RUNOFF AND CHEMICAL LOADING IN SMALL WATERSHEDS IN THE TWIN CITIES METROPOLITAN AREA, MINNESOTA

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CONVERSION FACTORS

For readers who prefer to use metric units, conversion factors for terms used in this report are listed below:

Multiply	By	To obtain
foot (ft)	0.3048	meter (m)
inch (in)	25.40	millimeter (mm)
mile (mi)	1.609	kilometer (km)
square mile (mi^2)	2.590	square kilometer (km^2)
acre	0.4047	hectare (ha)
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)

RUNOFF AND CHEMICAL LOADING IN SMALL WATERSHEDS IN THE TWIN CITIES METROPOLITAN AREA, MINNESOTA

By M. A. Ayers[1], R. G. Brown[2], and G. L. Oberts[3]

ABSTRACT

Flow, rainfall, and water-quality data were collected during 1980 for 15 to 30 rainfall and snowmelt events on 6 rural and 11 urban watersheds in the Twin Cities Metropolitan Area. Event or daily flow and load models (for seven constituents) were developed and used with runoff and rainfall data for 1963-80 to compute 2-year frequency annual and seasonal flows and loads for each watershed.

In models of storm-sewered watersheds, total storm rainfall proved to be the most significant factor controlling runoff and loads. Depending on the watershed type, antecedent soil-moisture indices or rainfall intensity also were important factors in estimating runoff.

Annual runoff from storm-sewered watersheds averaged about 27 percent of annual precipitation, ranging from 13 to 57 percent. Runoff in urban main-stem streams ranged from 13 to 20 percent and was related to the percent of urbanization in the watershed. Annual runoff in rural watersheds ranged from 6 to 20 percent of annual precipitation.

The percentage storm-runoff response increased with increasing storm size for watersheds with storm sewers, more so for the steeper than the flat watersheds. Runoff responses ranged from 2 to 22 percent of rainfall for a 0.1-inch rain and from 14 to 52 percent for a 2-inch rain. As much as 75 percent of the runoff from a 2-inch rain was derived from pervious areas in the steeper, storm-sewered watersheds.

As a result of storm and seasonal differences in runoff response to rainfall, the seasonal distribution of runoff and loads for the rural watersheds did not follow seasonal rainfall patterns. Instead, runoff and loads were greatest in the snowmelt period and declined through the year in response to decreasing soil moisture and pervious-area runoff. Seasonal runoff and loads from urban watersheds more closely followed seasonal rainfall patterns with a maximum in the summer. Urban storm-sewered watersheds responded to virtually every rainfall event.

Based on 18 years of simulated record, the runoff and loads expected to be equaled or exceeded on a long-term average of every 2 years in each watershed were used in an attempt to generate regression models with basin characteristics. Unfortunately, all attempted groupings of sites yielded unreliable models.

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There is need for load-mitigating measures in the steeper, more urbanized watersheds of the metropolitan area. Wetlands and other low-intensity land uses were found to be important factors in controlling loading of urban and rural streams. Loads in rural streams were highly dependent upon factors affecting runoff. Therefore, practices that increase rainfall retention near the source or that reduce channel conveyance likely will reduce rural runoff and loads.

INTRODUCTION

Background

Studies throughout the United States indicate that materials carried in nonpoint-source runoff contribute significantly to water-quality degradation of streams (Federal Water Pollution Control Administration, 1969; Lager and Smith, 1974; Sliter, 1976; Bradford, 1977; Sonzogni and others, 1980). However, the amount of materials in runoff from individual basins differs considerably from area to area and from storm to storm within an area, indicating a need for local data (McElroy and others, 1976; Sonzogni and others, 1980).

In the Twin Cities Metropolitan Area, preliminary estimates of the average annual nonpoint-source loads of various constituents (in tons per year) have been made through a local PL92-500 section 208 study (Oberts and Jouseau, 1979). These estimates are based on literature values of constituent concentrations for various land-use categories and on estimates of discharge. The estimates indicate that annual loads of chemical oxygen demand, suspended solids, nitrate, lead, and zinc from nonpoint sources probably equal or exceed the annual point-source loads for metropolitan-area streams. Drainage basins suspected of being source areas for the most serious nonpoint problems have been identified. The 208 Phase I study established that a water-quality study of nonpoint-source runoff from representative urban and agricultural watersheds in the metropolitan area was needed to define relationships between land use, watershed characteristics, and the quantity, quality, and timing of runoff.

A Phase II 208 study was initiated in October 1979 (Ayers and others, 1980). The following statements summarize the more important findings of the study from earlier reports.

-- Concentration levels for many constituents in nonpoint-source runoff during snowmelt can greatly exceed the level recommended for streams and lakes in the area (Oberts, 1982).

-- Detectable levels of pesticides are transported with runoff from agricultural areas, particularly when such events occur shortly after pesticide application (Oberts, 1982).

-- Watersheds in which even a small amount of construction is underway contribute extraordinarily high loads of particulate matter and soluble constituents; however, properly designed detention systems reduce loads in runoff (Oberts, 1982).

-- Concentrations of soluble constituents and particulate matter are both high in runoff in the Twin Cities Metropolitan Area, and methods to reduce these constituents should be considered to a greater extent in management approaches (Oberts, 1982).

-- Atmospheric sources of various constituents can be significant in total-runoff loading, particularly of nitrogen and lead (Brown, 1983).

Objectives

As cited by Ayers and others (1980), the objectives of the Phase II 208 study were to (1) quantify and characterize storm and annual nonpoint-source runoff loads for representative watersheds, (2) provide information on transport mechanisms of water-quality constituents, and (3) develop a method to estimate storm and annual water-quality loadings from unsampled watersheds. The study was intended to provide better definition of the relationships between land use, watershed characteristics, and the quantity, quality, and timing of runoff so that effective alternatives to deal with nonpoint-source related problems can be identified by the Metropolitan Council of the Twin Cities.

The purpose of this report is to present the interpretations and relationships that were derived from analyses of runoff and chemical loading. Objectives (1) and (2) above were satisfied and are presented in this report. However, reliable regression models to satisfy objective (3) were not obtained. Follow-up work by Brown (1984; R. G. Brown, written commun., 1984), using data from this study and from six other metropolitan area watersheds, led to a set of reliable estimating equations.

Description of the Study Area

The study area encompasses about 3,000 mi^2 of the Twin Cities Metropolitan Area (Anoka, Carver, Dakota, Hennepin, Ramsey, Scott, and Washington Counties). The population of the metropolitan area is about 2,000,000; the largest concentration is in the central cities of Minneapolis and St. Paul at a density of about 22,000 people per square mile (Oberts and Jouseau, 1979).

Land use in the metropolitan area is 43 percent agricultural, 27 percent urban, and 30 percent open space (Oberts and Jouseau, 1979). Urban growth is concentrated around Minneapolis and St. Paul, with the most growth to the north, south, and west. The major agricultural areas are to the south and west in Dakota, Scott, and Carver Counties.

The topography of the metropolitan area is characterized by gently undulating, glaciated uplands dissected by the Mississippi, Minnesota, and St. Croix River valleys. Total relief is about 600 feet, ranging in altitude from less than 700 feet along the lower river reaches to more than 1,200 feet above sea level in northeastern Washington County and in Scott County.

Highlands in the eastern part of the area are part of the St. Croix terminal moraine. The area is underlain by well-drained loamy soils and till. Drainage patterns are poorly defined in the eastern highlands, and many lakes and wetlands occur in depressions. Highlands to the south and west also are moraine areas of well-drained loamy soils, but drainage patterns are better defined than in the eastern highlands and the soils are better suited for agriculture. Many lakes and wetlands occur in depressions or as components of the stream systems.

The major outwash areas generally are characterized by sandy, well-drained soils. Outwash in Dakota County is particularly well suited to intensive farming with the aid of irrigation. Soils underlying flood plains of the major streams generally are poorly drained.

The northern part of the metropolitan area is characterized by flat-lying outwash deposits. The fine, sandy soils generally are well drained, but a high water table has created many marshes, peat bogs, and shallow lakes. Sod and vegetable farms are common.

The climate of the area is characterized by generally mild, humid summers and relatively long, severe winters. Normal annual precipitation is 27 inches, with 44 inches of snow in winter. May and June generally are the wettest months and February the driest. Most rain comes with frontal storms, but some occurs with warm-weather convective storms.

Data Collected From Selected Watersheds

The rationale for site selection and data collection was discussed by Ayers and others (1980) and Oberts (1982). Data on discharge and water quality were collected from six agricultural watersheds (A1-A6), four urban main-stem watersheds (U1-U4), and seven urban storm-sewered watersheds (S1-S7) (fig. 1; table 1). Data on rainfall quantity were available or collected at 12 sites (all agricultural sites except A2, and all storm-sewered sites). Data on rainfall quality were collected at six sites (fig. 1). A separate analysis of rainfall quality was made by Brown (1983). Details on data collection, instrumentation, laboratory analysis (including quality assurance), basin characteristics, and all the data collected and used in the study are given in Payne and others (1982). Table 1 contains a general description of data collected at each site. Forty-four basin characteristics were determined for each selected watershed (Payne and others, 1982).

Methods of Data Analysis

All discharge data were determined by means of stage-discharge relationships for each site (Payne and others, 1982), except Purgatory Creek (site U2, fig. 1) which was estimated from flow data at a long-term U.S. Geological Survey gaging station 2 miles downstream (site P). Daily loads were computed either (1) on an event basis at storm-sewer sites and at main-stem sites during large events using instantaneous discharge and water-quality data or (2) on a

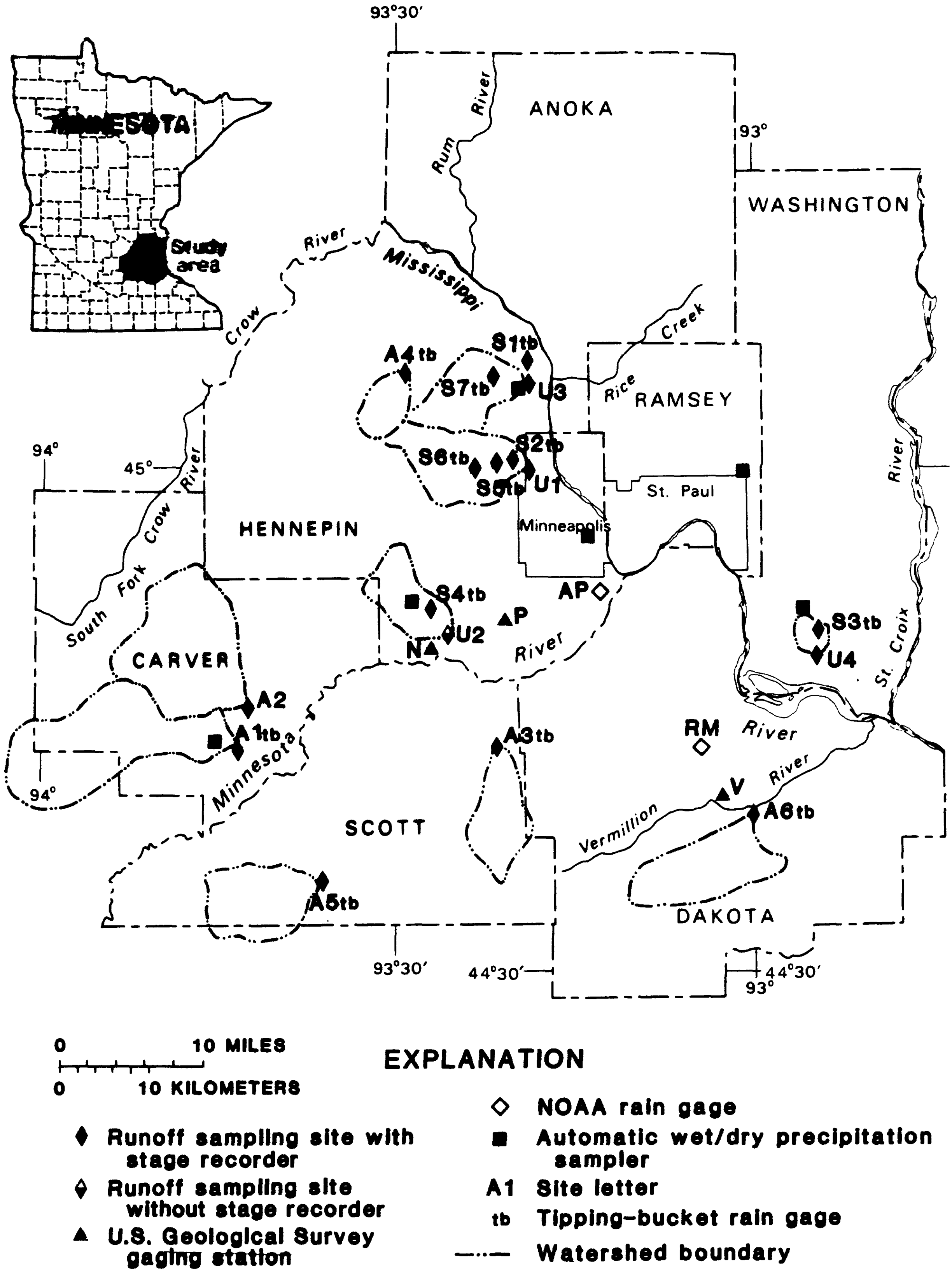

Figure 1.--Sampling sites for runoff and rain in the Twin Cities Metropolitan Area

Table 1.--Data collected at each sampling site for 1980

Site	Site location and drainage area	Stage-recorder interval	Rain-recorder interval	Water-quality sampling	Sampling emphasis	Major land use, in percent of watershed
A1	Bevens Creek at County road 41 (82.9 mi^2)	15-min	15-min	automatic 0.5-12 hrs	solids nutrients	90 agricultural 62 cropland 6 wetland and lakes
A2	Carver Creek at County Hwy 140 (65.2 mi^2)	15-min	none	event intensive manual	solids nutrients	74 agricultural 43 cropland 19 wetland and lakes
A3	Credit River at County Road 68 (23.2 mi^2)	15-min	15-min	event intensive manual	solids nutrients	75 agricultural 33 cropland 14 wetland and lakes
A4	Elm Creek at County Hwy 10 (14.3 mi^2)	15-min	15-min	automatic 0.5-12 hrs	solids nutrients	75 agricultural 34 cropland 17 wetland and lakes
A5	Raven Stream at County Road 61 (32.4 mi^2)	15-min	15-min	event intensive manual	solids nutrients	80 agricultural 74 cropland 6 wetland and lakes
A6	So.Fk. Vermillion River at Co. Hwy 66 (30.8 mi^2)	15-min	15-min	automatic 0.5-12 hrs	solids nutrients	87 agricultural 70 cropland 5 wetland and lakes
U1	Bassett Creek at County Hwy 66 (31.7 mi^2)	15-min	none	automatic 0.5-12 hrs	solids nutrients metals	64 urban 15 wetland and lakes

Table 1.--Data collected at each sampling site for 1980--Continued

Site	Site location and drainage area	Stage-recorder interval	Rain-recorder interval	Water-quality sampling	Sampling emphasis	Major land use, in percent of watershed
U2	Purgatory Creek below Staring Lake ($24.0 mi^2$)	correl. with site P	none	event intensive manual	solids nutrients metals	59 urban 19 wetland and lakes
U3	Shingle Creek at Noble Avenue ($22.9 mi^2$)	15-min	none	automatic 0.5-12 hrs	solids nutrients metals	45 urban 13 wetland and lakes
U4	80th Street storm sewer ($1.55 mi^2$)	5-min	none	event intensive manual	solids nutrients metals	89 urban 2 wetland and lakes
S1	Estates Drive storm sewer ($0.22 mi^2$)	5-min	5-min	automatic 15-60 min	solids nutrients metals	99 urban (94 med. density residential)
S2	Highway 100 storm sewer ($0.47 mi^2$)	5-min	5-min	automatic 15-60 min	solids nutrients metals	100 urban 20 commercial
S3	Iverson Avenue storm sewer ($0.15 mi^2$)	5-min	5-min	automatic 15-60 min	solids nutrients metals	46 urban (33 med. density residential)
S4	PDQ-Valley View Road storm sewer ($0.13 mi^2$)	5-min	5-min	automatic 15-60 min	solids nutrients metals	100 urban (69 low dens. res.) (19 multi-family)

Table 1.—Data collected at each sampling site for 1980--Continued

Site	Site location and drainage area	Stage-recorder interval	Rain-recorder interval	Water-quality sampling	Sampling emphasis	Major land use, in percent of watershed
S5	Sandburg Avenue storm sewer (0.12 mi^2)	5-min	5-min	automatic 15-60 min	solids nutrients metals	94 urban (85 light industrial)
S6	Wesley Park storm sewer (0.33 mi^2)	5-min	5-min	automatic 15-60 min	solids nutrients metals	90 urban (83 med. density residential)
S7	Yates Avenue storm sewer (0.35 mi^2)	5-min	5-min	automatic 15-60 min	solids nutrients metals	82 urban (52 med. density residential)

daily basis for smaller events and recessions at main-stem sites using mean daily discharge and water-quality data. Load models, least-squares linear regression (Roscoe, 1975) models of daily load versus daily runoff, were then developed for each of the following constituents: chemical oxygen demand (COD), total suspended solids (TSS), total ammonia plus organic nitrogen (TKN), dissolved nitrite plus nitrate nitrogen (NN), total phosphorus (TP), total chloride (Cl), and total lead (Pb).

Summer (April 16-November 15) and winter (November 16-April 15) models of daily flows also were developed with stepwise multiple regression procedures. Winter models of daily flows were developed for all sites while summer models only were developed for main-stem sites. Various functions of 1980 daily discharge for one of the two long-term gaging stations (Vermillion River, site V, and Purgatory Creek, site P; fig. 1) were regressed with 1980 daily discharge at each site for the respective periods to obtain the daily-flow models. Daily rainfall at the Rosemount rain gage (site RM, fig. 1) also proved useful as an additional variable in summer models. The models were used to estimate 1963-80 daily discharges from November 16 to April 15 for all sites and from April 16 to November 15 for main-stem sites. The 1963-80 synthetic daily flows then were used with the load models to estimate 1963-80 daily loads for the same time periods.

Summer daily discharges and loads from 1963-80 at the storm-sewer sites were estimated using flow and load-regression models that were developed using rainfall characteristics. In these models, total storm runoff or load was a function of as many as four storm characteristics, such as total rainfall, maximum hourly intensity, depth of rain for previous day, and other characteristics calculated from the 1980 rainfall record at each site. The models then were used with the 1963-80 rainfall characteristics at the Minneapolis-St. Paul airport (site AP, fig. 1) to estimate 1963-80 storm runoff and loads for each site. Where applicable, site AP rainfall characteristics were adjusted by one of the weighting factors listed below to account for areal differences in mean summer rainfall within the metropolitan area (Kuehnast and Baker, 1978).

Weighting factor for areal differences in mean warm-weather rainfall

Site--	S1	S2	S3	S4	S5	S6	S7
Factor--	1.12	1.12	1.15	1.21	1.18	1.15	1.15

Annual and seasonal frequency distributions of the 1963-80 daily runoff and loads were used to obtain the annual and seasonal runoff and loads that would be expected to be equalled or exceeded, on the average, once every 2 years. These are referred to as the 2-year recurrence annual and seasonal runoff and loads for each site. Seasonal computations were made for runoff and loads using the following seasons:

Season	Dates		Hydrologic significance
winter	Nov.16-Dec.31	-	winter frozen period
snowmelt	Jan.1-Apr.15	-	winter/spring snowmelt
spring	Apr.16-Jun.15	-	higher soil moisture/high soil exposure
summer	Jun.16-Sep.15	-	increasing vegetation/ decreasing soil moisture
fall	Sep.16-Nov.15	-	fall dieback/harvest period

DEVELOPMENT OF 1963-80 RUNOFF AND LOAD MODELS

Runoff Models for Base-Gage Sites

The first step in the process of estimating long-term loads at the study sites was to review discharge records from U.S. Geological Survey gaging stations (base gages) to determine long-term flow-frequency statistics. Three stations with at least 5 years of data were suitable for analysis; Vermillion River at Empire (VERMI), site V, from 1974-80; Purgatory Creek at Eden Prairie (PURGA), site P, from 1976-80; and Nine Mile Creek at Bloomington (NMILE), site N, from 1963-76. Winter and summer daily flow models were developed for sites V and P with the overlapping periods of record at site N to estimate flows for 1963-74 at site V and for 1963-76 at site P. Estimates of flow at sites V and P for periods of missing record from 1963-80 were developed from data at site N using the following equations:

Summer (April 16 - November 15)

$$VERMI = 2.35 + 2.55 * NMILE + 74.9 * LRP - 32.9 * ROSEP$$

$$PURGA = 0.06 + 0.452 * LNN + 0.294 DNN - 3.94 * LAP$$

VERMI: $R^2 = 0.87$, SEE = 39

PURGA: $R^2 = 0.80$, SEE = 24

Winter (November 16 - April 15)

$$VERMI = 24.2 * NMILE - 0.124 * LNN + 0.347 * JULIN$$

$$PURGA = -2.37 + 1.15 * NMILE - 0.513 * DNN + 0.069 * JULIN$$

VERMI: $R^2 = 0.81$, SEE = 36

PURGA: $R^2 = 0.81$, SEE = 31

where

VERMI is flow of the Vermillion River, site V, in ft^3/s;

PURGA is flow of Purgatory Creek, site P, in ft^3/s;

NMILE is flow of Nine Mile Creek, site Nn, in ft^3/s;

LNN is previous day's flow of Nine Mile Creek, site N, in ft^3/s;

DNN is NMILE - LNN, in ft^3/s;

ROSEP is the daily rainfall at the Rosemount site, Rm, in inches;

LRP is the previous day's rainfall at ROSEP, in inches;

LAP is the previous day's rainfall at the Twin Cities International Airport, site AP, in inches;

JULIN is the Julian date if the Julian date is less than 320; if the Julian date is greater than 320, then JULIN is equal to 367 minus the Julian date;

R^2 is the coefficient of determination for the equation; and

SEE is the standard error of estimate for the equation.

Runoff Models for Study Area

Winter and summer daily flow models were developed (table 2) to estimate flow at each of the study sites from long-term-flow records at base gages (sites V and P). Daily flows at all sites were used to calibrate the models during 1980. The models then were used to estimate mean daily flows at the study sites from 1963-80. All winter models (table 2) included variables that were a function of VERMI, PURGA, or JULIN. In contrast, the summer models (table 2) include variables that were a function of VERMI, PURGA, or JULIN for agricultural (A1-A6) and urban main-stem (U1-U4) sites, and a function of

Table 2.—Regression models for estimating
[flow in cubic

Site	Winter models (November 16 - April 15)	R^2	SEE
A1	$-48.1 + 8.43(\sqrt{NEXTV}) + 0.224*JULIN$	0.75	29
A2	$-2.09 + 0.827*PURGA + 1.47*NEXTP$	.85	19
A3	$-32.0 + 5.84(\sqrt{VERMI}) + 0.061*JULIN$	.74	26
A4	$-5.32 + 0.165*VERMI - 0.004*DVN$	.83	34
A5	$-40.0 + 7.52(\sqrt{NEXTV}) + 0.042*JULIN - 0.812*DVVSR$	.76	24
A6	$1.06 + 0.279*NEXTV$	.78	19
U1	$-12.0 + 2.45(\sqrt{VERMI}) + 0.112*JULIN$	.75	16
U2	$-0.801 + 0.512*LPP + 0.034*JULIN + 0.210*PURGA$	.73	21
U3	$-12.5 + 2.68(\sqrt{NEXTV}) + 0.034*JULIN + 0.085*DVNSR$	.81	23
U4	$-0.33 + 0.034*NEXTV - 0.012*LVV - 0.014*JULIN$	.79	18
S1	$-0.049 + 0.043*NEXTV - 0.014*VERMI$	.80	19
S2	$-0.041 + 0.013*NEXTV - 0.014*LVV$	.77	21
S3	No flow during the winter	---	---
S4	$-0.256 + 0.081\ LOG(NEX2V) + 0.254\ LOG(DVN)$	.74	29
S5	$-0.365 + 0.113\ LOG(NEX2V) + 0.011*JULIN + 0.233\ LOG(DVN)$	.81	26
S6	$-0.153 + 0.021*NEXTV - 0.014*LVV$	.73	27
S7	$-0.72 + 0.013*NEX2V + 0.012*DVN + 0.013*LVV$	.76	31

Note: The equations for the storm sewers were developed using the same rainfall found in table 4.

VERMI = flow of the Vermillion River, in ft^3/s.
NEXTV = next day's flow of the Vermillion River, in ft^3/s.
NEX2V = two days in advance flow at the Vermillion River, in ft^3/s.
LVV = previous day's flow of the Vermillion River, in ft^3/s.
DVN = NEXTV - LVV.

DVVSR = /VERMI - /LVV.
DVNSR = /NEXTV - /LVV.
PURGA = flow of Purgatory Creek, in ft^3/s.
NEXTP = next day's flow of Purgatory Creek, in ft^3/s.
LPP = previous day's flow of Purgatory Creek, in ft^3/s.

ROSEP = total daily precipitation at the Rosemount rain gage.
LRP = previous day's total precipitation at the Rosemount rain gage.
L7RP = previous 7 day's total precipitation at the Rosemount rain gage.

mean daily flows between 1963 and 1980
feet per second]

Summer models (April 16 - November 15)	R^2	SEE
-3.98 + 621 + VERMI - 0.071*JULIN	0.79	26
19.9 + 0.802*PURGA + 0.081*JULIN	.79	19
-18.3 + 0.512*VERMI	.87	13
0.202 + 0.491*PURGA	.84	18
6.51 + 0.082*NEXTV - 0.041*JULIN	.77	31
-19.5 + 0.572*VERMI + 0.044*JULIN	.72	29
18.7 + 12.0*ROSEP + 24.7*LRP + 9.33*L7RP - 0.-072*JULIN	.83	17
0.234 + 0.684*PURGA	.86	26
2.831 + 10.2*ROSEP + 7.17*LRP + 3.01*L7RP	.81	22
-0.109 + 1.94*L3RP2 - 0.243*ROSEP2	.84	19
(-0.021 + 0.0133*TRAINA + 0.012*DERNP3)26.9*0.222	.74	23
(-0.011 + 0.154*TRAINA + 0.0192*MAX1H)26.9*0.474	.83	18
(-0.32 + 0.154*TRAINA + 0.121*DERNP3)26.9*0.152	.82	14
(-0.133 + 0.311*TRAINA + 0.085*RATMAX) 26.9*0.131	.76	28
(-0.411 + 0.424*TRAINA) + 0.131*RATMAX)26.9*0.125	.81	29
(-0.022 + 0.0132*TRAINA + 0.043*DERNP7)26.9*0.333	.87	26
(-0.033 + 0.0132*TRAINA + 0.011*DURNF)26.9*0.359	.74	21

characteristics as the load model. Description of the independent variables is

ROSEP2 = $ROSEP^2$.
L3RP2 = previous 3 day's total precipitation squared at the Rosemount rain gage.
JULIN = Julian date if <320.
JULIN = 367 - Julian date if >319.

NEXTP = next day's flow at Purgatory Creek, in ft^3/s.
MAX1H = maximum hourly rainfall intensity, in inches per hour.
TRAINA = total amount of precipitation for the storm, in inches.
RATMAX = MAX1H/TRAINA.
DURNF = duration of storm, in minutes.

DERNP3 = amount of precipitation accumulated during previous 72 hours, in inches.
DERNP7 = amount of precipitation accumulated during previous 168 hours or 7 days, in inches.
R^2 = Coefficient of determination for the model.
SEE = Standard error of estimate for the model.

weighted-rainfall characteristics at site AP for storm-sewered sites (S1-S7). Flow response was slower at sites A2, A4, and U2, and correlated best with PURGA, whereas, flow at the flashier urban sites did not correlate well with either PURGA or VERMI for summer conditions. The quicker responses at these sites in the summer were more directly related to various rainfall functions (table 2) than to functions of flow at the slower-responding base gages.

The SEE (standard error of estimate) for the runoff models ranged from 13 to 34 percent, averaging about 22 percent for summer models and about 24 percent for winter models. Although the error for any predicted daily value of flow would be approximated by SEE, the difference in predicted versus observed annual runoff values in 1980 was less than 10 percent (table 3).

Load Models for Study Sites

Models of daily loads (table 4) of COD, TSS, TKN, NN, TP, CL, and Pb were developed from 1980 daily discharge and load data for all sites. Daily load models for the storm-sewered sites were for the winter period only. Load models at storm-sewered sites for summer periods (table 4) were developed using 1980 storm loads and rainfall characteristics.

Table 4 also lists the resulting R^2 and SEE for each model. Most R^2 values for the agricultural and urban main-stem sites are in the upper 0.80's, with SEE values ranging from 5 to 20 percent. By comparison, the storm-sewered sites have somewhat lower R^2 values (high 0.70's to the middle 0.80's) and higher SEE values (15 to 30 percent). The seemingly better predictability of the main-stem models can be attributed to the slower runoff response of the streams at main-stem sites. The predicted and observed loads for 1980 (table 3) generally were within 10 percent.

Implications of Runoff and Load Models

Conceptually, there should be some difference in the formulation of flow and load models between sites and between constituents at a given site. In fact, differences were observed once each best-fit model was derived. Also, a model of flow for the entire year should be less accurate than separate models of flow for distinct seasons. Results of the two approaches verified that splitting the procedure into warm- and cold-weather periods, summer and winter models, indeed gave better results. Lag and offset functions (such as previous-day or next-day) of rainfall and flow were found to be important additional independent variables because they account for variability in the response characteristics of each watershed (for example, runoff of a large watershed lagging a day behind that of a smaller watershed). JULIN functions were found to be important as surrogate variables for differences in the hydrologic response of a watershed owing to seasonal changes in such things as temperature (winter), rainfall characteristics, vegetation cover, evapotranspiration, and soil moisture.

Discharge at agricultural and urban main-stem sites was found to be the only variable that could be used to estimate loads for these sites (table 4). Loads generated in these watersheds are directly related to discharge. This relationship suggests that implementation of land-use practices that control runoff volume (runoff retention) would reduce loads. The majority of runoff retention could be focused on controlling runoff during snowmelt and early spring because the majority of the annual loading occurs during those periods. Runoff retention could be accomplished by utilizing or creating storage along drainage ways, such as wetlands and settling ponds.

As would be expected, the volume of rain during the storm (TRAINA) was the most significant independent variable in the equation for total storm runoff volume during the summer (table 2) for all storm-sewered watersheds. Antecedent soil-moisture indexes (either DERNP3 or DERNP7, table 2) were found to be important variables in the equations for sites S1, S3, and S6. These sites are in watersheds with a high percentage of pervious area which is known to be sensitive to these antecedent soil moisture variables. However, variables related to rainfall intensity (MAX1H or RATMAX, table 2) proved important in models for storm-sewered sites with more impervious watersheds (S2, S4, S5, and S7).

At all seven storm-sewered sites, peak flow (PEAKQ, table 2) primarily was a function of rainfall-intensity factors (MAX1H, RATMAX, and AVGINT). However, antecedent soil moisture (DERNPD or DERNP3, table 2) was a significant second variable in equations for the two more pervious watersheds, sites S3 and S6.

As in the flow models, the volume of rain during the storm (TRAINA) was the most significant independent variable in the equations for total storm loads during the summer (table 4) for all storm-sewered watersheds. Equations developed for total storm runoff (table 2) and total storm loads during summer (table 4) for all the storm-sewered watersheds include similar independent variables, indicating that the factors that influence flow volume and loads are similar. Loads from watersheds with extensive impervious area (watersheds above sites S2, S4, S5, and S7) are related to rainfall-intensity factors. Loads from watersheds with large amounts of pervious area (watersheds above sites S1, S3, and S6) are related to antecedent soil-moisture indexes.

Retention of snowmelt and spring runoff in storm-sewered watersheds would be effective in reducing annual loads since most of the annual loading occurs during this time period. Also, for watersheds with high percentages of impervious area, it appears important to provide on-site or other proximate retention storage to reduce runoff and loads.

RESULTS OF 1963-80 RUNOFF AND LOAD MODELS

Runoff and Load Frequency

The 1963-80 daily loads of each constituent for each site were estimated with the daily or storm-load models and 1963-80 daily flows or storm characteristics. The daily loads then were summed within each season and each year.

Table 3.--Observed and predicted

[Runoff values in inches,

Site	Runoff		Lo TSS		COD		TKN	
	Observed	Pre-dicted	Observed	Predicted	Observed	Predicted	Observed	Predicted
A1	1.86	1.93	997,725	917,907	1,678,202	1,644,379	76,964	82,928
A2	2.11	2.06	649,835	710,965	1,635,782	1,567,764	60,505	57,678
A3	3.42	3.31	365,225	401,106	823,066	989,010	34,419	36,789
A4	4.02	4.09	85,387	78,698	542,689	498,867	17,327	16,796
A5	2.30	2.33	500,025	429,963	845,209	798,106	43,478	41,786
A6	6.65	6.39	3,056,625	3,986,797	1,205,939	1,162,752	56,726	60,974
U1	5.36	4.98	1,583,590	1,478,967	1,118,924	1,207,365	44,575	42,111
U2	3.14	2.98	218,460	206,379	603,796	751,675	16,687	15,622
U3	3.69	3.85	446,780	427,874	536,507	499,997	25,017	29,018
U4	3.24	3.20	32,050	26,998	52,850	49,768	1,840	1,965
S1	5.63	5.22	7,753	6,976	15,575	17,692	529	487
S2	6.41	6.31	34,704	34,989	50,650	46,765	761	659
S3	2.43	2.43	174,700	165,697	9,571	10,672	327	356
S4	4.96	4.83	59,537	57,462	8,838	7,973	594	609
S5	10.42	9.99	103,490	98,796	20,317	19,679	872	821
S6	7.03	7.30	73,363	67,978	28,910	29,136	886	799
S7	4.41	4.48	35,710	33,476	35,446	37,565	1,116	994

runoff and loads for 1980

load values in pounds]

ad

NN		TP		Cl		Pb	
Observed	Predicted	Observed	Predicted	Observed	Predicted	Observed	Predicted
65,315	71,567	17,426	18,163	855,863	926,378	---	---
12,229	11,674	17,412	16,967	653,830	510,679	114.9	110.7
7,343	6,786	8,306	9,679	130,642	126,786	93.2	78.5
2,269	1,967	2,882	2,696	277,731	299,371	47.6	52.4
41,156	39,567	7,955	8,010	179,840	167,976	48.2	46.3
91,207	89,566	10,402	9,978	217,575	210,011	---	---
9,321	8,167	7,508	7,508	1,759,300	1,963,479	748.0	699.6
529	478	1,095	996	467,300	399,971	39.3	48.4
3,734	3,565	3,266	3,476	637,650	566,736	502.4	519.6
543	496	435	496	31,815	29,766	47.7	46.1
93	79	138	149	16,240	15,167	38.8	31.7
188	209	126	116	28,233	30,176	165.0	149.8
26	31	163	178	19	17	6.8	6.1
75	69	156	141	1,644	1,562	9.0	7.6
125	256	68	59	17,200	16,767	29.2	25.9
531	605	209	196	12,091	11,676	221.6	257.9
155	163	141	163	12,022	11,176	23.9	21.0

Table 4.—Regression models for estimating daily loads, based either on mean daily flow or on rainfall characteristics

	R^2	SEE		R^2	SEE
A1					
COD = 5.77*(FLOW)$^{1.06}$	0.99	3	TP = 1.50*(FLOW)$^{0.98}$	0.93	16
TSS = 5.27*(FLOW)$^{1.06}$	.87	11	Cl = (13.4 + 11.5*FLOW)^{2}	.81	43
TKN = 2.49*(FLOW)$^{1.11}$	.96	9	Pb = 5.12+(FLOW)$^{1.81}$	.85	87
NN = 0.554*(FLOW)$^{1.53}$	.95	19			
A2					
COD = 5.86*(FLOW)$^{1.07}$	0.98	3	TP = 2.11*(FLOW)$^{0.82}$	0.83	28
TSS = 4.97*(FLOW)$^{1.06}$	.92	8	Cl = (500 + 127*FLOW)^{2}	.89	5
TKN = 2.76*(FLOW)$^{1.01}$	.97	7	Pb = 4.11*(FLOW)$^{1.19}$	.83	19
NN = 1.20*(FLOW)$^{0.99}$	.83	28			
A3					
COD = 5.61*(FLOW)$^{1.09}$	0.99	3	TP = 0.38*(FLOW)$^{1.43}$	0.96	22
TSS = 3.45*(FLOW)$^{1.42}$	.84	18	Cl = 4.37*(FLOW)$^{0.93}$	.99	3
TKN = 2.08*(FLOW)$^{1.18}$	.98	7	Pb = 2.85*(FLOW)$^{0.93}$	.95	36
NN = (-0.34 + 1.92*FLOW)^{2}	.90	31			
A4					
COD = 5.86*(FLOW)$^{1.00}$	0.99	3	TP = 0.07*(FLOW)$^{1.19}$	0.95	6
TSS = 4.03*(FLOW)$^{0.99}$	.83	14	Cl = 5.34*(FLOW)$^{0.94}$	.99	3
TKN = 2.36*(FLOW)$^{1.02}$	.97	8	Pb = (-0.09 + 0.05*FLOW)^{2}	.86	21
NN = 0.36*(FLOW)$^{1.25}$	.88	9			
A5					
COD = 5.60*(FLOW)$^{1.12}$	0.99	3	TP = 0.32*(FLOW)$^{1.28}$	0.99	15
TSS = 4.18*(FLOW)$^{1.35}$	.96	11	Cl = 4.92*(FLOW)$^{0.88}$	.98	5
TKN = 2.25*(FLOW)$^{1.22}$	.99	7	Pb = 2.85*(FLOW)$^{0.38}$	.88	19
NN = 2.54*(FLOW)$^{1.13}$	.98	8			

Table 4.--Regression models for estimating daily loads, based either on mean daily flow or on rainfall characteristics--Continued

	R^2	SEE		R^2	SEE
			A6		
$COD = (-76.9 + 31.1*FLOW)^{2}$	0.81	10	$TP = 3.56*(FLOW)^{2.07}$	0.81	8
$TSS = 1.65*(FLOW)^{2.17}$	.87	14	$Cl = 5.49*(FLOW)^{7.57}$	.94	4
$TKN = 1.31*(FLOW)^{1.95}$	.85	15	$Pb = (-5.08 + 0.56*FLOW)^{2}$	.92	12
$NN = 4.79*(FLOW)^{0.19}$	.81	4			
			U1		
$COD = 4.71*(FLOW)^{1.25}$	0.94	4	$TP = 0.56*(FLOW)^{1.33}$	0.93	10
$TSS = 5.78*(FLOW)^{0.54}$	.79	8	$Cl = 4.96*(FLOW)^{1.31}$	.74	6
$TKN = 1.42*(FLOW)^{1.27}$	.92	7	$Pb = (0.09 + 0.03*FLOW)^{2}$	.75	37
$NN = 0.02*(FLOW)^{1.22}$	.89	11			
			U2		
$COD = 5.66*(FLOW)^{1.03}$	0.99	2	$TP = 1.15*(FLOW)^{1.23}$	0.94	7
$TSS = 4.12*(FLOW)^{1.24}$	.80	14	Cl = No equation	--	--
$TKN = 2.23*(FLOW)^{0.96}$	.99	4	$Pb = (-0.11 + 0.18*FLOW)^{2}$	.88	18
$NN = 1.31*(FLOW)^{1.00}$	.98	2			
			U3		
$COD = 4.07*(FLOW)^{1.54}$	0.81	8	$TP = (0.34 + 0.27*FLOW)^{2}$	0.92	7
$TSS = 3.24*(FLOW)^{1.76}$	.76	11	$Cl = (17.3 + 2.86*FLOW)^{2}$	.95	20
$TKN = (1.60 + 0.71*FLOW)^{2}$	.90	10	$Pb = (-0.04 + 0.12*FLOW)^{2}$	.74	16
$NN = (0.75 + 0.26*FLOW)^{2}$	.83	20			
			U4		
$COD = 6.34*(FLOW)^{0.82}$	0.99	2	$TP = 1.19*(FLOW)^{0.99}$	0.89	14
$TSS = 5.18*(FLOW)^{0.71}$	.77	11	$Cl = (967 + 387*FLOW)^{2}$	.94	10
$TKN = 2.95*(FLOW)^{0.84}$	.89	9	$Pb = 0.53*(FLOW)^{0.37}$	.87	13
$NN = (2.08 + 1.54*LOG(FLOW)^{2}$	.81	16			

Table 4.--Regression models for estimating daily loads, based either on mean daily flow or on rainfall characteristics--Continued

	2	SEE		R^2	SEE
S1 (November 16 - April 15)					
COD = 67.3 + 2,662*RUNOFF	0.79	13	TP = -0.65 + 37.6*LOG(RUNOFF)	0.93	19
TSS = 57.5 + 1.412*RUNOFF	.84	13	Cl = 155 + 149*RUNOFF	.92	19
TKN = 5.12*(RUNOFF)$^{1.19}$	.96	16	Pb = 0.27 + 4.06*RUNOFF	.93	14
NN = 2.38*(RUNOFF)$^{0.75}$	.82	16			
S1 (April 16 - November 15)[1]					
COD = 35.2 + 0.89*NDRDO2 - 236*DERNP3 + 184* DERNP7	0.86	18	NN = (0.28 + 1.11*TRAINA + 0.10*RATMAX)^2	0.84	15
TSS = 4.09(NDRDO2)$^{0.23}$ (DERNP7)$^{-0.12}$ (PEAKQ) 0.77	.73	29	TP = (-0.14 + 0.65*TRAINA + 0.01*NDRDO2 + 0.01*DURNF + 41*AVGINT)^2	.75	13
TKN = (0.06 + 1.54*TRAINA + 0.01*DURNF + 75* AVGINT^2	.83	7	Cl = 1.41 + 10.1*MAX1H	.94	27
			Pb = 0.08 + 0.21*TRAINA + 0.01*NDRDO2 + 0.14* DERNP7	.89	18
S2 (November 16 - April 15)					
COD = 7.35*(RUNOFF)$^{0.22}$	0.79	6	TP = -0.18 + 49.9*RUNOFF	0.96	17
TSS = 40.9 + 8,462*RUNOFF	.99	2	Cl = (1,054 + 3,761*RUNOFF)^2	.81	13
TKN = -0.68 + 382*RUNOFF	.86	9	Pb = (0.63 + 9.8*RUNOFF)^2	.95	18
NN = Insufficient data for regression					
S2 (April 16 - November 15)[1]					
COD = 6.92 + 1,853*TRAINA - 455*DERNP7 - 26,552* AVGINT	0.93	12	NN = 1.17 + 8.96*TRAINA	0.89	9
TSS = 614 + 5.178*MAX1H	.93	16	TP = 0.81 + 11.2*MAX1H	.96	27
TKN = 0.69 + 59.4*MAX1H - 3.51*DERNP7 - 850* AVGINT	.95	14	Cl = 42.6 + 111*DERNP7	.99	5
			Pb = 0.93 + 5.98*TRAINA	.93	17

Table 4.--Regression models for estimating daily loads, based either on mean daily flow or on rainfall characteristics--Continued

	R^2	SEE		R^2	SEE
		S3 (November 16 - April 15)			
		---No flow---			
		S3 (April 16 - November 15)[1]			
COD = 208 + 898*TRAINA + 194*DERNP7 - 0.39*DURNF	0.98	28	NN = -0.31 + 2.22*TRAINA - 1.27*MAX1H + 0.23*DERNP7	0.93	21
TSS = 4,930 + 19,300*TRAINA + 4,507*DERNP3 - 6.42*DURNF	.92	11	TP = -2.47 + 1.51*TRAINA - 0.01*DURNF + 3.03*DERNP3	.95	9
TKN = 4.0 + 29.7*TRAINA - 0.012*DURNF + 4.07*DERNP3	.97	16	Cl = -1.5 + 132*AVGINT + 2.94*RATMAX + 0.01*DURNF	.94	9
			Pb = -0.24 + 0.62*TRAINA + 0.13*DERNP7	.99	3
		S4 (November 16 - April 15)			
COD = 7.89*(RUNOFF)$^{1.07}$	0.89	18	TP = 0.01 + 14.6*RUNOFF	0.88	21
TSS = 6.93*(RUNOFF)$^{0.77}$	.91	12	Cl = 5.25(RUNOFF)$^{0.12}$	.95	7
TKN = -0.45 + 87.6*RUNOFF	.99	1	Pb = 0.42*(RUNOFF)$^{0.87}$	.94	17
NN = -2.37 + 29.1*RUNOFF	.92	18			
		S4 (April 16 - November 15)[1]			
COD = -16.4 + 1,249*TRAINA - 1.8*DURNF	0.89	8	TP = -6.16 + 11.89*TRAINA + 5.11*RATMAX	0.83	13
TSS = -1,853 + 1,3687*MAX1H	.96	29	Cl = -0.10 + 183*AVGINT + 2.96*MAX1H	.99	4
TKN = -19.9 + 40.7*TRAINA + 16.4*RATMAX	.90	11	Pb = -0.07 + 1.31*MAX1H - 0.24*DERNP3	.85	9
NN = 2.81*TRAINA + 0.97*RATMAX - 0.41*DERNP3	.97	16			

Table 4.—Regression models for estimating daily loads, based either on mean daily flow or on rainfall characteristics--Continued

	R^2	SEE		R^2	SEE
S5 (November 16 - April 15)					
COD = 32.3 + 2,680*RUNOFF	0.82	7	TP = 2.49*(RUNOFF)$^{1.17}$	0.76	14
TSS = 7.48*(RUNOFF)$^{0.71}$	.74	10	Cl = 301 + 4,080*RUNOFF	.96	16
TKN = 1.16 + 61.1*RUNOFF	.99	5	Pb = 0.11 + 5.45*RUNOFF	.81	16
NN = 0.88 + 20*RUNOFF	.82	17			
S5 (April 16 - November 15)[1]					
COD = 184 - 2,097*RUNOFF	0.87	23	NN = -0.64 + 2.32*TRAINA + 0.34*DERNP7 + 0.63*RATMAX	0.93	29
TSS = 273 + 521*DERNPD - 2*DURNF + 6,870*TOTRUN	.93	20	TP = (0.08 + 0.34*PEAKQ)^2	.71	21
TKN = 0.37 + 12.3*DERNPD - 9.6*DERNP3 + 36.8*TOTRUN	.94	18	Cl = 82.9 + 236.7*DERNP3	.63	22
			Pb = -0.13 + 0.01*NDRDO2 + 0.03*PEAKQ	.81	27
S6 (November 16 - April 15)					
COD = (3.3 + 133*RUNOFF)^2	0.96	8	TP = 0.71 + 46*RUNOFF	0.96	9
TSS = (4.6 + 109*RUNOFF)^2	.76	18	Cl = 373 + 2,214*RUNOFF	.99	15
TKN = (0.44 + 27.3*RUNOFF)^2	.77	15	Pb = 2.45*(RUNOFF)$^{11.3}$	.91	17
NN = 0.06*(RUNOFF)$^{9.7}$	.84	6			
S6 (April 16 - November 15)[1]					
COD = 53.5 + 2,295*TRAINA + 79.3*DERNP7	0.90	26	TP = 1.4 + 3.9*MAX1H + 0.96*DERNP7	0.89	29
TSS = 189 + 1,758*TRAINA	.85	15	Cl = Insufficient data for regression	--	--
TKN = -0.98 + 7.4*TRAINA + 4.18*DERNPD + 8.1*RATMAX	.95	15	Pb = -0.44 + 0.01*NDRDO2 + 0.01*DURNF + 0.23*PEAKQ + 14.0*AVGINT	.88	23
NN = 2.88 + 1.35*LOG(MAX1H) + 1.36*DERNP7	.83	26			

Table 4.—Regression models for estimating daily loads, based either on mean daily flow or on rainfall characteristics--Continued

	R^2	SEE		R^2	SEE
S7 (November 16 - April 15)					
COD = 143 + 2.51-*RUNOFF	0.83	10	TP = -0.27 + 33.5*RUNOFF	0.94	21
TSS = 108 + 651*RUNOFF	.78	12	Cl = 1,978 - 3,097*RUNOFF	.84	16
TKN = -2.1 + 247*RUNOFF	.86	14	Pb = 1.31*(RUNOFF)$^{0.19}$	.93	26
NN = 1.43 + 69.4*RUNOFF	.80	16			
S7 (April 16 - November 15)[1]					
COD = 1,042 + 150*TRAINA + 554*DERNP7 + 2.9*DURNF	0.79	15	TP = -0.07 + 2.71*MAX1H - 3.27*DERNPD^2	0.80	23
TSS = -0.53 + 40*MAX1H - 62*DERNPD^2	.99	4	Cl = 84.6 + 121*DERNP7 - 77,543*AVGINT	.75	13
TKN = -0.26 + 6.9*MAX1H - 9.9*DERNPD^2	.79	18	Pb = 0.062 + 0.33*DERNP3 - 0.01*PEAKQ + 14.3* TOTRUN	.89	28
NN = 1.44 - S5.31 + MAX1H - 1.29*DERNP3 - 1.33* RATMAX + 51.1*TOTRUN	.58	21			

[1] Loads are predicted on a storm basis instead of a daily basis.

LOG = natural logarithm.
FLOW = mean daily discharge, in ft^3/s.
RUNOFF = total daily runoff for the watershed, in inches.
TRAINA = total amount of precipitation for the storm, in inches.
TOTRUN = total runoff for the storm in that watershed, in inches.
DURNF = duration of storm, in minutes.
MAX1H = maximum hourly rainfall intensity, in inches per hour.
AVGINT = TRAINA/DURNF or average intensity, in inches per hour.
RATMAX = MAX1H/TRAINA.
NDRDO2 = number of hours without precipitation preceding storm.
DERNPD = amount of precipitation accumulated during previous 24 hours, in inches.
DERNP3 = amount of precipitation accumulated during previous 72 hours, in inches.
DERNP7 = amount of precipitation accumulated during previous 168 hours, in inches.
PEAKQ = peak discharge during storm, in ft^3/s.
R^2 = coefficient of determination for model.
SEE = standard error of estimate for model.

Annual and seasonal frequency distributions for each site and constituent were computed (see section on Methods of Data Analysis) and the 2-year frequency loads and runoff, which are those loads and runoff expected to be equalled or exceeded on a long-term average of every 2 years, were calculated (table 5).

Annual-Runoff Response

The annual-runoff response, defined as the ratio of 2-year frequency annual runoff to 2-year frequency annual precipitation expressed as a percentage, for all the study watersheds is listed below.

Annual-Runoff Response

Agricultural watersheds

Site A1 = 6	Site A2 = 12	Site A3 = 14
Site A4 = 14	Site A5 = 9	Site A6 = 20

Urban watersheds

Main stems

Site U1 = 20	Site U2 = 17
Site U3 = 13	Site U4 = 17

Storm sewered

Site S1 = 25	Site S2 = 27	Site S3 = 13
Site S4 = 28	Site S5 = 57	Site S6 = 33
	Site S7 = 22	

As might be expected, the annual-runoff responses were highest for the urban storm-sewered watersheds, with an average response of about 27 percent. The low response for site S3 was due to the extensive amount of pervious area in the watershed. Responses for sites S1 and S7 also were lower as a result of the flat topography and sandy soils of the pervious area in these watersheds. In contrast, the response of the highly impervious watershed, site S6, approaches 60 percent. The annual responses seem to be related to the percentage of effective impervious area in each storm-sewered watershed, which suggests that impervious area contributions to runoff loads are significant.

Table 5.—Total annual loads and runoff of 2-year frequency for each study site

Site	Runoff (inches)	Load, in pounds						
		COD	TSS	TKN	NN	TP	Cl	Pb
A1	1.93	1,721,274	1.023,333	77,853	55,055	18,174	835,566	566
A2	3.47	2,735,436	1,084,136	99,720	20,094	27,155	936,521	197
A3	3.80	870,074	306,872	34,398	8,103	6,949	149,899	107
A4	4.05	546,284	86,099	17,358	2,174	2,788	283,462	40
A5	2.52	879,601	418,754	41,249	42,443	7,129	206,752	47
A6	5.90	991,815	2,069,924	40,261	86,391	7,182	188,810	885
U1	5.90	1,191,123	1,065,115	47,243	9,984	7,841	1,846,659	105
U2	4.96	957,737	362,054	26,086	835	1,809	*	66
U3	4.03	585,048	460,412	24,658	3,698	3,192	641,948	478
U4	4.88	100,986	70,210	3,441	912	665	120,537	149
S1	7.50	22,414	11,807	739	134	191	39,949	56
S2	8.10	81,472	41,377	740	287	135	58,917	218
S3	3.80	16,482	288,248	498	45	253	25	13
S4	8.00	6,680	86,126	905	*	246	11,073	12
S5	17.00	31,022	145,625	1,310	163	94	33,956	42
S6	10	29,460	97,136	724	178	286	25,215	172
S7	6.80	75,884	58,567	1,584	158	187	58,303	37

* Insufficient data for estimation.

The annual runoff for the four urban main stems (sites U1-U4) ranged from 13 to 20 percent of the annual precipitation. The response was directly related to the percentage of urbanization in each watershed except for site U4. This site has a considerable amount of in-channel storage area in the watershed, allowing for more infiltration and ground-water recharge, and a somewhat lower percentage response than expected from the level of urbanization.

Annual runoff response was around 14 percent for the agricultural watersheds (sites A1-A6). The highest response, 20 percent, was at site A6 because of the well-sustained high base flow. The much lower responses for sites A1 and A5 are likely due to the low base flows above the gage sites in these watersheds.

Storm-Runoff Response

The storm-runoff responses, defined as the ratio of storm runoff to storm rainfall as a percentage, for the seven storm-sewered watersheds are listed below. The storm-response analysis was not done for urban or agricultural main-stem watersheds because hydrographs overlap too much to compute individual storm-event hydrographs. Generally, there was a nonlinear increase in response with increasing storm size. Storm-runoff response at sites S1 and S7 (the flat, sandy watersheds) changed little with increasing rainfall volume, due essentially to a large amount of impervious area and an apparently insignificant runoff from pervious areas. The response values at all sites for 1.0- and 2.0-inch storms may be a few percentage points less than actual because some delayed responses (caused by base flows and other factors) were not included in the calculations. This is especially true for site S5, which has a large amount of detention storage on roof tops.

Site	EAREA[1]	Percentage response by storm size			Regression[2] coefficient
		0.1 inch	1.0 inch	2.0 inch	
S1	17	10	14	17	13
S2	26	4	28	38	30
S3	4	2	11	14	15
S4	8	7	27	35	31
S5	54	22	37	52	42
S6	15	18	25	45	13
S7	13	14	15	15	19

1 Effective impervious area of the watershed as a percent.
2 Regression coefficient for TRAINA in table 2 (times 100).

The percent responses for 0.1-inch rainfall are all somewhat less than would be expected based on the EAREA (percentage of effective impervious area) for each watershed. This probably results from the effects of detention storage on impervious areas. Responses at Sites S2 and S5 are small, but both contain a large amount of impervious area in parking lots (and roof-top storage in S5) that may provide storage in depressions.

Of the three storm sizes, the 1.0-inch storm responses are most directly related to EAREA for each watershed. Most responses are higher than would be expected from EAREA, indicating that pervious areas also are contributing runoff, especially at sites S3, S4, and S6, which are the steeper watersheds. Although the response at site S5 is the highest, it is still considerably lower than would be expected from EAREA; again, roof-top storage in this light-industrial area may be the reason.

The storm-runoff responses for 2-inch storms are a combined function of EAREA and pervious-area response, where the steeper watersheds (sites S3, S4, and S6) have sizeable runoff from pervious areas and the flat, sandy watersheds (sites S1 and S7) do not. Again, roof-top and other detention storage greatly affects storm response at site S5 and contributes to delayed flows not included here in calculations of storm response.

There are significant water-quality-loading implications as a result of runoff-response dependence on storm size for urban storm-sewered watersheds. Generally, the effect of detention storage in impervious areas on runoff loading becomes insignificant at around 0.25 inch of rain, below which runoff loading is derived principally from effective impervious areas. Above this amount, runoff from pervious areas plays an increasingly significant role; more so in steeper urban watersheds in which as much as 75 percent of the runoff from a 2-inch storm may be derived from pervious areas (sites S3 and S4). Hence, the source of load constituents expands as storm size increases. This is in contrast to an almost negligible pervious-area response in the flat, sandy watersheds (sites S1 and S7) even for 2-inch storms. As a result, the annual runoff response is lower at sites S1 and S7, as is the annual load response (assuming the same type of impervious areas).

Seasonal-Runoff Response

The seasonal-runoff response, defined as the ratio of 2-year frequency seasonal runoff to 2-year frequency seasonal precipitation expressed as a percentage, for each watershed is fairly consistent within each of the groupings shown below. However, major differences between groups occurred primarily during summer and fall, seasons when most of the agricultural-watershed responses were considerably less than 10 percent. These low responses in agricultural watersheds are a result of pervious area runoff being reduced by high evapotranspiration and low soil moisture that occur in summer and fall. The response in urban watersheds ranged between 10 and 68 percent in summer and fall depending on the relative importance of pervious area runoff in each watershed. The percentage response from urban watersheds was less variable from season to season due to the role of impervious area contributions to runoff. The winter season responses in all watersheds are affected by snowfall accumulation and frozen-soil conditions.

2-year frequency seasonal runoff response by season					
Site	Snowmelt	Spring	Summer	Fall	Winter
	Agricultural watersheds				
A1	25	11	1	1	3
A2	46	12	5	2	20
A3	38	16	9	3	4
A4	36	20	10	10	3
A5	41	7	2	1	3
A6	49	25	11	20	30
	Urban main-stem watersheds				
U1	33	27	26	12	12
U2	50	19	10	10	24
U3	32	12	15	14	11
U4	34	15	22	10	4
	Urban storm-sewered watersheds				
S1	33	26	25	18	9
S2	35	26	31	18	8
S3	--	18	19	11	--
S4	47	24	29	16	12
S5	54	63	68	43	12
S6	44	34	35	23	11
S7	40	22	21	14	6

The snowmelt season yielded the highest percent response (about 40 percent) in all watersheds except S5. The higher yield is a result of frozen-soil conditions, delayed melting of snow that fell earlier in the winter, and rainfall during snowmelt. The high responses at sites A2, A6, and U2 during the fall and winter seasons reflects the high base-flow discharge in these watersheds.

Seasonal Distribution of Runoff and Loads

The percentage of the annual runoff that occurs in each season, defined as the ratio of long-term median seasonal to long-term median annual runoff as a percentage, depends on the type of watershed (table 6). Seasonal runoff in agricultural watersheds was greatest in the snowmelt period (January 1-April 15) and gradually declined throughout the year. In contrast, the seasonal

Table 6.—Distribution of annual precipitation, runoff, and loads by season and watershed group

Group[1]	Percent of annual by season				
	Snowmelt	Spring	Summer	Fall	Winter
			Precipitation		
Site AP rain gage	17	25	34	17	6
			Runoff		
Agricultural	49	26	15	6	4
Urban	31	22	32	10	5
Storm-sewered	23	25	38	12	2
			COD		
Agricultural	52	27	14	5	2
Urban	34	23	30	10	3
Storm-sewered	34	20	32	10	4
			TSS		
Agricultural	54	25	14	5	2
Urban	34	20	33	8	5
Storm-sewered	19	27	43	9	2
			TKN		
Agricultural	53	26	14	5	2
Urban	33	22	32	10	3
Storm-sewered	27	25	36	9	2
			NN		
Agricultural	55	23	14	5	3
Urban	33	21	32	9	4
Storm-sewered	32	22	32	10	4
			TP		
Agricultural	55	24	14	4	3
Urban	35	21	35	7	2
Storm-sewered	24	26	38	9	3

Table 6.—Distribution of annual precipitation, runoff, and loads by season and watershed group—Continued

Group[1]	Snowmelt	Spring	Summer	Fall	Winter
	Percent of annual by season				
			Pb		
Agricultural	52	30	12	4	2
Urban	34	21	32	8	5
Storm-sewered	39	14	31	9	4
			Cl		
Agricultural	46	29	15	6	4
Urban	32	21	34	9	2
Storm-sewered	83	2	2	1	12

[1] Agricultural includes sites A1-A6; urban includes sites U1-U4; and storm-sewered includes sites S1, S2, S4-S7; site S3 was not used because of the effects of construction in the watershed on runoff and loads.

distribution of runoff in the more impervious urban watersheds, especially storm-sewered watersheds, generally reflects the distribution of precipitation (table 6) with a maximum contribution in summer (June 16-September 15). A lower percentage contribution in fall and winter is due to reduced response from pervious areas caused by reduced soil-moisture conditions.

The seasonal distribution of loads for COD, TSS, TKN, NN, TP, Pb, and Cl was nearly the same as the distribution of runoff from each watershed, illustrating the dominant role of runoff volume in generating loads. However, there tended to be a disproportionate load (relative to runoff) associated with the snowmelt season for the storm-sewered watersheds (Sites S1-S7) for COD, TKN, NN, Pb, and Cl, but not for TSS and TP.

Seasonal Concentration Trends

Average flow-weighted seasonal concentrations were determined using the following equation:

$$\text{Concentration (in milligrams per liter)} = \frac{\text{Load (in pounds)}}{\text{Runoff (in inches)} * 4622}$$

where the load and runoff are the medians of the 1963-80 seasonal values derived from regression modeling for each watershed. Trends in average concentration from season to season for each site were compared. Results of the comparison are given below.

	Trends in average seasonal concentrations from snowmelt to winter[1]		
	Sites with less than 20 percent variation	Sites with 20-100 percent decrease	Sites with other trends
COD	A2, A4, U1, U2, S6, S7	A1, A3, A5, A6, U3, U4, S1, S2, S4, S5	S4, much variation
TSS	A2, A4, U4, S5, S6	A1, A3, A5, A6, U2, U3, S2, S2, S7	U1, 30-percent increase S4, 6-fold summer high
TKN	A2, A4, A5, U2, U4, S1, S4, S5, S6	A1, A3, A6, U1, U3, S2, S7	--
NN	A3, U1, U2, U4, S2, S7	A1, A2, A4, A5, U3, S1, S4, S6	A6, 50-percent increase S5, much variation
TP	A1, U1, U4	A2, A3, A4, A5, U2, U3, S1, S2, S7	A6, 700-percent increase S4, summer high S1 and S7, spring high
Cl	A1, A2	U4	other agricultural and urban sites on main stems, 20-40 percent increase storm sewers, 100-fold decrease spring to fall

[1] Trends at Site S3 were not included because of the effects of construction in the watershed on loads.

Seasonal concentrations of the six constituents generally were either stable or declining from snowmelt to winter at most sites. Watersheds with higher percentages of wetlands and lakes and slower runoff responses tended to have the most stable concentrations. Concentrations of the six constituents were also stable in some storm sewer watersheds, suggesting that the source of loading is consistent throughout the year.

Many of the agricultural and urban main-stem sites exhibited declining concentrations from snowmelt to winter, likely in response to decreasing erosion and transport owing to increasing vegetation cover and to decreasing runoff owing to decreasing soil moisture. Concentrations in runoff from storm-sewered watersheds was fairly stable except during snowmelt, which gives an appearance of declining concentration over the year.

Runoff from most agricultural and urban main-stem watersheds showed a slight increase in Cl concentrations over the year, probably reflecting the effects of evapotranspiration and ground-water discharge in summer and fall. The storm-sewered watersheds, however, showed a 100-fold decrease in Cl during spring, summer, and fall as compared to the winter and snowmelt periods when deicing salts are used.

Concentrations of NN in runoff at site A6 increased 50 percent during the year, which is opposite to the normally expected decline in concentrations of NN during summer and fall. Irrigation-return flows in this high-base-flow watershed are a likely source of NN. TP concentrations for this site declined 7-fold from snowmelt to winter, likely due to a low TP concentration in base flow.

The effects of a small amount of construction in the watershed above site S4 were reflected in highly variable COD and summer highs in TSS and TP. Concentrations of TP were high at sites S1 and S7 in spring rather than during snowmelt, but still declined 20 to 100 percent over the year.

SUMMARY AND CONCLUSIONS

Nonpoint-source runoff was studied in 6 agricultural and 11 urban watersheds typical of the Twin Cities Metropolitan Area. Objectives of the study were to quantify and characterize storm and annual runoff and loads from representative watersheds, provide information on transport mechanisms of problematic water-quality constituents, and develop a method for estimating storm and annual runoff and loads from unsampled watersheds in the study area. All but the last objective were met. Followup work by Brown (1984; R. G. Brown, written commun., 1984) led to a set of reliable estimating equations.

Flow, precipitation, and water-quality data were collected for 15 to 30 storms and for most snowmelt periods in 1980. Event or daily-flow and load models (COD, TSS, TKN, NN, TP, Cl, and Pb) were developed for summer and winter weather conditions. The models were used with long-term daily runoff and rainfall data to compute 1963-80 daily flows and loads for each selected watershed. The models were highly dependent upon the hydrologic characteristics of each watershed.

As would be expected, total-storm-rainfall volume proved to be the most significant factor in models of both runoff and loads in storm-sewered watersheds. Storm runoff from watersheds with large percentages of pervious area was related to antecedent soil-moisture indices; whereas, storm runoff from the more impervious watersheds was related to various rainfall-intensity factors.

Peak-flow volume was primarily a function of rainfall intensity, although antecedent-soil moisture also affected peak flows significantly in the steeper, more-pervious watersheds.

In addition to total rainfall, factors related to rainfall intensity and to runoff from pervious areas also were significant in load models. Factors related to reduced loads owing to washoff by previous rains were significant only for load models of the more impervious watersheds. The role of particle or constituent accumulation on surfaces during dry weather was significant only for TSS, TP, and Pb models in a flat sandy watershed where runoff was derived principally from impervious areas.

The 2-year frequency annual and seasonal flows and loads computed from 1963-80 data were analyzed for various trends. Annual runoff responses were highest for storm-sewered watersheds, averaging about 27 percent of the mean annual precipitation for that period. Annual runoff responses were found to be related to the percent of effective impervious area in all storm-sewered watersheds, suggesting that runoff contributed from pervious areas is significant even in highly urbanized environments.

Annual runoff response for urban main-stem watersheds ranged from 13 to 20 percent and was found to be directly proportional to the percentage of urbanization in each watershed. Annual runoff response was about 14 percent for agricultural watersheds.

The 2-year frequency seasonal runoff response was greatest in all watersheds during snowmelt (January 1-April 15), averaging about 40 percent of the seasonal precipitation. The high seasonal response was primarily related to runoff from pervious areas owing to the combined effect of frozen soil and melting of snow that fell earlier in the winter. However, large differences between watersheds were evident during summer and fall owing to the influence of evapotranspiration and low soil moisture in lowering pervious-area runoff. Responses from agricultural watersheds were considerably less than 10 percent; whereas, responses from urban watersheds ranged between 10 and 68 percent for these seasons. Response from the urban watersheds was more consistent from season to season owing to contributions from impervious areas and response to virtually all rainfall events regardless of season.

The storm-runoff response from the seven storm-sewered watersheds increased with storm size, more so for the steeper watersheds than for the two flat, sandy watersheds. With less than about 0.25 inch of rain, runoff was derived principally from effective impervious areas. Detention storage in impervious areas apparently lowered the response from very small rains (less than 0.1 inch). With more than 0.25 inch of rain, runoff from pervious areas played an increasingly significant role, more so in the steeper watersheds. As much as 75 percent of the runoff following a 2-inch rain was derived from pervious areas in steeper watersheds. In the flat, sandy watersheds the pervious area runoff after a 2-inch rain was negligible. Storm-runoff response for 2-inch rains ranged from 14 to 52 percent of the rainfall, which contrasts with a range of 2 to 22 percent for a 0.1-inch rain at the seven sites.

Although an analysis of storm response was not possible for main-stem watersheds because of storm overlap, the difference in response between small and large storms probably was considerably greater than differrences between storm-sewered watersheds owing to the large amount of pervious area in the main-stem watersheds. The literature abounds with evidence, and it was observed in this study, that larger storms often dominate nonpoint-source runoff and loading from pervious watersheds.

As a result of differences in storm and seasonal responses to rainfall, there were contrasting differences in the distribution of runoff and loads over the annual cycle. The seasonal distribution of runoff in the more impervious urban watersheds, especially those with storm sewers, followed closely the distribution of annual rainfall by season, with maximum contributions in summer (June 16-September 15). The percentage of runoff during snowmelt was somewhat higher (frozen ground and delayed melting) and was somewhat lower during fall and winter (low soil moisture and less response from pervious areas). In contrast, the percentage distribution of runoff in agricultural watersheds did not follow the seasonal distribution of precipitation. Runoff from agricultural watersheds was by far greatest in the snowmelt period and gradually declined throughout the year owing to decreasing soil moisture.

Seasonal distribution of loads of COD, TSS, TKN, NN, TP, Pb, and Cl followed nearly the same distribution as runoff from each site, which results from the dominating role of runoff in generating loads. However, there tended to be disproportionate loads relative to runoff during snowmelt in the storm-sewered watersheds for COD, TKN, NN, Pb, and Cl, but not for TSS and TP.

Average flow-weighted seasonal concentrations were reasonably stable (less than 20 percent variation) through the year at the main-stem sites with a higher percentage of wetlands and lakes in the watersheds and with slower runoff responses. Seasonal concentrations at some storm-sewered sites also were stable, suggesting a consistency of source or mechanisms. Most of the rest of the watersheds exhibited declining (20 to 100 percent) seasonal concentrations through the year, likely in response to both decreasing erosion and transport associated with increasing amounts of vegetation cover and to decreasing runoff response resulting from decreasing soil moisture. Storm-sewered watersheds exhibited stable seasonal concentrations in all but the snowmelt period, which gives an overall appearance of declining concentrations during the year.

Results of this study suggested that as topographic relief and urbanization in a watershed increase, runoff volume and the need for measures to control runoff also will increase. A strong dependence of loading on runoff volume suggested that any practices that increase detention of rainfall at or near the source will reduce runoff volumes and, concommittently, most constituent loads.

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