volumes for the three urban catchments in Bellevue, Wash.

The data in table 20 also indicate that the standard errors of estimate for two out of three uncalibrated models differ little from those of the calibrated model; however, for the Surrey Downs model the standard error of estimate for the calibrated model is 25 percent compared to 41 percent for the uncalibrated model.

An analysis of some of the details of the simulated runoff volumes (not shown) reveals that most of the simulated total runoff is from effective impervious areas. For the calibration periods, median runoff volumes from pervious areas were only 6, 2, and less than 1 percent of the total runoff volumes from the Lake Hills, Surrey Downs, and 148th Avenue SE catchments, respectively. Therefore, the computed runoff volumes are mostly a function of the effective impervious area and should not be strongly dependent on soil-moisture or infiltration parameters.

Sensitivity tests with the Lake Hills model, the one for which pervious-area runoff was largest, show that doubling or halving KSAT or BMSN increased the standard error for the calibration period from 15 percent to values as high as 23 percent (table 20). Because of the relative insensitivity of the computed runoff to values of KSAT and BMSN, the calibrated values of these parameters are probably very sensitive to small errors in observed runoff volume.

As indicated in table 20, the calibration period for all three catchments was in the last half of 1980. The verification period was split; part preceded and part followed the calibration period. Although it is preferable to have the entire verification period precede the calibration period in order that the verification data be independent of occurrences during the calibration period, the split verification period was used because the model was calibrated before the data for the latest verification period were available. All storms that were used for calibration and verification had rainfall amounts equal to or greater than 0.10 inch. All data used for the model of the 148th Avenue SE catchment were from the period without detention.

Model construction

To simulate the discharge hydrograph of a catchment using a model, it is necessary that the geometry and hydraulic characteristics of the drainage area and channel network be represented in such a manner that the characteristic times for runoff are properly simulated. This implies that the model properly simulates runoff flow velocities and flow-path lengths. The maps on plates 1 to 3 and schematic drawings in figures 4 through 6 show how each catchment was segmented and represented in the model. In this report the overland flow segments that are shown on the maps and are identified by letters on both the maps and schematic diagrams are called physical segments. They are represented in the model by one or more model segments as indicated on the schematic diagrams. Tables 21 through 23 list numerical values of the various parameters that describe the segments. Values for all soil-moisture and infiltration parameters were the same as for the calibrated runoff-volume model (table 20).

TABLE 21.--Values of parameters for overland-flow and channel segments in model of Lake Hills catchment

Name	Length (ft)	Slope (ft/ft)	Roughness parameter	Pipe diameter (ft)	Fraction effective impervious	Theisen coefficients* 1	Theisen coefficients* 2
Overland flow segments							
PF01	164.4	0.060	0.15	--	0.0	0.07	0.93
IF01	25.0	.042	.015	--	1.0	.21	.79
IF02	32.5	.043	.015	--	1.0	.12	.88
IF03	45.0	.050	.015	--	1.0	.00	1.00
IF04	73.0	.047	.015	--	1.0	.09	.91
IF05	110.0	.033	.015	--	1.0	.02	.98
IF06	274.0	.020	.015	--	1.0	.00	1.00

*Theisen coefficient No. 1 is for rain gage at catchment outlet, No. 2 is at St. Louise Parish.

Name	Length (ft)	Slope (ft/ft)	Roughness parameter	Pipe diameter (ft)
Channel segments				
CH01	244	0.036	0.015	2.00
CH02	501	.006	.015	1.00
CH03	1,295	.026	.015	1.00
CH04	288	.013	.015	1.67
CH05	516	.009	.015	1.50
CH06	375	.036	.015	1.33
CH07	400	.040	.015	1.00
CH08	316	.017	.015	1.50
CH09	583	.050	.015	1.00
CH10	864	.045	.015	1.00
CH11	708	.098	.015	1.00
CH12	1,043	.020	.015	1.00
CH13	1,532	.016	.015	1.00
CH14	882	.018	.015	1.50
CH15	856	.011	.015	1.00
CH16	1,274	.065	.015	1.00
CH17	313	.026	.015	1.00
CH18	1,579	.038	.015	1.00

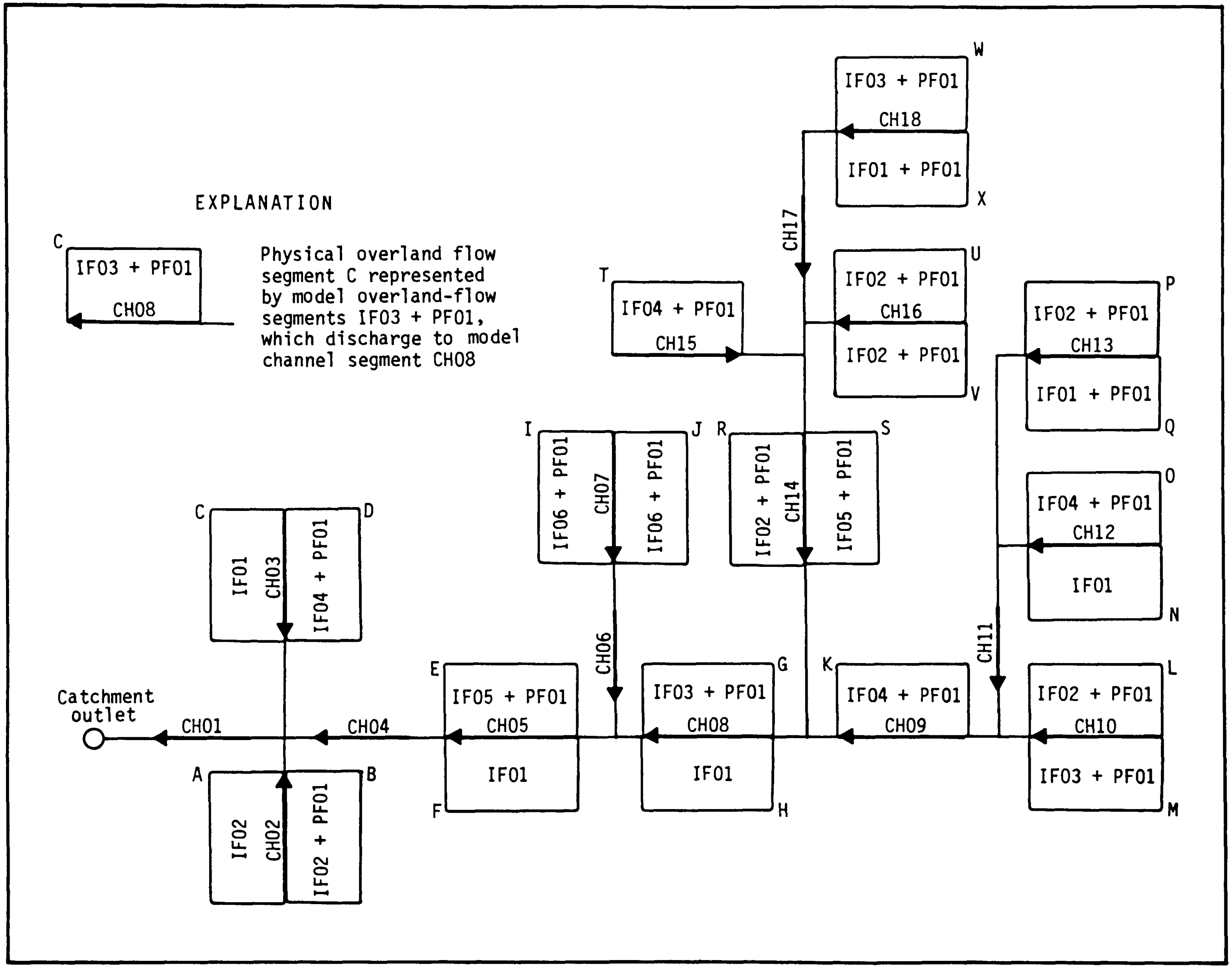


FIGURE 4.--Schematic representation of segments in model of Lake Hills catchment.

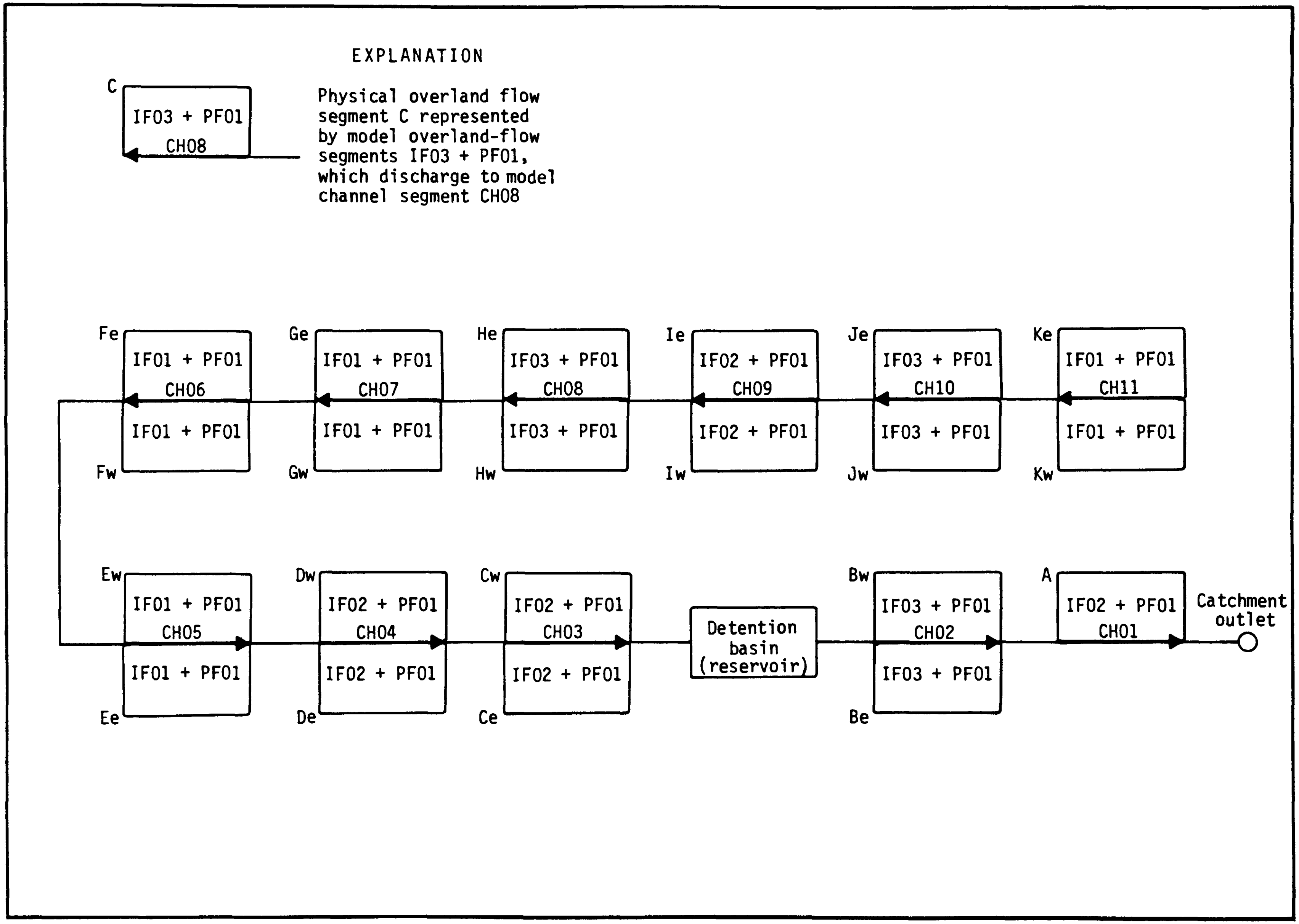


FIGURE 5.--Schematic representation of segments in model of 148th Avenue SE catchment.

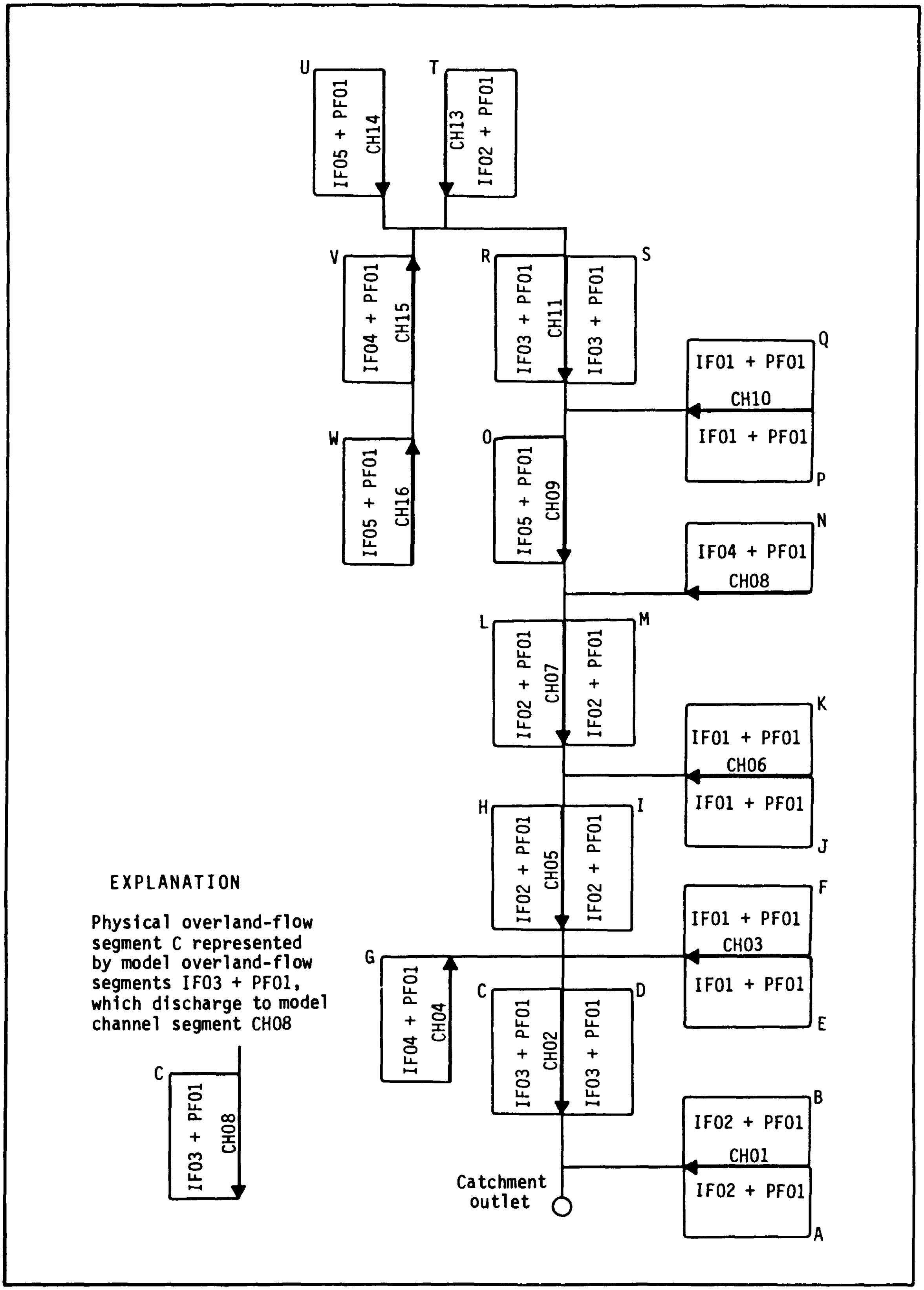


FIGURE 6.--Schematic representation of segments in model of Surrey Down catchments.

TABLE 22.--Values of parameters for (a) overland-flow and channel segments, and (b) for reservoir in model of 148th Avenue SE catchment

Name	Length (ft)	Slope (ft/ft)	Roughness parameter	Pipe diameter (ft)	Fraction effective impervious	Theisen coefficients* 1	Theisen coefficients* 2
(a)							
Overland-flow segments							
PF01	67.4	0.020	0.15	--	0.0	0.21	0.79
IFP1	23.0	.021	.015	--	1.0	.00	1.00
IF02	42.0	.028	.015	--	1.0	.33	.67
IF03	67.0	.034	.015	--	1.0	.48	.52

*Theisen coefficient No. 1 is for the rain gage at catchment outlet, No. 2 is at Robinswood School.

Name	Length (ft)	Slope (ft/ft)	Roughness parameter	Pipe diameter (ft)
Channel segments				
CH01	744	0.026	0.015	2.00
CH02	952	.004	.015	2.25
CH03	229	.011	.015	2.25
CH04	297	.019	.015	2.25
CH05	200	.015	.015	2.25
CH06	203	.008	.015	2.25
CH07	261	.001	.015	2.25
CH08	463	.003	.015	2.00
CH09	233	.003	.015	1.30
CH10	553	.089	.015	1.00
CH11	824	.004	.015	1.00

(b) Reservoir

Outflow discharge (ft^3/s)	Storage (ft^3/s) x (hr)
0	0
0.0001	0.0001
.066	.001
.200	.095
.249	.196
.306	.353
.702	.386
1.90	.447
2.81	.492
4.52	.579

TABLE 23.--Values of parameters for overland-flow and channel segments in model of Surrey Downs catchment

Name	Length (ft)	Slope (ft/ft)	Roughness parameter	Pipe diameter (ft)	Fraction effective impervious	Theisen coefficients* 1	Theisen coefficients* 2	Theisen coefficients* 3
Overland-flow segments								
PF01	170.5	0.108	0.15	--	0.0	0.24	0.34	0.43
IF01	25	.035	.015	--	1.0	.21	.38	.41
IF02	35	.037	.015	--	1.0	.32	.00	.68
IF03	42	.033	.015	--	1.0	.51	.00	.49
IF04	55	.066	.015	--	1.0	.42	.42	.16
IF05	130	.046	.015	--	1.0	.00	.80	.20

*Theisen coefficient No. 1 is for rain gage at catchment outlet, No. 2 is at Bellevue Senior High School, No. 3 is at Surrey Downs Elementary School.

Name	Length (ft)	Slope (ft/ft)	Roughness parameter	Pipe diameter (ft)
Channel segments				
CH01	746	0.005	0.015	1.00
CH02	815	.014	.015	2.00
CH03	703	.016	.017	**16.00
CH04	1,844	.011	.015	1.00
CH05	512	.012	.015	1.50
CH06	893	.009	.015	1.00
CH07	762	.022	.015	1.25
CH08	425	.014	.017	**16.00
CH09	198	.051	.015	1.00
CH10	763	.015	.015	1.00
CH11	781	.019	.015	1.00
CH13	643	.011	.015	1.00
CH14	427	.016	.015	1.00
CH15	802	.022	.015	1.00
CH16	1,506	.016	.015	1.00

** Approximates gutter.

The drawing of the segment boundaries on the maps was done with the guidance of the suggestions of Alley and Smith (1982a). The segmentation of both the Surrey Downs and Lake Hills catchments was controlled mostly by a desire to preserve the geometry of the storm-sewer networks and associated drainage areas. Segmentation of the 148th Avenue SE catchment, for which the main sewer system is a linear feature, was controlled by the shape of the catchment boundary, the location of catch basins, and the location of the detention basins.

As shown on the schematic drawings, most physical overland-flow segments are represented by two model segments, one that is 100-percent effective impervious area, and another that is a mixture of pervious and noneffective impervious areas. Separate model segments were used for the different types of areas in order for the model to properly represent the overland-flow lengths across effective impervious areas. Most effective impervious areas are adjacent to the storm sewers (channel segments) in narrow strips whose dimensions perpendicular to the channel segments are small compared to the corresponding dimensions of the entire physical segments (pls. 1-3). Therefore, if single model segments that are mixtures of pervious and of effective and ineffective impervious areas were used to represent the physical segments, the flow paths for overland flow across the effective impervious areas would be much too long. Consequently, the use of single segments could cause large errors in the simulation when runoff from effective impervious surfaces is the largest part of the total runoff.

The schematic diagrams also show that model overland-flow segments with the same name are used in the representation of more than one physical segment in a catchment. The reason for this is economy. In the model, runoff from an overland-flow segment is computed for a unit width of the segment, and this runoff is used as a discharge per unit length to channel segments. Therefore, physical segments with similar physical characteristics were assigned to groups, and each physical segment of a given group was represented in the model by a standardized model segment. In this way the number of overland-flow segments for which routing computations had to be made was reduced. The number of standardized model segments used to represent the effective impervious areas in the three catchments ranged from three to six. Because the overland-flow lengths (perpendicular to the channels) of the standardized model segments differed slightly from the actual lengths, the channel-segment lengths had to be adjusted so that the effective impervious area in the model (overland-flow segment length multiplied by channel segment length) equaled the effective impervious area in the physical segment. Consequently, the slope of the model channel segment also had to be adjusted so that the kinematic-wave traveltimes for the model and physical channel were the same. Tables 21 through 23 list values of the parameters for the model channel segments. Data for the actual storm-sewer system appear on plates 1 through 3.

Because only a small part of the total runoff from the study catchments came from pervious or ineffective impervious areas, only one standardized model overland-flow segment was used in each model for the representation of these areas. Because the length of the channel segments was determined by the effective impervious overland-flow segments, the area of pervious plus ineffective impervious surface is usually not correct for any given physical segment. However, the sum of these areas for the entire catchment is correct.

Model calibration and verification

The routing model of each catchment was calibrated by varying the coefficient ALPADJ so as to minimize the sum of the squares of the differences between logarithms of simulated and observed peak discharges. The storms used for calibrating this model were the same as those used for calibrating the runoff-volume model (table 20).

Table 24 gives values of ALPADJ and standard errors of estimate for peak discharges simulated by the calibrated model for both calibration and verification periods, and for other simulations. The calibrated values of ALPADJ ranged from 0.5 to 1.0, and the standard errors of estimate of the calibrated models for simulations during the calibration periods ranged from 22 to 26 percent. However, increasing the calibrated values of ALPADJ by 20 or 25 percent increased the standard errors of estimate by only 1 percentage point or less. Experiments performed with the model (not shown) indicated that the standard error of estimate is a function of the method chosen to solve the kinematic-wave equations, and of the computation-time-step length. Therefore, the errors are not only a function of the model parameters and the concepts upon which the model is based, but also a function of the numerical scheme that is used to solve the equations.

All simulations with the routing model used the effective impervious areas and soil moisture and infiltration parameters that were obtained from the calibrated runoff-volume model. Consequently, no error estimates can be given for peak discharges simulated with an uncalibrated model. However, as a first estimate one may assume that the relative errors in peak discharge caused by errors in estimates of effective impervious area, and soil moisture and infiltration parameters are probably similar to the resulting errors in runoff volume.

Table 24 shows that standard errors for simulations during the verification periods were all higher than during the calibration periods, ranging from 23 to 37 percent. Two verification periods were simulated with the 148th Avenue SE model, one without and one with storm-water detention. The models used for both periods were the same except for the inclusion of a detention reservoir (see fig. 5). The standard errors for both periods were nearly the same.

Figure 7 compares simulated with observed peak discharges for each catchment. The plotted data for Surrey Downs suggest that the model is biased at the higher discharges. For peak discharges higher than about 5 ft^3/s, all the simulated discharges are higher than observed. Although the reason for the apparent bias is unknown, these data are consistent with the results of the regression analysis. In that analysis the exponent for maximum rainfall rate in the equation for peak discharge in the Surrey Downs catchment was less than unity. This is believed to be physically improbable unless something in the catchment, such as a blocked or undersized pipe, hinders the flow at high discharge rates. However, a careful visual inspection of all storm-sewer lines in the catchment revealed no blockages. Furthermore, flooding of streets by backed-up water in the storm sewer was never observed.

The plotted data for Lake Hills and for 148th Avenue SE with detention also suggest some model bias at the higher discharges. Estimated peak discharges are less than observed when flows are greater than about 10 ft^3/s for Lake Hills and greater than about 2 ft^3/s for 148th Avenue SE with detention. The reason for this apparent bias is unknown.

On the graph for Lake Hills, the simulated peak discharges for a number of storms are more than twice those observed. An inspection of the rainfall data for these storms revealed that for many, the peak discharge was the result of an intense rain of short duration, often 5 minutes or less. Therefore, one may conclude that sharp-peaked hydrographs are insufficiently attenuated in the model. This is a known property of the method-of-characteristics numerical-solution method (Alley and Smith, p. 32, 1982a).

TABLE 24.--Summary of calibration, verification and sensitivity testing of rainfall-runoff routing models of three urban catchments in Bellevue, Wash. Standard errors are computed for peak-discharge rates

Catchment, period modeled,[1] and comments	Standard error of estimate (pct) *	Kinematic wave celerity multiplier, ALPADJ
Lake Hills		
C, calibrate ALPADJ	23	1.0
V, verify calibrated model	37	1.0
C, test sensitivities to ALPADJ	23	1.2

[1] C: 28 storms during the period Aug. 15, 1980, to Dec. 31, 1980.
V: 71 storms during the periods Feb. 18, 1980, to July 15, 1980 and Jan. 1, 1981, to Jan. 31, 1982.

Catchment, period modeled,[1] and comments	Standard error of estimate (pct) *	Kinematic wave celerity multiplier, ALPADJ
148th Avenue SE		
C, calibrate ALPADJ without detention	26	0.8
V, verify calibrated model without detention	30	.8
D, verify calibrated model with detention	27	.8
C, test sensitivity to ALPADJ	27	1.0

[1] C: 27 storms during the period Aug. 15, 1980, to Dec. 5, 1980.
V: 19 storms during the periods July 8, 1980, to July 15, 1980, and Dec. 24, 1980, to Mar. 5, 1981.
D: 16 storms during the period Apr. 8, 1981, to Aug. 31, 1981.

Catchment, period modeled,[1] and comments	Standard error of estimate (pct) *	Kinematic wave celerity multiplier, ALPADJ
Surrey Downs		
C, calibrate ALPADJ	22	0.5
V, verify calibrated model	23	.5
C, test sensitivity to ALPADJ	23	.6

[1] C: 25 storms during the period Aug. 15, 1980, to Dec. 31, 1980.
V: 85 storms during the periods Dec. 31, 1979, to July 15, 1980, and Jan. 1, 1982, to Jan. 31, 1982.

Note: All computations used the method of characteristics with a computation-time-step length of 2.5 minutes; rainfall input data were in 5-minute increments.

*Calculated by method given by Hardison (1971).

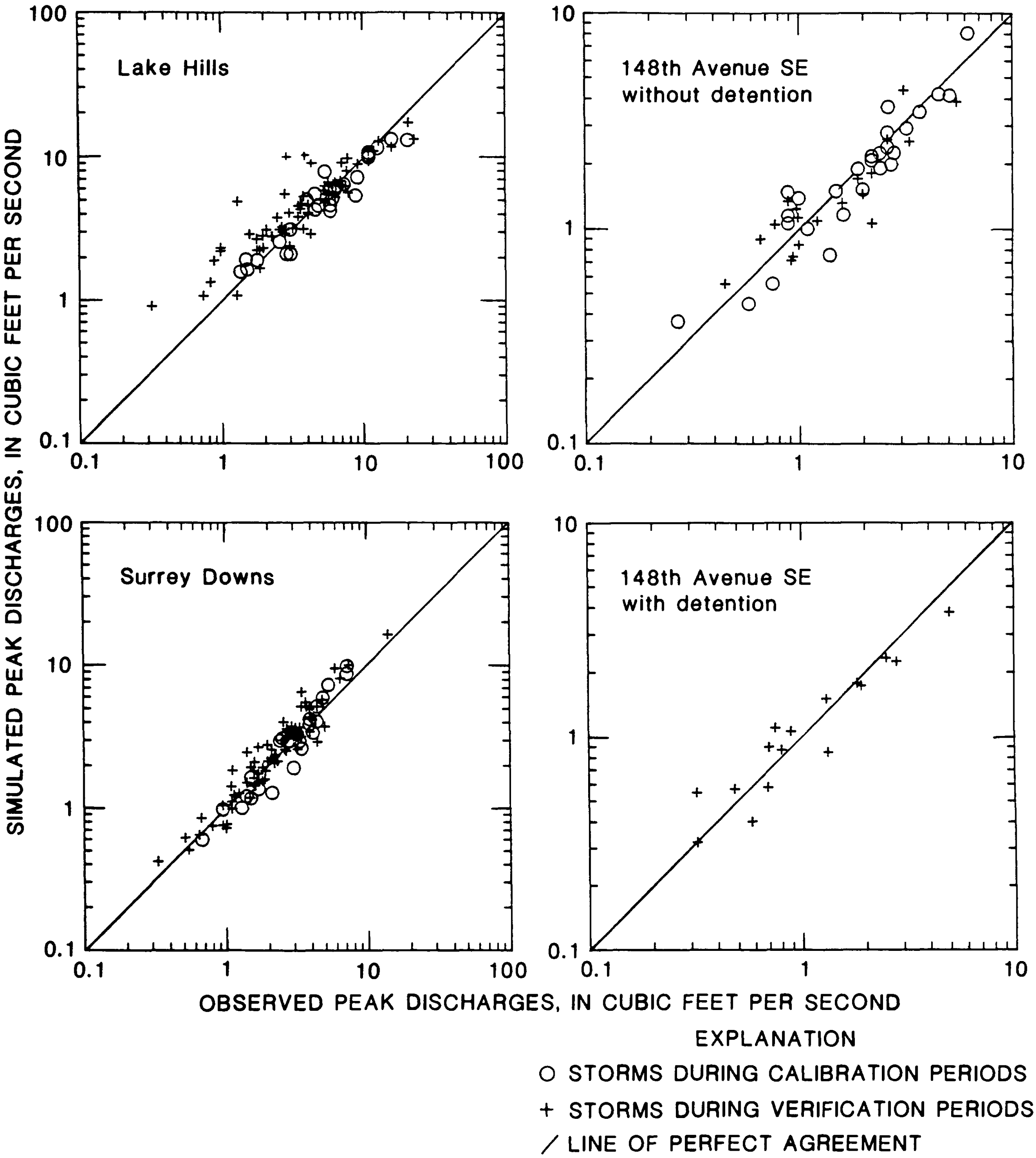


FIGURE 7.--Comparison of simulated and observed peak discharges for the three catchments in Bellevue, Wash.

QUALITY OF RUNOFF

Data

The quality of storm-water runoff was determined by analyzing discrete samples taken with automatic samplers at the outlets of each of the three catchments. In addition, samples were taken manually at the inlet and outlet of the 148th Avenue SE detention system during storms when the detention system was used. From 23 to 37 storms were sampled in each catchment. Samples from most storms were analyzed for the constituents listed in table 25, which gives the minimum, median, and maximum of observed concentrations. Selected samples from a few storms were also analyzed for other constituents, including additional organic compounds and metals. Ebbert, Poole, and Payne (1985) give, in tabular form, all the water-quality data collected during this study. They also present graphs showing rainfall, water discharge, specific conductance, and suspended-sediment concentration as functions of time for most of the sampled storms. Typically, the concentrations of most constituents were determined in five to eight samples per sampling site per storm. However, nearly twice as many samples were often analyzed for specific conductance and suspended-sediment concentration.

In addition to the tables and graphs of concentrations in the individual samples, Ebbert, Poole, and Payne (1985) also give loads, expressed in masses of constituent per unit area of catchment, in the runoff from individual storms. The loads were computed by numerically integrating the products of concentration and water discharge over the duration of storm events. Included with the loads are hydrologic data for each storm, such as rainfall amounts and intensities and runoff amounts, loads attributed to impurities in the precipitation, and estimates of the amount of dry atmospheric deposition during the period between the sampled storm and the previous storm with 0.2 inch or more of rainfall. All these data are stored in the U.S. Geological Survey urban hydrology data base (Doyle and Lorens, 1982). The discharge and precipitation data at 5-minute intervals and concentrations of the individual samples are also stored in the Survey's data storage and retrieval system WATSTORE.

Some of the loads computed in this study can be compared with loads obtained during the companion investigation by the City of Bellevue. They collected discharge-weighted composite samples with automatic samplers at the outlets from the Surrey Downs and Lake Hills catchments during most storms. Constituent loads were computed by multiplying the concentrations in the composite samples by the volumes of water discharged during the storms. For a few of the storms the starting and ending times used to compute loads were nearly the same for both studies. The same discharge data were used in both studies for load computations; however, the City of Bellevue had their own discharge-measurement system for controlling their sampler.

TABLE 25.--Maximum, minimum, and median concentrations of water-quality constituents in storm runoff. Data are for all storms sampled during study. Values are in milligrams per liter unless noted. (From Ebbert, Poole, and Payne, 1985)

CONSTITUENT OR PROPERTY	148TH AVENUE 12119730				LAKE HILLS 12119725				SURREY DOWNS 12120005			
	MAX.	MIN.	MEDIAN	NO. OF SAMPLES	MAX.	MIN.	MEDIAN	NO. OF SAMPLES	MAX.	MIN.	MEDIAN	NO. OF SAMPLES
Specific conductance (microsiemens/cm at 25 °C)	690	15	47	369	1480	12	33	515	303	15	44	415
PH (UNITS)	7.9	3.4	6.7	305	7.3	5.8	6.7	430	7.6	5.9	6.7	358
CHEMICAL OXYGEN DEMAND	320	14	79	186	780	8	44	266	410	9	58	229
CARBONACEOUS BIOCHEMICAL OXYGEN DEMAND, 5-DAY	40	0.8	8.4	109	33	0.0	5.4	115	36	0.0	6.1	97
CARBONACEOUS BIOCHEMICAL OXYGEN DEMAND, ULTIMATE	115	3.5	20	39	77	3.5	19	51	99	4.0	20	48
SUSPENDED ORGANIC CARBON	18	0.2	2.6	183	40	0.0	1.8	242	38	0.1	2.0	213
DISSOLVED ORGANIC CARBON	47	2.6	8.3	189	120	1.3	6.2	266	74	0.2	7.9	226
FECAL COLIFORM BACTERIA, 0.7 UM-MF (COLONIES PER 100 ML)	19000	1	645	94	66000	1	1000	120	24000	1	1300	112
SUSPENDED SOLIDS, RESIDUE AT 105 DEG. C	2740	6	72	324	1410	1	34	470	662	2	43	386
DISSOLVED SOLIDS, RESIDUE AT 180 DEG. C	131	12	39	60	788	8	32	94	138	12	34	87
DISSOLVED NITRITE PLUS NITRATE (AS N)	2.1	0.04	0.26	189	2.9	0.00	0.15	272	4.5	0.06	0.23	230
DISSOLVED AMMONIA (AS N)	6.5	0.00	0.20	188	7.2	0.00	0.09	271	2.3	0.00	0.12	230
TOTAL AMMONIA PLUS ORGANIC NITROGEN (AS N)	45	0.25	1.20	189	15	0.27	0.98	268	12	0.21	1.10	230
DISSOLVED AMMONIA PLUS ORGANIC NITROGEN (AS N)	33	0.23	0.68	188	9.8	0.00	0.56	269	7.5	0.00	0.66	229
TOTAL PHOSPHORUS (AS P)	9.20	0.02	0.15	198	2.90	0.01	0.15	266	5.60	0.02	0.14	222
DISSOLVED PHOSPHORUS (AS P)	7.20	0.00	0.06	189	0.73	0.01	0.06	268	3.50	0.00	0.05	228
TOTAL LEAD (UG/L AS PB)	1500	4	210	196	4800	5	110	267	1800	5	99	230

Table 26 shows loads of constituents common to both investigations, and rainfall and runoff. The agreement between loads computed by the two studies ranges from good to poor. The best general agreement is between loads of dissolved solids. The root-mean square of the differences between these loads is only 10 percent. The good agreement between loads of dissolved solids is not surprising considering that there is usually less sampling error associated with a dissolved constituent than a suspended one, and that dissolved-solids concentrations were determined from measurements of specific conductance, a relatively simple measurement. The one large difference between dissolved-solids loads for Surrey Downs on January 15-16, 1982, is suspected to be the result of an error in the measurement of specific conductance. For other constituents the root-mean square of the percentage differences ranges from 18 to 69 percent. The differences between loads computed by both studies generally range from a few percent to about 50 percent and are probably the result of differences in both sampling errors and sample analyses.

TABLE 26.--A comparison of constituent loads in storm runoff obtained in the study by the U.S. Geological Survey compared with those obtained in the study by the City of Bellevue. Loads are in pounds per acre

Catchment	Agency	Begin, date-time	End, date-time	Rain-fall (in.)	Run-off (in.)	Chemical oxygen demand	Dis-solved solids[1]	Sus-pended solids[2]	Total ammonia plus organic nitrogen	Total phos-phorous	Total recover-able lead
Lake Hills	USGS	6- 5-81 1410	6- 5-81 2200	0.43	0.082	1.1	0.48	1.6	0.033	0.0096	0.0050
	City of Bellevue	6- 5-81 1435	6- 5-81 2025	.43	.080	.81	.51	1.6	.036	.0098	.0036
	USGS	6-30-81 1555	6-30-81 2000	.28	.057	2.0	.61	3.3	.064	.011	.0070
	City of Bellevue	6-30-81 1625	6-30-81 2325	.33	.063	1.8	.68	2.3	.058	.017	.0072
	USGS	12- 3-81 1510	12- 4-81 0115	.11	.026	.27	.45	.15	.0040	.00035	.00053
	City of Bellevue	12- 3-81 0945	12- 4-81 0005	.16	.036	.31	.54	.43	.011	.00093	.00081
	USGS	1-15-82 1025	1-16-82 1145	.92	.31	1.6	1.6	2.0	.039	.0085	.0046
	City of Bellevue	1-15-82 1115	1-16-82 1120	.98	.33	1.9	1.8	4.0	.036	.0082	.0074
Surrey Downs	USGS	6- 5-81 1400	6- 5-81 2200	.32	.054	.94	.37	1.1	.018	.0022	.0029
	City of Bellevue	6- 5-81 1420	6- 5-81 2020	.33	.053	.80	.36	1.3	.019	.0036	.0024
	USGS	6-30-81 1615	6-30-81 2000	.22	.032	1.1	.41	1.3	.031	.0051	.0028
	City of Bellevue	6-30-81 1630	6-30-81 2300	.25	.035	1.2	.38	2.2	.034	.0096	.0032
	USGS	12- 3-81 1510	12- 4-81 0100	.16	.032	.49	.61	.28	.0057	.00036	.00078
	City of Bellevue	12- 3-81 0925	12- 4-81 0040	.19	.042	.45	.64	.68	.0062	.0012	.00094
	USGS	1-15-82 1100	1-16-82 1145	.97	.23	1.8	1.6	2.2	.032	.0037	.0039
	City of Bellevue	1-15-82 1125	1-16-82 1135	1.1	.28	2.4	5.5	.96	.046	.011	.0063

[1]For both studies the dissolved-solids concentrations (in milligrams per liter) used in load computations were obtained by multiplying specific conductance (in microsiemens per centimeter) by 0.78 (see Ebbert, Poole, and Payne, 1985).

[2]For the study by the City of Bellevue loads of suspended solids were obtained by subtracting loads of dissolved solids from loads of total solids.

Forms of Runoff Loads

A few statistics computed for the loads data are included in this section to aid in later interpretations of the runoff water-quality data. Table 27 lists the minimum, maximum, and median values of percentages of loads of various constituents that were in suspension. Median values for each of the three catchments indicate that about two-thirds of the total solids and phosphorous loads and one-third of the ammonia plus organic nitrogen, total nitrogen, and organic carbon loads were in suspension.

Table 28 lists the percentages of the different forms of nitrogen in the total nitrogen load. The median values for each of the three catchments are fairly consistent, indicating that about 15 percent of the total nitrogen load is in the form of dissolved nitrate plus nitrite, 10 percent dissolved ammonia, 40 percent dissolved organic nitrogen, and 35 percent suspended ammonia plus organic nitrogen.

Table 29 shows the percentages of loads that originate in the precipitation. Although the range of percentages for a constituent at a station is large, the median percentages for all stations consistently show that for some constituents precipitation is often a major source of the material in the observed load. For example, about one-third of the total nitrogen in runoff is from nitrogen in rainfall.

TABLE 27.--Maximum, minimum, and median percentages of total constituents loads that are in suspended form, and number of storms

Constituent	Catchment											
	Lake Hills				148th Avenue SE				Surrey Downs			
	Maximum	Minimum	Median	Number	Maximum	Minimum	Median	Number	Maximum	Minimum	Median	Number
Solids[1]	95	23	62	33	86	28	70	19	89	31	62	29
Organic carbon	61	3	28	30	47	9	30	17	50	6	21	25
Ammonia plus organic nitrogen	82	3	37	31	84	12	38	17	69	5	46	25
Total nitrogen[2]	78	2	32	31	77	10	30	17	64	4	39	25
Phosphorous	90	5	62	30	94	29	72	16	92	27	61	24

[1]Sum of dissolved solids computed from specific conductance plus suspended sediment.
[2]Sum of dissolved nitrite plus nitrate and total ammonia plus organic nitrogen.

TABLE 28.--Maximum, minimum, and median values of percentages of various forms of nitrogen that make up total nitrogen loads, and number of storms

Constituent	Catchment											
	Lake Hills				148th Avenue SE				Surrey Downs			
	Maximum	Minimum	Median	Number	Maximum	Minimum	Median	Number	Maximum	Minimum	Median	Number
Dissolved nitrate plus nitrite	35	2	14	31	36	8	21	18	40	6	16	25
Dissolved organic nitrogen	78	14	44	31	55	13	36	17	64	25	36	25
Dissolved ammonia	34	0	10	31	27	0	13	18	25	0	9	25
Suspended ammonia plus organic nitrogen	78	2	32	31	77	10	30	17	64	4	39	25

TABLE 29.--Maximum, minimum, and median percentages of runoff loads due to constituents present in precipitation

Constituent	Catchment											
	Lake Hills				148th Avenue SE				Surrey Downs			
	Maximum	Minimum	Median	Number	Maximum	Minimum	Median	Number	Maximum	Minimum	Median	Number
Suspended sediment	11	1	4	19	7	0	1	10	16	0	2	14
Dissolved solids[1]	55	0	12	11	39	0	0	4	21	0	12	8
Dissolved organic carbon	51	0	23	19	33	3	13	12	39	7	14	19
Suspended organic carbon	75	0	5	18	11	1	4	13	32	0	4	18
Total organic carbon	38	0	16	16	25	3	10	11	28	6	11	18
Chemical oxygen demand	100	1	23	19	57	1	10	12	100	7	14	19
Total recoverable lead	43	1	6	24	46	2	4	13	48	2	13	21
Dissolved nitrate plus nitrite	100	0	57	23	95	1	36	13	100	0	31	21
Dissolved ammonia	100	4	86	23	100	8	35	13	100	2	78	21
Dissolved ammonia plus organic nitrogen	100	12	50	18	65	15	23	9	100	10	36	18
Total ammonia plus organic nitrogen	100	5	36	23	64	14	21	13	75	13	32	22
Total nitrogen[2]	100	7	38	23	64	10	26	13	79	11	37	21
Dissolved phosphorous	41	0	10	18	90	0	3	9	52	0	5	18
Total phosphorous	21	0	2	23	9	0	4	14	14	0	4	21

[1]Dissolved-solids concentrations in runoff but not in precipitation computed from specific conductance.
[2]Sum of dissolved nitrate plus nitrite and total ammonia plus organic nitrogen.

NOTE: For some storms the computed contribution of precipitation to runoff load exceed the observed runoff load. In these cases 100 percent was listed as the maximum percentage.

Effects of Street Sweeping on Runoff Water Quality

To provide data for evaluating the effect of street sweeping on runoff quality, the same storms were sampled in Lake Hills and Surrey Downs. Although it was not possible to take discrete samples in these two catchments simultaneously, care was taken to use nearly the same starting and ending times in the computation of loads for the two catchments. The effects of street sweeping on runoff water quality were evaluated by using statistical tests to compare loads and discharge-weighted average concentrations computed for individual storms at Surrey Downs with similar data for Lake Hills. The discharge-weighted average concentrations were computed by dividing loads by runoff volumes. The test results (table 30) indicated that there is little probability that street sweeping affected the water quality of runoff. Analyses of data collected by the City of Bellevue (Pitt, 1983) lead to the same conclusion.

Method of Analysis

Because street sweeping was found to decrease the amount of dirt on the streets, one might expect that street sweeping would improve the runoff quality. Consequently, when average concentrations are plotted as they were in figure 8, the data for each constituent might be expected to define three different relations as hypothesized in figure 9. A central relation would fit data collected when neither catchment was swept; a relation lying above or to the left of the central one would fit data collected when Lake Hills was swept; and a third relation lying below and to the right of the others would fit data collected during periods when Surrey Downs was swept. However, visual inspection of figure 8 reveals no obvious separation of data by street sweeping. Visual inspection of similar plots of loads per unit area (not shown) also failed to show any separation by street sweeping.

In spite of the lack of any visually apparent difference between data collected during periods when different catchments were swept, a statistical analysis was used in an attempt to detect differences. Table 30 summarizes the results of these tests by giving estimates of the probabilities that street sweeping affected average concentrations and loads, and ratios of average concentrations and of loads between swept and unswept catchments.

TABLE 30.--Probabilities that there are differences between loads or average concentrations in storm runoff from swept and unswept catchments, and values of 10^{-c} which are approximations of geometric mean ratios (swept/unswept) of loads or average concentrations. Probabilities and ratios obtained from regression analyses (see text) performed on logarithms of data

Constituent	Number of storms	Load		Average concentration	
		Probability (pct)	10^{-c} (approx. ratio)	Probability (pct)	10^{-c} (approx. ratio
Suspended solids	27	46	0.91	1	1.00
Dissolved solids[1]	30	21	1.02	29	1.02
Total organic carbon[2]	25	59	.94	26	.98
Suspended organic carbon	25	1	1.00	25	1.03
Dissolved organic carbon	25	76	.82	65	.94
Chemical oxygen demand	25	28	1.03	93	1.11
5-day BOD	12	45	1.01	88	1.14
Fecal-coliform bacteria	12	44	.77	34	.79
Total lead	25	30	1.05	68	1.11
Dissolved nitrite plus nitrate	25	20	.97	3	1.00
Dissolved ammonia	25	38	1.08	49	1.17
Total ammonia plus organic nitrogen	25	65	.92	40	.97
Suspended ammonia plus organic nitrogen[3]	25	79	.77	98	.67
Dissolved ammonia plus organic nitrogen	25	48	.96	19	.99
Total nitrogen[4]	25	48	.95	5	1.00
Total phosphorous	24	8	1.01	84	1.15
Suspended phosphorous[3]	24	57	1.11	59	1.15
Dissolved phosphorous	25	95	.85	68	.92

[1]Computed from specific conductance.

[2]Computed as sum of dissolved and suspended components.

[3]Computed as difference between total and dissolved components.

[4]Computed as sum of dissolved nitrite plus nitrate and total ammonia plus organic nitrogen.

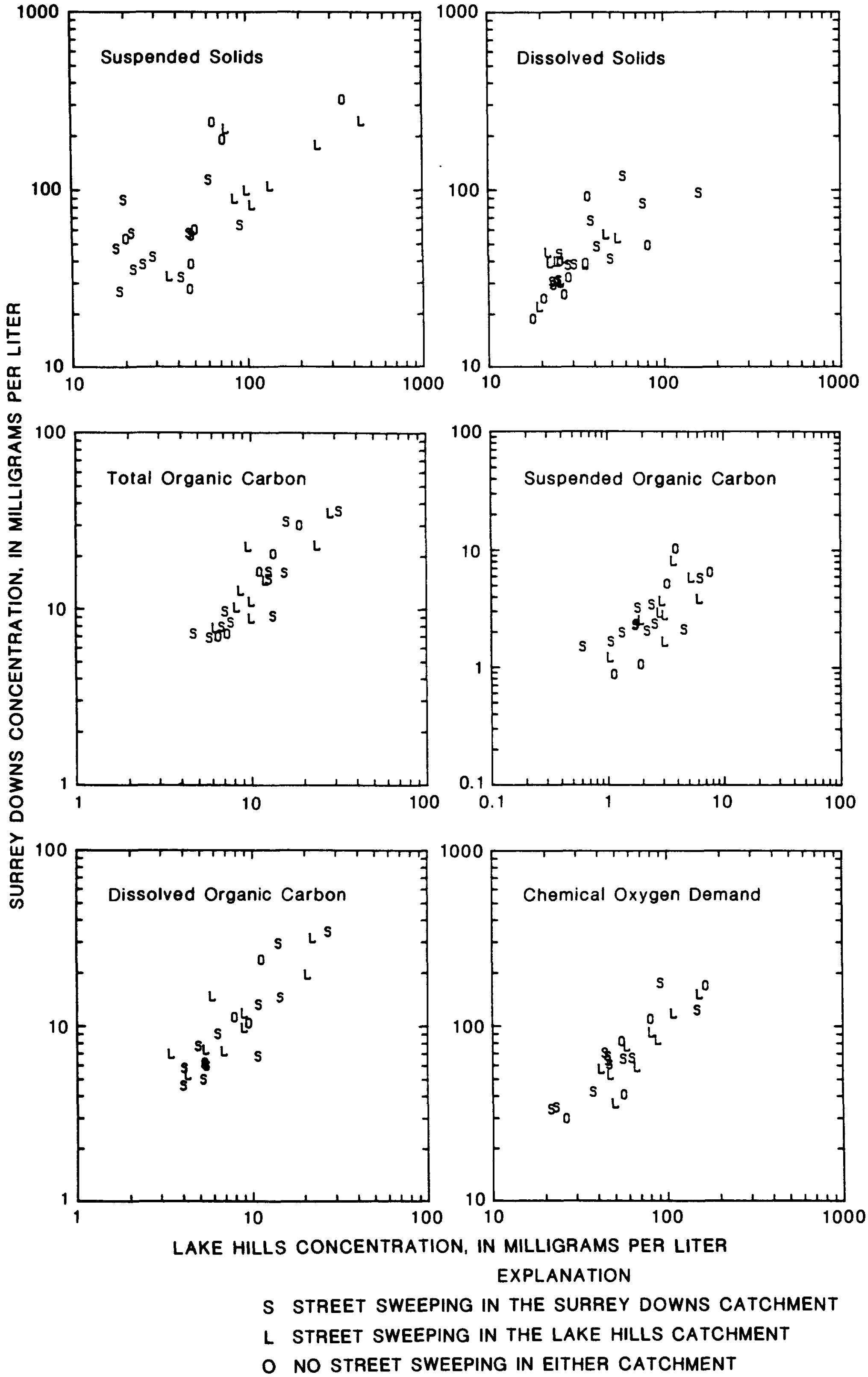


FIGURE 8.--Discharge-weighted average-constituent concentrations computed for individual storms in runoff from Surrey Downs plotted against those from Lake Hills.

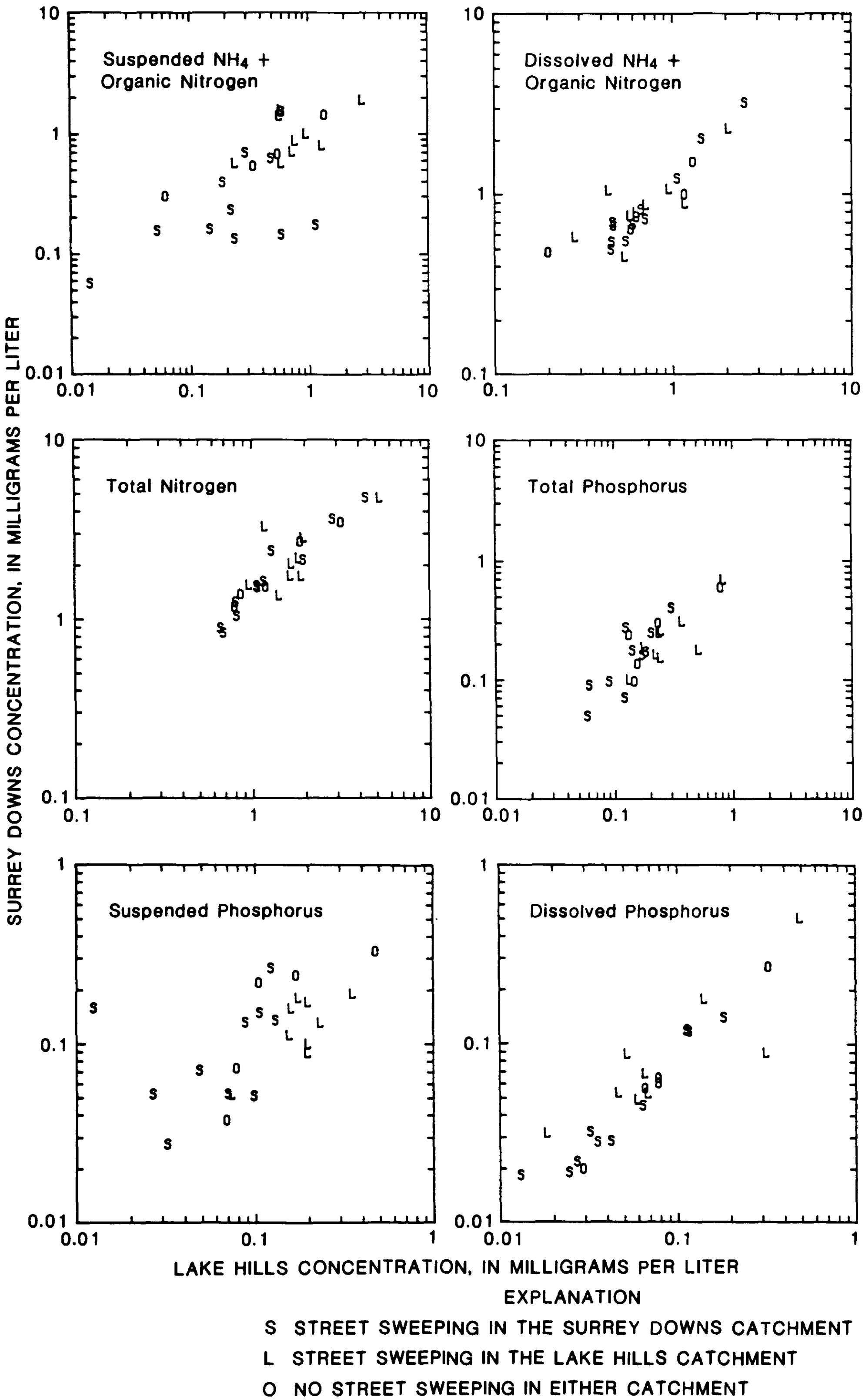


FIGURE 8.--Continued

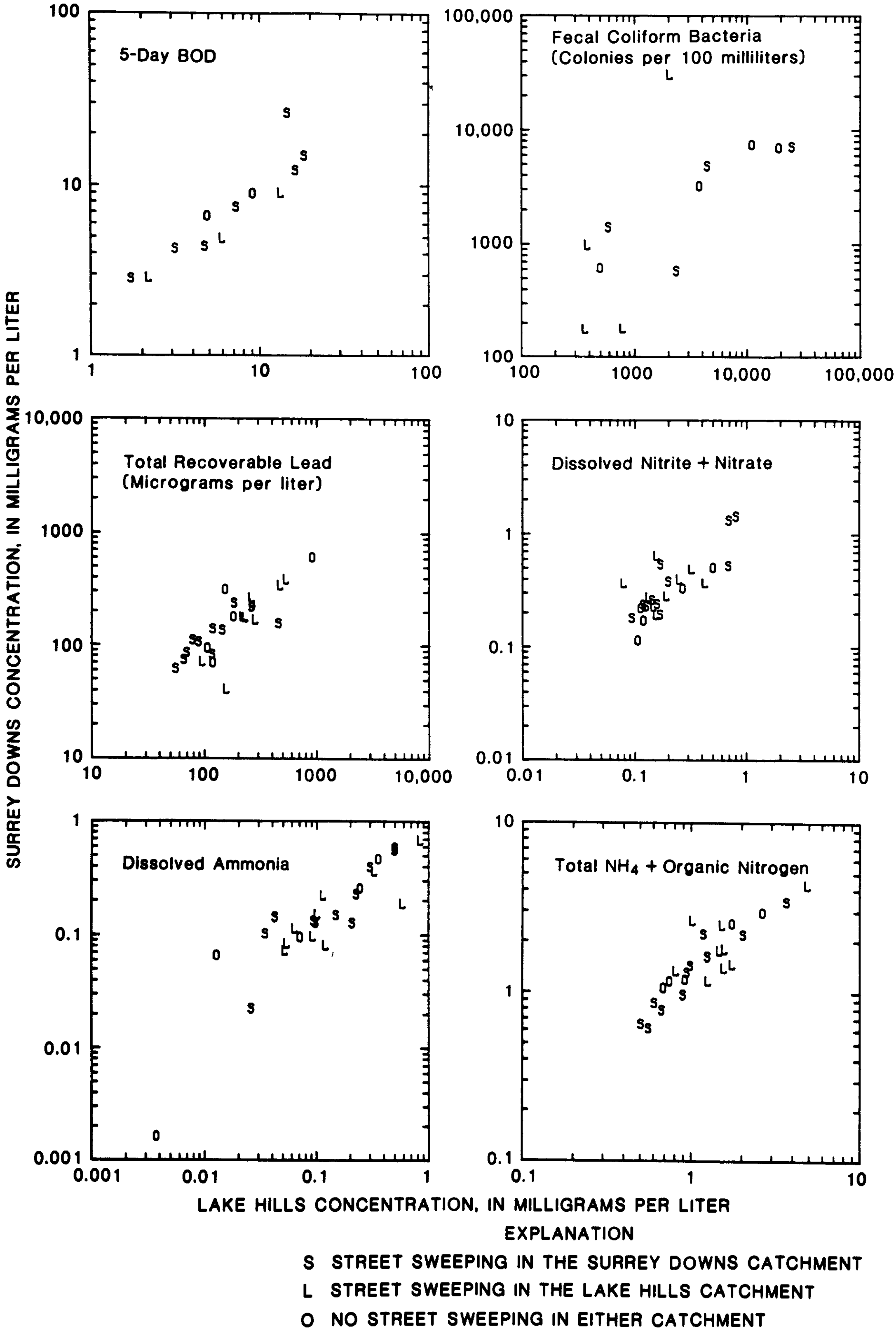


FIGURE 8.--Continued

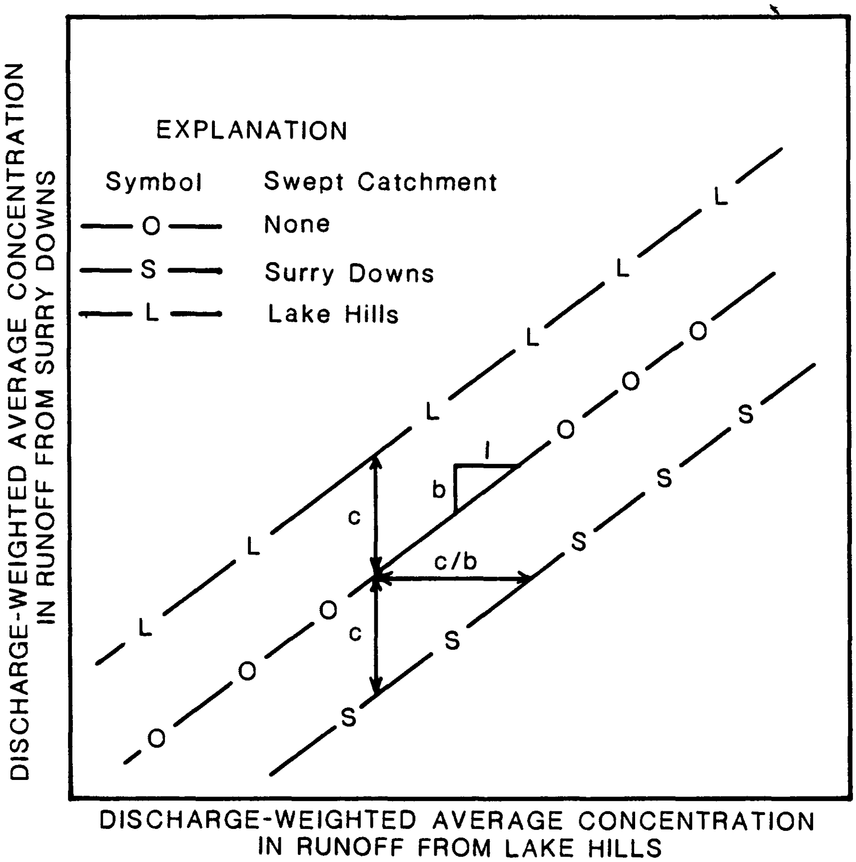


FIGURE 9.--Hypothetical comparison of discharge-weighted average concentrations in runoff from two catchments, showing effects of street sweeping.

In the analysis, linear regression was used to relate load per unit area and average concentration in one catchment as a function of the same quantity in the other catchment and a qualitative dummy variable that is a function of street sweeping. The regression equation chosen was

$$\log_{10} X_S = a + b \log_{10} X_L + cD, \quad (1)$$

which can be rewritten as

$$X_S = 10^a X_L{}^b 10^{Dc} \quad . \quad (2)$$

The variable X_S is the load per unit area or average concentration in Surrey Downs; X_L is the corresponding variable for Lake Hills, and a, b, and c are regression coefficients selected to minimize the mean square of the difference between the logarithms of the observed value of X_S and those obtained with equation 1. The variable D is a dummy variable that is a function of street sweeping.

If street sweeping has a similar effect on runoff water quality in both catchments, a logical choice of values for D is:

D = -1 when Surrey Downs is swept,
= 1 when Lake Hills is swept, and
= 0 when neither catchment is swept.

In addition to providing estimates of the values of each of the coefficients above, the regression analysis also provided estimates of the confidence with which one can reject the null hypothesis that any of the coefficients are zero. (The confidence is determined using a two-tailed Student's t test.) The confidence for c, expressed in percent, can be interpreted as the probability that there is a difference in runoff water quality from swept and unswept catchments. The magnitude of c is also a measure of the difference in water quality between swept and unswept periods. Although the exact meaning of c is complex, the quantity 10^{-c} can be interpreted loosely as the ratio between loads or average concentrations for a catchment when it is swept and when it is unswept. The following paragraph explains why this interpretation can be used.

Note that when neither catchment is swept (D = 0) the terminal multiplier on the right-hand side of equation 2, 10^{cD}, is unity; when Surrey Downs is swept (D = -1) the multiplier is 10^{-c}. Therefore, in some cases 10^{-c} is the ratio of loads or average concentrations for Surrey Downs, X_S, between swept and unswept periods. When Lake Hills is swept (D = 1) the multiplier is 10^{c}, the reciprocal of 10^{-c}. Therefore, in other cases 10^{-c} is the ratio of loads or average concentrations raised to the power b for Lake Hills, X_L, between swept and unswept periods. When b is unity, 10^{-c} has the same interpretation for both catchments. Because the value of c is computed in a regression analysis that uses data collected both when Surrey Downs is swept and when Lake Hills is swept, the true physical interpretation of the multiplier 10^{-c} must be as some sort of average of the above described ratios for the two catchments.

It would have been possible to use two dummy variables in equation 1, one associated with street sweeping in each catchment, to obtain separate coefficients, and hence, probabilities and ratios for Lake Hills and Surrey Downs. However, because of the relatively large amount of scatter of the data in figure 8, the reliability with which one can evaluate regression coefficients is small and decreases with the number of coefficients that are determined. Therefore, in addition to a and b, only one coefficient, c, whose interpretation is not rigorous, was determined with as much reliability as possible, rather than two coefficients whose physical interpretations are rigorous, with less reliability.

In order for equation 1 to be valid for use in detecting the influence of street sweeping on runoff quality, certain implied assumptions must be justified. One is that the relations between logarithms of loads or average concentrations are linear. Inspection of figure 8 and similar graphs for loads (not shown) indicates that the data justify this assumption. Another is that street sweeping must have the same qualitative effect for both catchments (that is, either improve or degrade water quality). The fact that street sweeping had similar effects on street dirt in both Lake Hills and Surrey Downs (tables 11 to 14) suggests that this requirement was satisfied. Another implied assumption is that variations in differences in runoff quality between the two catchments caused by other factors, such as constituent concentrations in rainfall and runoff loads from pervious surfaces, must either be removed from the data or be small relative to the effects of street sweeping. The analysis of wet-atmospheric deposition (table 4) showed little difference between constituent concentrations in rainfall at the two sites. Results of numerical modeling of runoff showed that the amount of runoff from pervious surfaces was usually small; however, nothing is known about the quality of this runoff.

Results of Analyses

The data in table 30 show that for most constituents street sweeping had little effect on either loads or average concentrations. The approximate geometric mean ratios differ from unity by less than 15 percent for most constituents, and the probabilities that the loads or average concentrations are affected by street sweeping exceed 75 percent for only a few constituents. For the three constituents for which the probabilities associated with loads exceeded 75 percent, the ratios are less than unity, indicating that water quality is improved during periods of street sweeping. However, of the four constituents for which the probabilities associated with average concentrations exceeded 75 percent, only two indicate improved water quality during periods of sweeping. For the other two the ratios are greater than unity, indicating poorer water quality during periods of sweeping than during periods of not sweeping.

For suspended solids and dissolved solids, the two constituents for which the data are most numerous in terms of both number of storms and number of discrete-sample analyses per storm, the data reveal no significant difference in water quality as a result of street sweeping.

The result that street sweeping had little effect on suspended solids was unexpected because street sweeping was found to decrease the amount of dirt on the streets. A probable reason for this result is that a large fraction of the suspended solids in runoff was silt and clay (sizes less than 63 um), which was the size class least affected by sweeping (see tables 12 and 13). Table 31 shows the size distribution of suspended sediment in the discrete samples for which size distributions were determined. The data show that in many of the samples more than half the material was silt and clay. Concentrations of some constituents in street dirt (table 9) are highest in material of these size classes.

TABLE 31.--Size distributions of suspended sediment in outflow from three urban catchments in Bellevue, Washington

Catchment	Date	Time	Discharge (ft^3/s)	Suspended sediment concentrations (mg/L)	Suspended sediment sieve diameter, percent finer than: 1 mm	0.5 mm	0.25 mm	0.125 mm	0.062 mm
Lake Hills	Mar. 12, 1980	1505	0.41	40	100	100	92	85	75
	Feb. 19, 1981	0310	11	1,080	98	88	76	66	58
148th Ave. SE	Mar. 12, 1980	2005	.10	--	100	99	99	98	96
	July 6, 1981	2015	.51	101	--	--	--	--	99
	July 7, 1981	0110	1.8	91	--	--	--	--	79
Surrey Downs	Oct. 24, 1979	1055	.80	--	--	--	--	--	9
	Feb. 19, 1981	0250	1.8	--	--	--	--	--	63
	Feb. 19, 1981	0310	5.3	--	100	97	89	70	33

Effects of Detention

One of the five detention basins in the 148th Avenue SE storm sewer system was used in an investigation of the effects of detention on storm-water quality. A general description of the detention system is given in the introduction of this report and details, including sketches, are given in the data report (Ebbert, Poole, and Payne, 1985).

The system was operated in two modes, no detention and detention in basin No. 5, the farthest downstream. During the phase of the study when no water was detained, runoff was sampled at the catchment outlet. During detention, runoff was sampled at the catchment outlet and at the inlet and outlet of detention basin No. 5.

Method of Analysis

To determine the effects of detention on storm-runoff quality, Student's t tests on paired logarithms of data were used to compare discharge-weighted constituent concentrations in runoff for individual storms collected at the inlet to the detention basin with concentrations at the outlet (fig. 10).

Initial consideration was given to using data collected at the catchment outlet to test for effects of detention on storm-runoff quality. This was not done, however, because of the presence of additional uncontrolled variables. On September 1, 1981, the drainage from Robinswood Park was connected to the 148th Avenue SE storm sewer system, which was not anticipated when the project was planned. A second difficulty in using data collected at the catchment outlet to test for effects of detention was the inability to separate the effects of seasonal variability from the data.

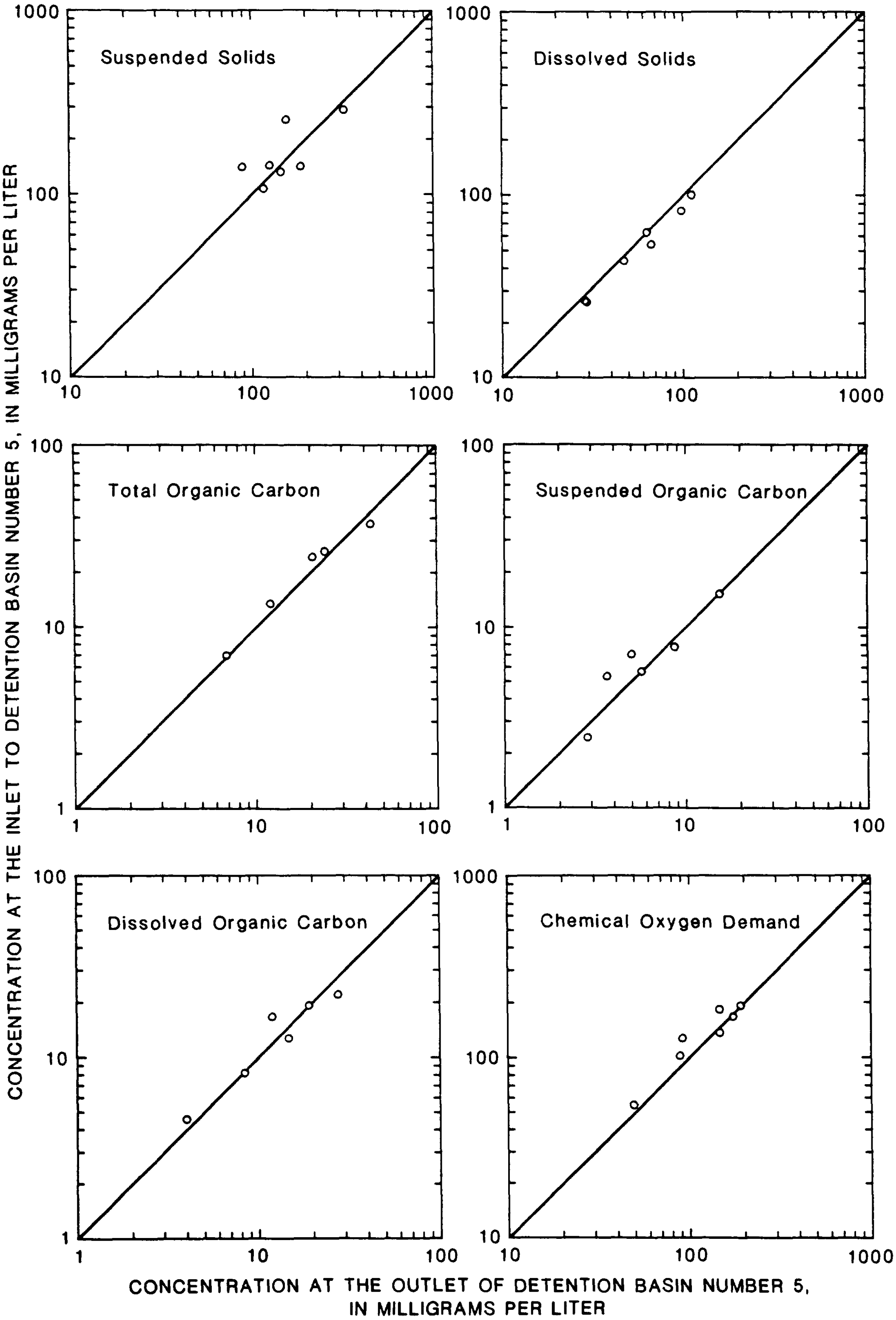


FIGURE 10.--Discharge-weighted average constituent concentrations computed for individual storms in runoff at the inlet to detention basin No. 5 plotted against those at the outlet.

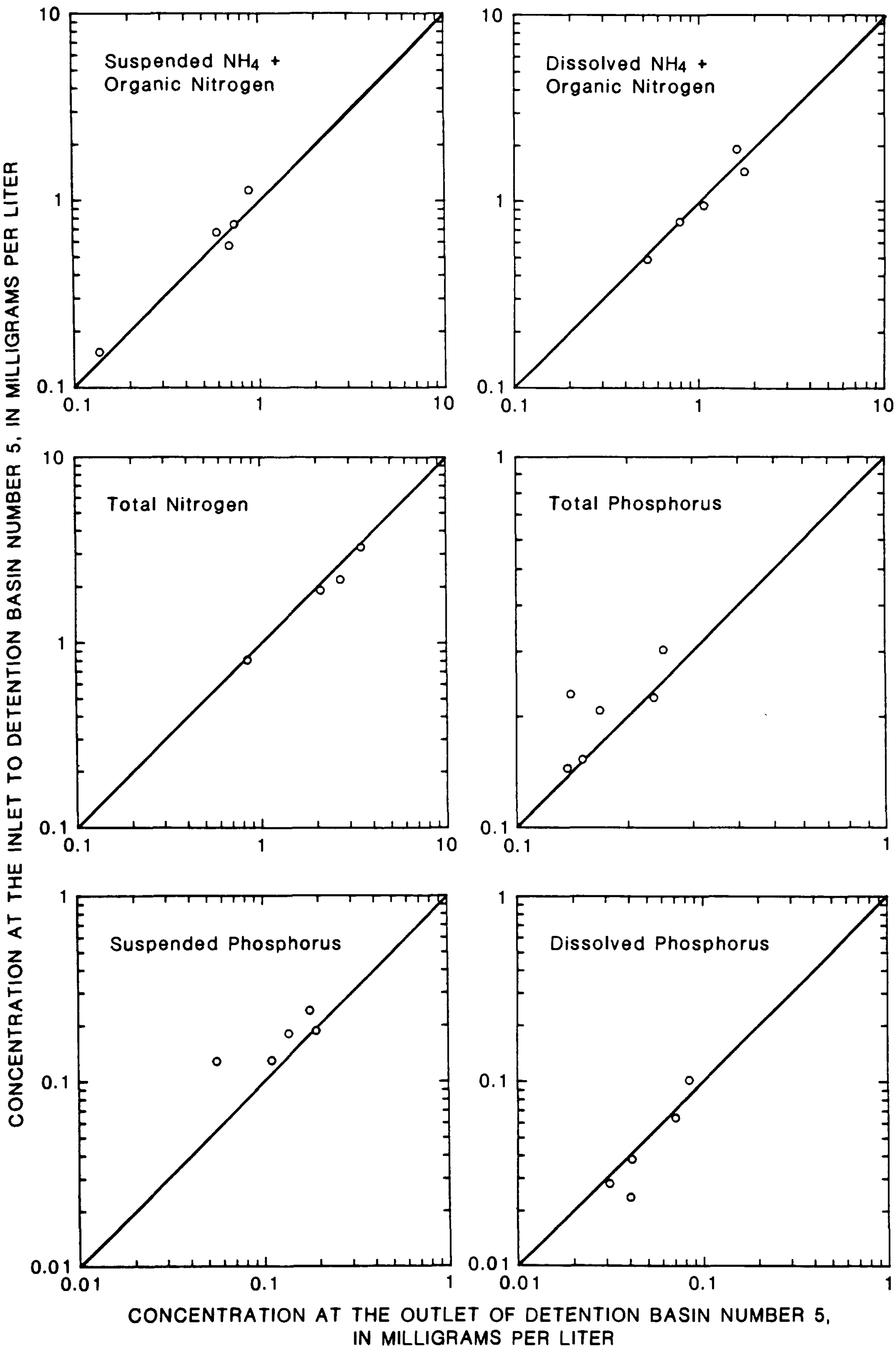


FIGURE 10.--Continued

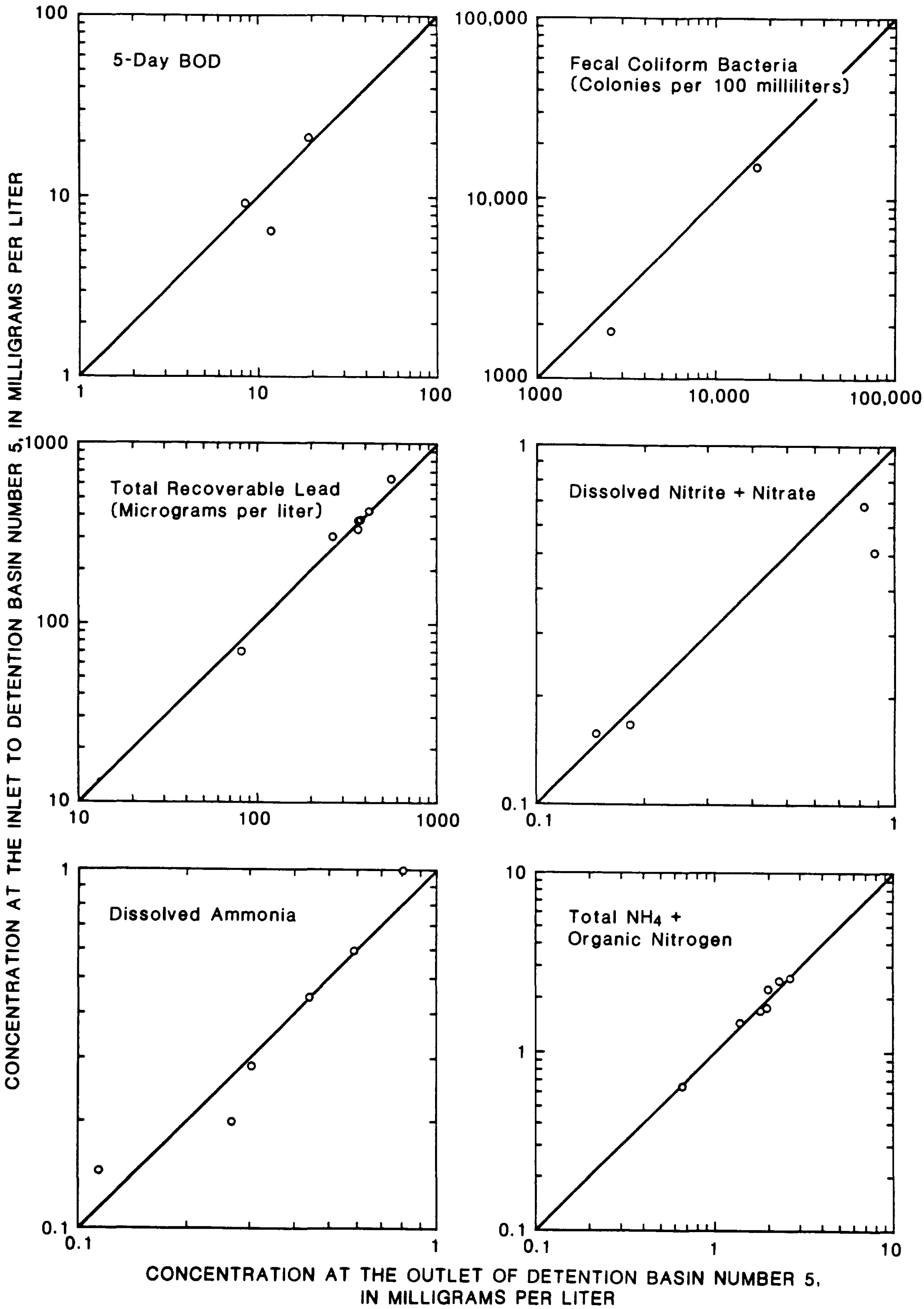


FIGURE 10.--Continued

Results of Analyses

The geometric means of the ratios of discharge-weighted average concentrations at the outlet of the detention basin to the concentrations at the inlet and the probabilities that the average concentrations at the inlet and outlet are different are listed in table 32. The ratios indicate that concentrations of most dissolved constituents are slightly higher in runoff sampled at the outlet of the detention system. The significance of the differences between outflow and inflow concentrations, as indicated by the probabilities, varies. There is a greater than 99-percent probability that average dissolved-solids concentrations at the outlet of the detention basin are different from those at the inlet. The geometric mean ratio (outflow/inflow) of average dissolved-solids concentrations is 1.11, indicating that the increase in concentration is small. Other dissolved constituents showing an increase in average concentrations include nitrite plus nitrate, ammonia plus organic nitrogen, and phosphorus. Of these, only for dissolved nitrite plus nitrate is the associated probability greater than 75 percent. Dissolved organic carbon and dissolved ammonia show slight but insignificant decreases in concentration.

TABLE 32.--Probabilities that average constituent concentrations in the outflow of detention basin No. 5 in the 148th Avenue SE catchment are different than those in the inflow, and geometric mean ratios (outflow/inflow) of the average concentrations. The probabilities were computed using two-tailed Student's t-tests on paired data

Constituent	Probability (pct)	Ratio	Number of storms
Suspended solids	46	0.93	7
Dissolved solids	99	1.11	7
Total organic carbon	60	.95	5
Suspended organic carbon	53	.93	6
Dissolved organic carbon	13	.99	6
Chemical oxygen demand	86	.91	7
5-day biochemical oxygen demand	40	1.15	3
Fecal-coliform bacteria	73	1.27	2
Total recoverable lead	13	.99	7
Dissolved nitrate plus nitrite	76	1.21	4
Dissolved ammonia	14	.98	6
Total ammonia plus organic nitrogen	11	1.00	7
Suspended ammonia plus organic nitrogen	60	.93	5
Dissolved ammonia plus organic nitrogen	51	1.05	5
Total nitrogen	93	1.10	4
Total phosphorus	89	.86	6
Suspended phosphorus	90	.74	5
Dissolved phosphorus	66	1.13	5

Geometric mean ratios for all suspended constituents indicate that average concentrations of these constituents were lower in the outflow from the detention basin than in the inflow. However, only for suspended phosphorus was the probability greater than 75 percent that inflow and outflow concentrations were different. The probability associated with concentrations of suspended solids, a constituent measured with a higher frequency per storm than other suspended constituents, was only 46 percent.

The effect of detention on average concentrations of total constituents seems to depend on the distribution of the constituent between the suspended and dissolved phases. Total organic carbon showed a slight but insignificant decrease in concentration, as did both suspended and dissolved organic carbon. Consistent with organic carbon, chemical-oxygen-demand concentrations in outflow were lower than those in the inflow. However, the probability that inflow and outflow concentrations of chemical oxygen demand were different is much higher than the corresponding probabilities for organic carbon. Total recoverable lead concentrations were nearly unchanged, a result consistent with that for suspended solids. Average total nitrogen concentrations were higher in the outflow, consistent with the increase in dissolved nitrite plus nitrate concentrations, which make up 70 percent of the total nitrogen in the runoff (median value, table 27).

Average concentrations of total phosphorus were lower in the outflow, consistent with suspended phosphorus concentrations composing 72 percent of the total phosphorus load (median value, table 27). Total ammonia plus organic concentrations were not affected by detention. This may represent the opposite effects upon the dissolved and suspended phases.

General Observations

Results of the statistical tests showed that the detention system did not significantly reduce average concentrations of most suspended constituents in storm runoff. This conclusion was confirmed in part by visual inspections of the detention system as described below.

The volume of the storm sewer behind the weir used to control flow below detention basin No. 5 was adequate to store runoff detained during about 70 percent of the storms that occurred during the detention phase of the study. For the other 30 percent of the storms, the volume of the sewer was insufficient to store all the detained water and some was backed up into the grassy depression that provided additional storage volume. Inspection of the grassy depression after a storm when water was stored in it showed only a trace of residual fine material on the blades of grass. Over the entire detention phase of the study, about 20 storms had runoff volumes large enough to cause storage of runoff in the grassy swale.

Visual inspection of the storm sewer above the weir showed that during the phase of the study when runoff was detained, there was a slow, continual accumulation of sediment during the summer months. Autumn storms, which are often more intense and of longer duration than summer storms, removed much of the deposited sediment, and by October 5, 1981, approximately one-half of the deposited sediment was scoured from the storm sewer above the weir. Resuspension of deposited sediment was observed by project personnel during the filling and emptying of the storm sewer at the beginnings and ends of storms, respectively, when the water depths in the sewer were lowest and the water velocities were highest. This effect is shown by increased suspended-sediment concentrations at the beginning and ends of storms (fig. 11).

Another factor limiting the effectiveness of the detention system in removing suspended material was the flow pattern when the surface elevation of the detained water reached or exceeded the elevation of the top of the weir. When this occurred, the detention time was approximately 30 minutes or less. This was sufficient time for settling of sand and some coarse silt; however, much of the finer material was probably transported directly through the detention system. Available data (table 31) indicate that most of the suspended sediment in storm runoff from 148th Avenue SE was finer than 62 um.

At the end of the study a rough approximation was made of the amount of sediment trapped by the detention system. This amount was less than one-tenth the total amount estimated to have been transported through the detention system. Clearly, all estimates of the effectiveness of the system in removing suspended material agree with the statistical results.

The effectiveness of the detention system in removing suspended material could have been improved by periodic removal of deposited sediment. The removal of deposited sediment at the end of the summer would have prevented the resuspension and transport of sediment that had been deposited over the spring and summer months.

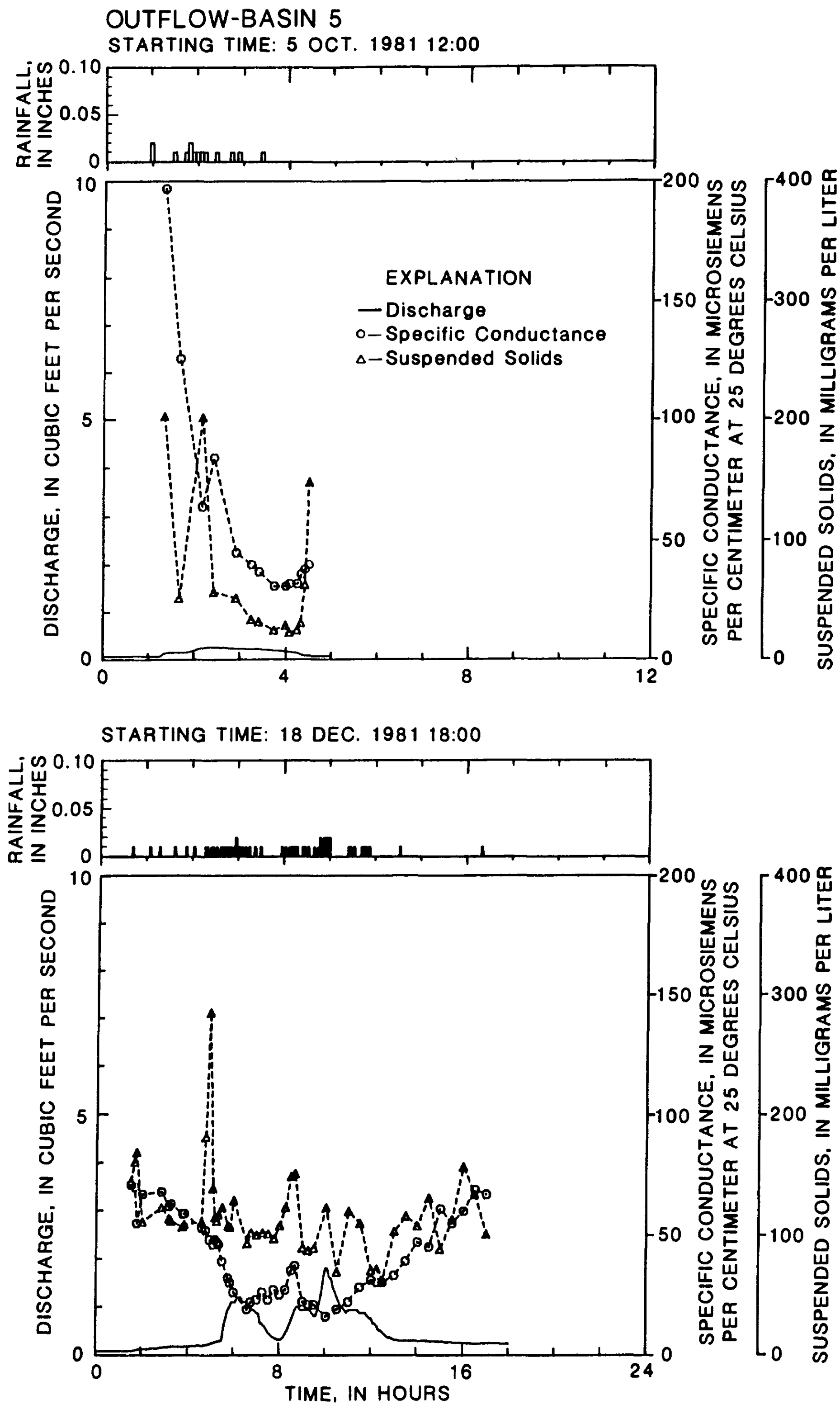


FIGURE 11.--Rainfall, discharge, and concomitant specific-conductance values and suspended-solids concentrations in runoff sampled at the outlet of detention basin No. 5. (From Ebbert, Poole, and Payne, 1985.)

Variations of Concentrations During Storms

This section discusses temporal variations of constituent concentrations observed during storms and relates the concentrations to runoff discharge. Although a numerical model for simulating runoff quality was not used in this study, the concepts and an equation that form the basis for many of the models were used as a basis for analyzing the data. In this way the applicability of the equations used in the models for simulating the temporal variations of concentrations during storms is also evaluated.

Examples of Data

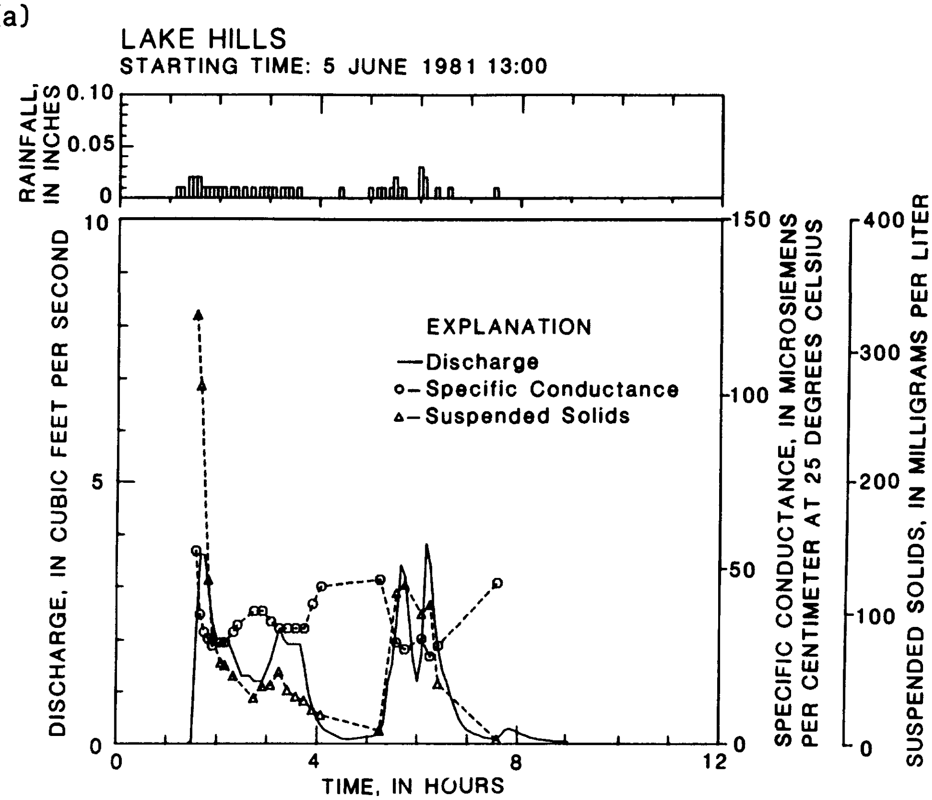
Figures 12a and 13a show temporal variations of suspended-solids concentrations and dissolved-solids concentrations (as shown by specific-conductance values) at Lake Hills during two storms with multiple discharge peaks. Data from these and other storms suggest that many of the constituent concentrations were functions of discharge. At times of high discharge, concentrations of suspended constituents usually were large and concentrations of dissolved constituents usually were small.

Figures 12b and 13b show suspended-solids concentrations and specific-conductance values plotted as functions of discharge for the two storms. The scatter of the data about the regression lines indicates that concentrations, especially of suspended solids, are also functions of other variables.

Initial suspended-solids concentrations during the first discharge peak of the June 5, 1981, storm (fig. 12a) were considerably larger than during the peak near the end of the storm, even though the magnitude of the discharges was nearly the same. These large initial suspended-solids concentrations usually deviate from any relation between discharge and concentration defined by data from the rest of a storm. The large suspended-solids concentrations observed near the beginning of this and some of the other storms may have been part of what has been referred to as a first flush--defined as "the condition, often occurring, in which a disproportionately high pollution load is carried in the first portion of urban runoff" (Alley, 1977, p. 107). However, for most storms sampled during this study the lengths of the apparent first flushes were of short duration and the loads during these parts of the storms were not large parts of the total storm loads.

The first flush phenomenon is not evident in the data for the January 15, 1982, storm (fig. 13a) either because it did not occur or because it was over before the first sample was taken. These data also show that suspended-solids concentrations were about the same near the times of the first and third discharge peaks, which were about the same magnitude. However, the concentrations near the time of the second peak were less than either the first or third peaks even though the magnitude of the second discharge peak was higher than either of the other two. This phenomenon, observed in data for other storms, indicates that the relation between discharge and concentration is not a simple one.

(a)



(b)

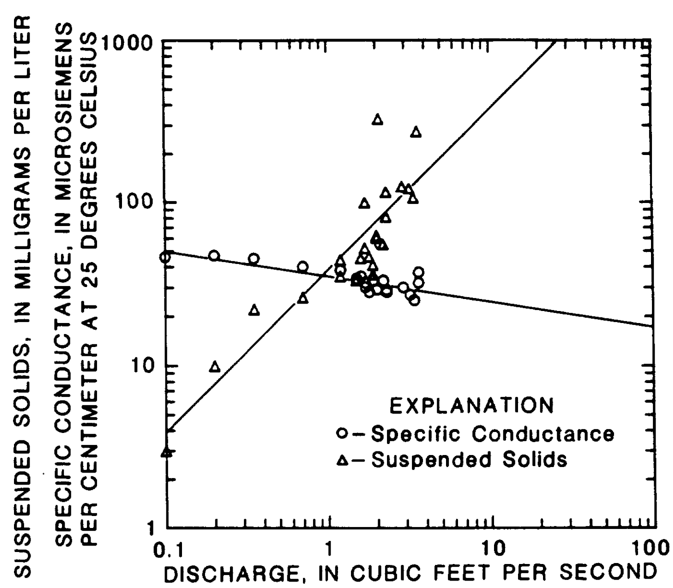


FIGURE 12.--(a) rainfall, runoff, and concomitant specific-conductance values and suspended-solids concentrations; and (b) specific-conductance values and suspended-solids concentrations as function of discharge for the June 5, 1981, storm at Lake Hills. The lines on (b) represent linear regression equations fit to logarithms of the data, R-square values are 0.44 for specific conductance and 0.78 for suspended solids.

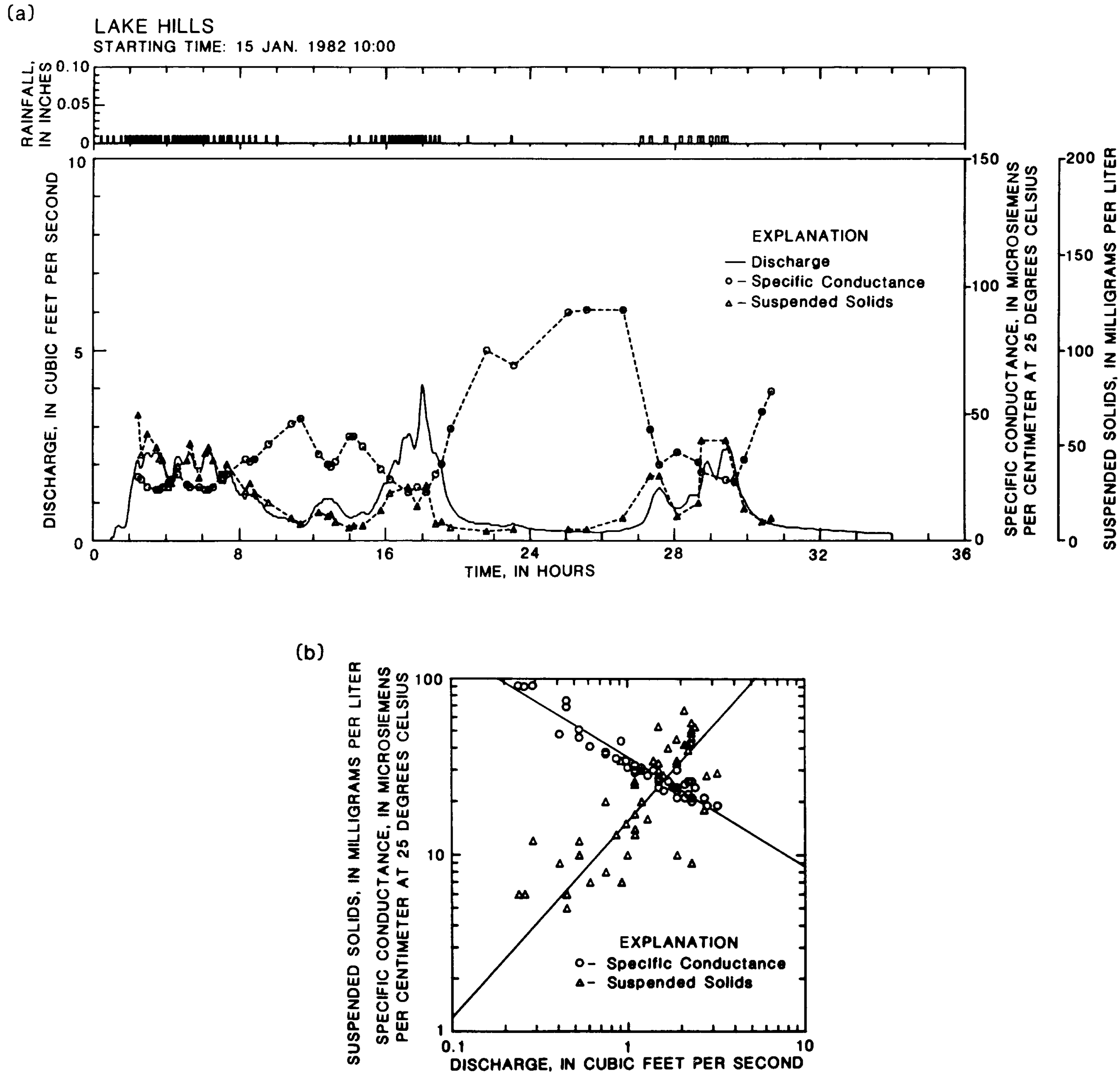


FIGURE 13.--(a) rainfall, runoff, and concomitant specific-conductance values and suspended-solids concentrations; and (b) specific-conductance values and suspended-solids concentrations as function of discharge for the January 15, 1982, storm at Lake Hills. The lines on (b) represent linear regression equations fit to logarithms of the data, R-square values are 0.93 for specific conductance and 0.60 for suspended solids.

Regression Analyses

In order to evaluate quantitatively how concentrations of suspended solids and dissolved solids are related to discharge, logarithms of suspended-solids concentrations and specific-conductance values were regressed against logarithms of discharge for each storm in which there were five or more data points. The regression equation used was

$$\log_{10} C = A + B \log_{10} Q \quad , \tag{3}$$

where C is concentration, Q is discharge, and A and B are regression coefficients. The results are summarized in table 33, which gives maximum, minimum, and median values of B, the slope of the regression lines, and r-square values. A positive value of B signifies that a concentration tends to be high at times of high discharge, and a negative value of B signifies the opposite.

The statistics in table 33 confirm that suspended-solids concentrations tended to be high at times of high discharge for all storms at each site. Median r-square values indicate that about half the variation of suspended-solids concentrations in Lake Hills and in Surrey Downs can be accounted for by variations in discharge. However, discharge accounts for only about one-fifth of the variation at 148th Avenue SE. Median values of B for dissolved-solids concentrations indicate that these concentrations tended to be low at times of high discharge at all sites, although the minimum values of B indicate that this was not the case for all storms. Median r-square values for dissolved solids were about the same as for suspended solids at Lake Hills, were higher at 148th Avenue SE, but were lower at Surrey Downs.

TABLE 33.--Maximum, minimum, and median values of the regression coefficient B, and of r-square for regressions of the form $\log_{10}$ (concentration) = A + B $\log_{10}$ (discharge) performed separately on data from individual storms. Regressions performed only on storms with five or more data points

Catchment	Suspended solids							Dissolved solids[1]						
	B			R-square			Number of storms	B			R-square			Number of storms
	Maximum	Minimum	Median	Maximum	Minimum	Median		Maximum	Minimum	Median	Maximum	Minimum	Median	
Lake Hills	1.7	0.01	0.65	0.93	<0.01	0.45	25	-0.62	0.21	-0.31	0.96	0.06	0.48	27
148th Avenue SE[2]	.45	.01	.19	.62	<.01	.13	5	-.62	.13	-.12	.80	.02	.26	6
Surrey Downs	2.01	.15	.87	.94	.01	.60	24	-1.03	.21	-.22	.91	.01	.38	26

[1]Regressions were preformed on specific conductance values.

[2]Regression analyses only on data from storms during period without detention.

Regressions were also performed on data sets created by combining all data from nearly all storms in a catchment. The regressions were done on logarithms of concentrations of all constituents, not just suspended and dissolved solids.

Prior to performing the analyses the data were modified by changing any concentrations that were reported as zero to values equal to one-half of the analytical detection limit. Also, a small percentage of the data were reported as greater than or less than the laboratory's detection limit; for these data the detection limits were used in the regression analyses.

Because concentration in runoff of matter originating on the surfaces of the catchment is of primary concern, it would be desirable to correct the concentrations used in the analyses by subtracting from them the concentrations in the rainfall. This was not done for two reasons. One is that the wet-atmospheric deposition samples were usually collected over a period of about 1 month, with very few samples of rainfall for individual storms. The other is that no information was available on the variations of constituent concentrations in rainfall during storms.

Table 34 summarizes the results of the analyses by giving, for each constituent, the value of B, which is the slope of the regression line and is a measure of how rapidly concentrations change with changing discharge. The table also gives the probability that B equals zero, and the r-square value for the regression. Without exception the values of B show that concentrations of suspended constituents tended to be high and concentrations of dissolved constituents tended to be low at times of high discharge. Values of B for total constituents were mixed, and the distribution of the constituent between the dissolved and suspended phase most likely determined the sign of B, as in the case of total lead, where B is positive and most lead is in the suspended phase.

For most constituents the probability that B is not zero is high, often 99 percent or greater, indicating a statistically significant relation between discharge and concentration. However, with the exception of suspended and dissolved solids, dissolved nitrite plus nitrate, and dissolved ammonia plus organic nitrogen, for most constituents the r-square values for the regressions were low, often less than 0.1. Consequently, most of the regression equations are not of much use for predicting concentrations from discharge. However, the fact that statistically significant relations exist is useful information and is used in the following section in a discussion of an equation that is commonly employed in existing numerical models for simulating runoff water quality.

TABLE 34.--Values of the regression coefficient B, values of r-square, and probabilities that B is not zero for regressions of the form $\log_{10}$ (concentration) = A + B $\log_{10}$ (discharge), performed separately for each catchment on data sets formed by combining data from all storms

	Catchment											
	Lake Hills				148th Avenue SE[1]				Surrey Downs			
	B	R-square	Proba- bility (pct)	Number of obser- vations	B	R-square	Proba- bility (pct)	Number of obser- vations	B	R-square	Proba- ability (pct)	Number of obser- vations
Suspended solids	0.51	0.35	>99	447	0.20	0.06	99	104	0.63	0.30	>99	386
Dissolved solids[2]	-.35	.49	>99	491	-.51	.41	99	113	-.38	.45	>99	415
pH[3]	-.12	.06	>99	406	-.22	.06	99	99	-.16	.06	>99	358
Total organic carbon	-.13	.07	>99	227	-.20	.13	99	55	-.07	.01	84	212
Suspended organic carbon	.33	.21	>99	228	.04	.01	42	55	.46	.22	>99	213
Dissolved organic carbon	-.27	.20	>99	253	-.30	.19	>99	56	-.23	.09	>99	226
Chemical oxygen demand	.03	<.01	58	252	-.13	.04	83	55	.12	.03	99	229
5-day BOD	-.37	.17	>99	114	-.41	.24	>99	43	-.24	.07	99	97
Fecal-coliform bacteria	-.07	<.01	37	107	-.05	<.01	21	39	.24	.02	85	112
Total lead	.24	.09	>99	254	.07	.01	41	56	.44	.21	>99	230
Dissolved nitrite plus nitrate	-.36	.18	>99	258	-.44	.28	>99	56	-.51	.39	>99	230
Dissolved ammonia	-.01	<.01	13	257	-.36	.17	>99	56	-.19	.02	96	229
Total ammonia plus organic nitrogen	.01	<.01	27	254	-.05	.02	69	56	.07	.01	92	230
Suspended ammonia plus organic nitrogen[4]	.24	.06	>99	252	.23	.06	93	55	.50	.18	>99	228
Dissolved ammonia plus organic nitrogen	-.12	.04	>99	255	-.27	.27	>99	55	-.14	.37	>99	229
Total nitrogen[5]	-.05	.01	85	254	-.11	.07	95	56	-.08	.02	95	229
Total phosphorus	.14	.04	>99	252	-.01	<.01	7	56	.13	.03	98	222
Suspended phosphorus[4]	.33	.13	>99	249	.13	.02	63	56	.23	.04	>99	220
Dissolved phosphorus	-.06	.01	79	254	-.10	.04	85	56	-.06	<.01	64	228

[1]Regression analyses only on data from storms during period without detention.
[2]Regression was done using specific conductance values.
[3]Regressions were on pH, not logarithms of pH.
[4]Concentrations computed as difference between total and dissolved concentrations.
[5]Sum of dissolved nitrite plus nitrate and total ammonia plus organic nitrogen

Modeling Concepts and Interpretation of Regressions

The values of B found in the above regressions and the values of r-square can be interpreted in the context of concepts and equations that are incorporated in numerical models that are used to simulate runoff water quality. The concept upon which many of the numerical models are based is that the rate at which a constituent is removed from a catchment is directly proportional to the mass of the constituent, L, on the catchment area, and the runoff discharge, Q (see, for example, Alley and Smith, 1982b). The process is described by the equation

$$\frac{dL}{dt} = -K_3 \, L \, Q \, F, \qquad (4)$$

where t is time; K_3 is a constant of proportionality called a washoff coefficient, and F is an availability factor that takes into account the fact that some fractions of a constituent are more easily washed off the surfaces of a catchment than other fractions. In a number of existing models F is assumed to be zero when Q is zero and to increase linearly with Q up to a maximum value of 1 at some specified value of Q. It is usually acknowledged that equation 4 is probably only applicable to constituents in suspended form on effective impervious surfaces. The concentrations, C, of constituents in runoff are obtained by dividing equation 4 by -Q to give

$$C = -\frac{dL}{dt}/Q = K_3 \, L \, F \quad . \qquad (5)$$

Without the inclusion of the availability factor in the above equations, the computed concentration C would decrease continuously during a storm because L must decrease with time.

The variations of suspended-solids concentrations with discharge during the multi-peaked storms shown in figure 12a and 13a demonstrate the necessity of including the factor F in the equations. However, the necessity of an availability factor might not be evident in a graph of data from a storm with a single discharge peak near the beginning of the storm.

Data from this type of storm, especially if the first sample is taken near the time of peak discharge, would show that concentrations of suspended constituents usually do decrease continuously with time during the storm because the discharge does also. Unfortunately, the inclusion of an availability factor in a model is not sufficient to simulate a first flush, nor will it simulate high suspended-solids concentrations late in a storm and low concentrations early in a storm if discharges are the same at both times, as was observed during the storm of January 15, 1982 (fig. 13a).

In order to put equation 5 into a form useful for interpreting the results of the regression analyses, two assumptions are made. One is that the availability factor can be approximated by the relation

$$F = H\,Q^{B} \quad , \tag{6}$$

where H and B are coefficients that may be different for each constituent. (The symbol B, which is a coefficient in equation 3 was intentionally used as an exponent in equation 6 for reasons that will be apparent.) The other assumption is that variations in L are small during a period for which the equation will be used, and therefore L in equation 5 can be replaced by some average value. With these assumptions equation 5 can be rewritten as

$$C = 10^{A}\,Q^{B} \tag{7a}$$

or

$$\log_{10} C = A + B \log_{10} Q \quad , \tag{7b}$$

where 10^{A} is a coefficient equal to the product of K_3, an average value of L, and H.

Equation 7b is the same as equation 3; consequently, the slope of the regression line B is the exponent in the assumed expression for the availability factor. When B is positive but less than one, as was the case for all suspended constituents (tables 33 and 34), the rate of change of F with Q decreases with increasing Q. Therefore, the variation of F with Q is similar to that used by Alley and Smith (1982b). Figure 14 compares, in a qualitative way, the form of the two functions.

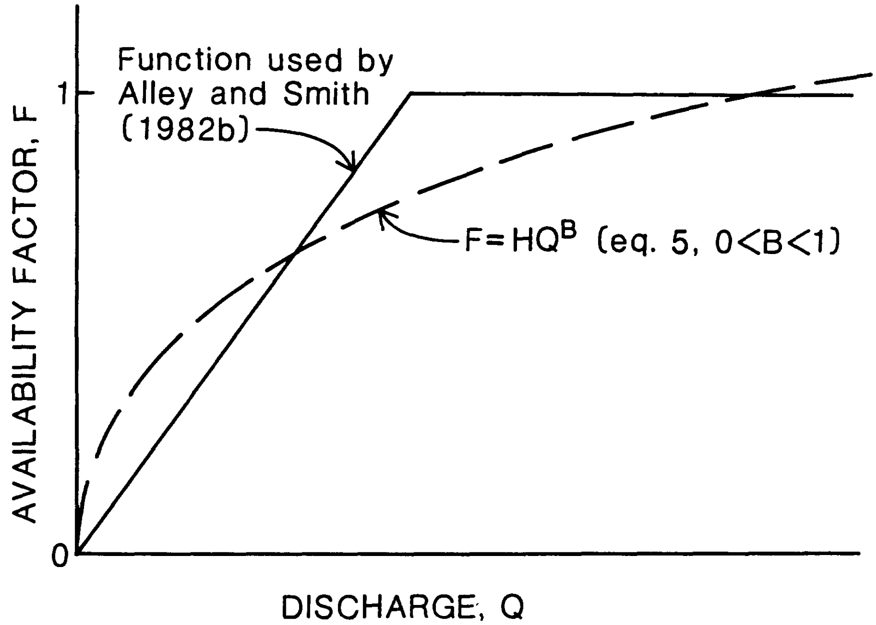


FIGURE 14.--Qualitative comparison of variations of availability factor with discharge as used by Alley and Smith (1982b) and equation 5.

An important assumption that was made in obtaining equation 7 was that the variation of L is small during the period for which the equation is used. This assumption is probably more nearly satisfied for the regressions done on data from individual storms (table 33) than those done on data from all storms combined (table 34). This may partly explain why the median values of r-square for suspended solids in table 33 are larger than the values in table 34. The same is not true of r-square values for dissolved solids, probably because equations 4 through 6 were not intended to apply to dissolved constituents. However, for lack of an alternative method, a numerical water-quality model possibly could be used to simulate dissolved constituents if an availability factor in the form of equation 6 with a negative value of B were used. This model would be based more on empirical relations than on physical processes. Judging from the values of r-square in tables 33 and 34, the simulated concentrations of dissolved constituents could be as good as those for suspended constituents.

SUMMARY AND CONCLUSIONS

Statistical analyses of loads and of discharge-weighted constituent concentrations in storm runoff from two similar residential areas (Surrey Downs and Lake Hills) showed that street sweeping had little effect on runoff water quality. Approximate geometric means of the ratios (swept/unswept) of loads or average concentrations differed from unity by less than 15 percent for most constituents. The number of constituents for which the ratios were larger than unity was nearly as large as the number of constituents for which the ratio was less than unity.

Although statistical analyses showed that runoff water quality was not significantly affected by street sweeping, two different statistical analyses of the street-dirt data collected by the City of Bellevue indicate that, on the average, amounts of street dirt on swept streets are less than on unswept streets, and that the difference decreases with decreasing particle size. The results of one analysis showed that for particle sizes less than 63 um there was more material on the swept streets than the unswept streets. The results of statistical analyses of chemical characteristics of street dirt vary; however, for most size classes and most constituents the concentrations in dirt from swept streets are on the average no higher than in dirt from unswept streets.

Comparison of discharge-weighted average concentrations of constituents in the inflow and outflow of the detention system in the 148th Avenue SE storm sewer for four to seven storms indicated that the detention system did not significantly alter the average concentrations in runoff. Typically, average concentrations of suspended constituents in the outflow were slightly lower than in the inflow, and average concentrations of dissolved constituents were slightly higher. Geometric mean ratios of average concentrations (outflow/inflow) were within 15 percent of unity for most constituents. Suspended-solids concentrations in discrete samples often increased towards the end of storms because of scouring of previously settled material in the detention system.

Analyses of wet-atmospheric deposition data showed little correlation between concentrations of different constituents in samples collected at a site. Concentrations of most constituents in wet-atmospheric deposition were similar at all sites. For most constituents the probability was less than 75 percent that concentrations in samples collected over the same period at different sites were different. Concentrations of various forms of nitrogen in rainfall were a significant source of nitrogen in storm runoff.

Analyses of dry-atmospheric deposition data showed that, for many constituents, probabilities were greater than 75 percent that concentrations in samples from different sites were different. Some of the site-to-site variability could be due to inadequacies in the sampling method and location of the collectors in the catchment rather than to differences in the average deposition in the study area. The poor efficiency of the dry-deposition collector was demonstrated in a statistical test showing that the mass of deposition did not correlate well with exposure time of the collector (r-square values were less than 0.25 for all sites).

Regression equations for estimating runoff volumes and peak discharge sites during individual storms were derived separately for each catchment using data from nearly all storms. The standard errors of estimates for these storms were 21 to 28 percent for runoff volume and 22 to 40 percent for peak discharge. The independent variables in the equation for volume are total rainfall and the amount of rainfall during the 3 days prior to the storm. For peak discharge the independent variables are maximum 15-minute rainfall rate and 3-day antecedent rainfall amount. Adding other variables did little to reduce the errors in any of the regression equations.

Runoff volumes simulated by calibrated deterministic numerical models of the catchments had standard errors of estimate of 25 to 34 percent for a verification period that was different from the calibration period. Similarly, standard errors of estimate for peak flows were 23 to 37 percent.

Concentrations of constituents in suspended form tend to be high and concentrations of constituents in dissolved form tend to be low when discharge is high; when discharge is low the reverse is true. These trends are confirmed by visual inspection of graphs of suspended-solids concentration and of specific-conductance values as functions of time during storms with multiple-peak discharges, by results of regressions analyses of suspended-solids concentrations and specific-conductance values in discrete samples from individual storms, and by regression analyses of concentrations of all constituents in discrete samples from all storms.

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