STORMWATER QUALITY PROCESSES FOR THREE LAND-USE AREAS IN BROWARD COUNTY, FLORIDA

U.S. GEOLOGICAL SURVEY
Water-Resources Investigations 81-23

Prepared in cooperation with the

BROWARD COUNTY TRANSPORTATION DEPARTMENT
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Stepwise, multiple, linear regression models were constructed for total nitrogen, total phosphorus, total carbon, chemical oxygen demand, total residue, lead, and zinc. Loadings, pounds per day per acre of hydraulically effective impervious area, were computed based on measured, modeled, and estimated loads for the three areas.

Atmospheric loads were estimated from chemical analyses of bulk precipitation collected at the highway and commercial sites. The atmospheric contribution to the runoff loads were 49 percent or more for all seven constituents at the two sites.

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CONVERSION FACTORS

For use of those readers who prefer to use metric (SI) units rather than inch-pound units, the conversion factors for the terms used in this report are listed below:

Inch-pound units	By	To obtain metric (SI) units
inch (in)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
acre	0.4047	hectare (ha)
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
pounds per day (lb/d)	0.454	kilograms per day (kg/d)

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ABSTRACT

Systematic collection and chemical analysis of stormwater runoff samples from three small urban areas in Broward County, Florida, were obtained between 1974 and 1977. Thirty or more runoff-constituent loads were computed for each of the homogeneous land-use areas. The areas sampled were single-family residential, highway, and a commercial shopping center.

Rainfall, runoff, and nutrient and metal analyses were stored in a data-management system. The data-management system permitted computation of loads, publication of basic-data reports and the interface of environmental and load information with a comprehensive statistical analysis system. Seven regression models relating water quality loads to characteristics of peak discharge, antecedent conditions, season, storm duration and rainfall intensity were constructed for each of the three sites.

Total water-quality loads were computed for the collection period by summing loads for individual storms. Loads for unsampled storms were estimated by using regression models and records of storm precipitation.

Loadings, pounds per day per acre of hydraulically effective impervious area, were computed for the three land-use types. Total nitrogen, total phosphorus, and total residue loadings were highest in the residential area. Chemical oxygen demand and total lead loadings were highest in the commerical area.

Loadings of atmospheric fallout on each watershed were estimated by bulk precipitation samples collected at the highway and commercial sites. Atmospheric contributions to runoff loads were 49 percent or more for all seven constituents at the two sites. Atmospheric loads exceeded the estimated stormwater runoff loads for total nitrogen, total phosphorus, and total zinc at the highway area. Total zinc from bulk precipitation exceeded runoff load at the commercial site.

INTRODUCTION

South Florida has an extensive system of drainage canals, which provide protection from flooding during extreme periods of rainfall. Many storm drains discharge directly into the canal system, affecting the composition of the surface-water quality. A cooperative program between the U.S. Geological Survey, Broward County Transportation Department, Broward County Environmental Quality Control Board, the Florida Department of Transportation, and the Florida Department of Environmental Regulation was initiated in 1974 to define stormwater loadings for three separate urban land-use areas. The three areas--single-family residential, highway, and commercial--were chosen to be representative of sewered urban areas of south Florida (fig. 1).

An automated instrumentation system, the urban hydrology monitor, was used to obtain time-synchronous rainfall, runoff, and water-quality samples. Water-quality samples for 30 or more rainfall-runoff periods were collected over 2 years at each land-use area. Nutrient, metal, and other water-quality constituents were determined for a wide variety of storm sizes and lengths of antecedent dry period.

The extensive basic data for each of the three areas were assembled in a data-management system that permitted formating and publishing the data and access to the data for analysis. Multiple regression analyses were used to gain insight into quality processes and to establish predictive equations relating storm loads of seven constituents to storm characteristics.

Purpose and Scope

The four objectives of this investigation were to:

1. Collect a systematic data base of rainfall, runoff, and water-quality for typical urban watersheds in south Florida,

2. describe the range of constituent concentrations and factors influencing concentrations,

3. estimate annual loads, and

4. transfer the water-quality load and concentration information to similar urban areas in south Florida.

The first objective has been realized by the publication of three basic-data reports containing detailed rainfall, runoff, and water-quality and load information. Various storm conditions affecting stormwater quality are assessed in this report through the use of correlation. Logical arguments to define concentrations in terms of runoff are also presented. Estimation of annual loads was accomplished by extrapolating statistically determined regression models or by using deterministic models. Extrapolation of statistical models to estimate annual loads are included in this report.

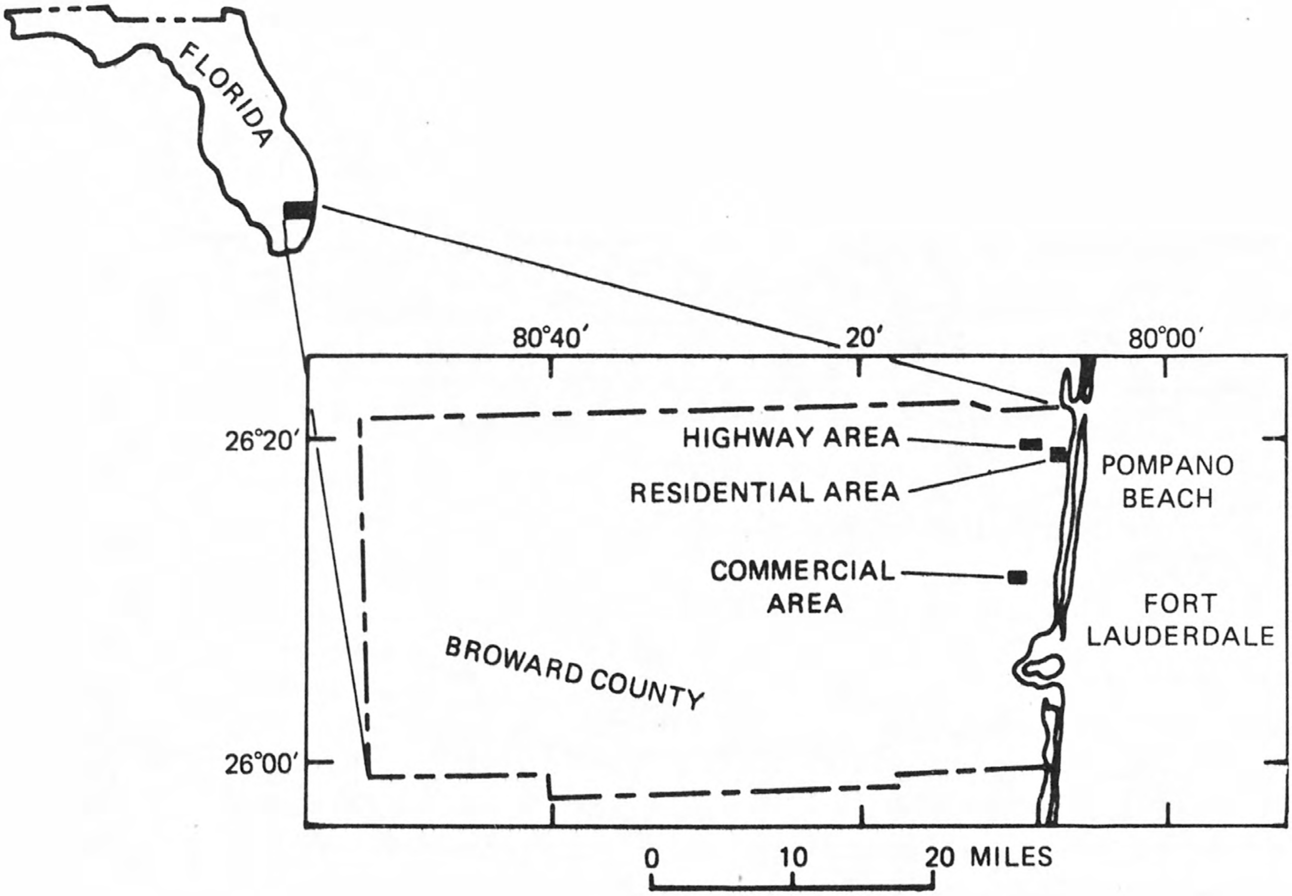

Figure 1.--Location of stormwater runoff areas in Broward County.

Data collected as part of this investigation have been used to calibrate a deterministic model, STORM (U.S. Army Corps of Engineers, 1976) by several regional and county agencies. A companion report (Miller, 1979) on the basin characteristics including detailed hydraulic information on the three areas, is designed to encourage further modeling efforts by interested investigators.

Transfer of the results to other similar areas of south Florida has been done with a variety of techniques by the 208 planning agencies in Dade, Broward, and Palm Beach Counties. Wider application of the data base is expected and encouraged by a free exchange of information with other investigators.

INVESTIGATION-AREA DESCRIPTIONS

Residential Watershed

A single-family residential area was chosen for investigation of stormwater quality because it represents the single largest unit of urban land use in southeast Florida (fig. 1). The area selected was considered very representative of Broward County and had a typical swale drainage system.

The single-family residential watershed of 40.8 acres is near Pompano Beach, Florida (fig. 2). The basin slopes gently to the east and is drained by a collector sewer system that gathers water that runs overland in shallow, grassed, road-side swales. The collector system feeds a 36-inch storm drain which eventually discharges water to an intracoastal waterway canal. Discharge is measured by gaging within the 36-inch storm sewer.

The 219 single-family residences are concrete block structures built around 1959 on lots averaging 80 feet by 100 feet. Little or no construction took place between April 1974 and September 1975, the period of data collection.

Fifty-six percent of the area is covered by bermuda grass growing on pervious muck which overlies quartz sand. The fine quartz sand has high permeability and infiltration capacity. The grassy swales through which water is routed generally infiltrate water rapidly. As a result, the 44 percent impervious area (roofs, driveways, and streets) are not hydraulically interconnected except under conditions of intense rain of long duration.

Basic data for the residential site have been summarized in an open-file report (Mattraw and others, 1978). Mattraw and Sherwood (1977) estimated annual loads from the area using an empirical, seasonally-adjusted, rainfall model.

Highway Watershed

The highway watershed was chosen to ascertain the impact of moderate-volume traffic on stormwater quality. The area selected had negligible runoff from adjacent commercial and residential areas.

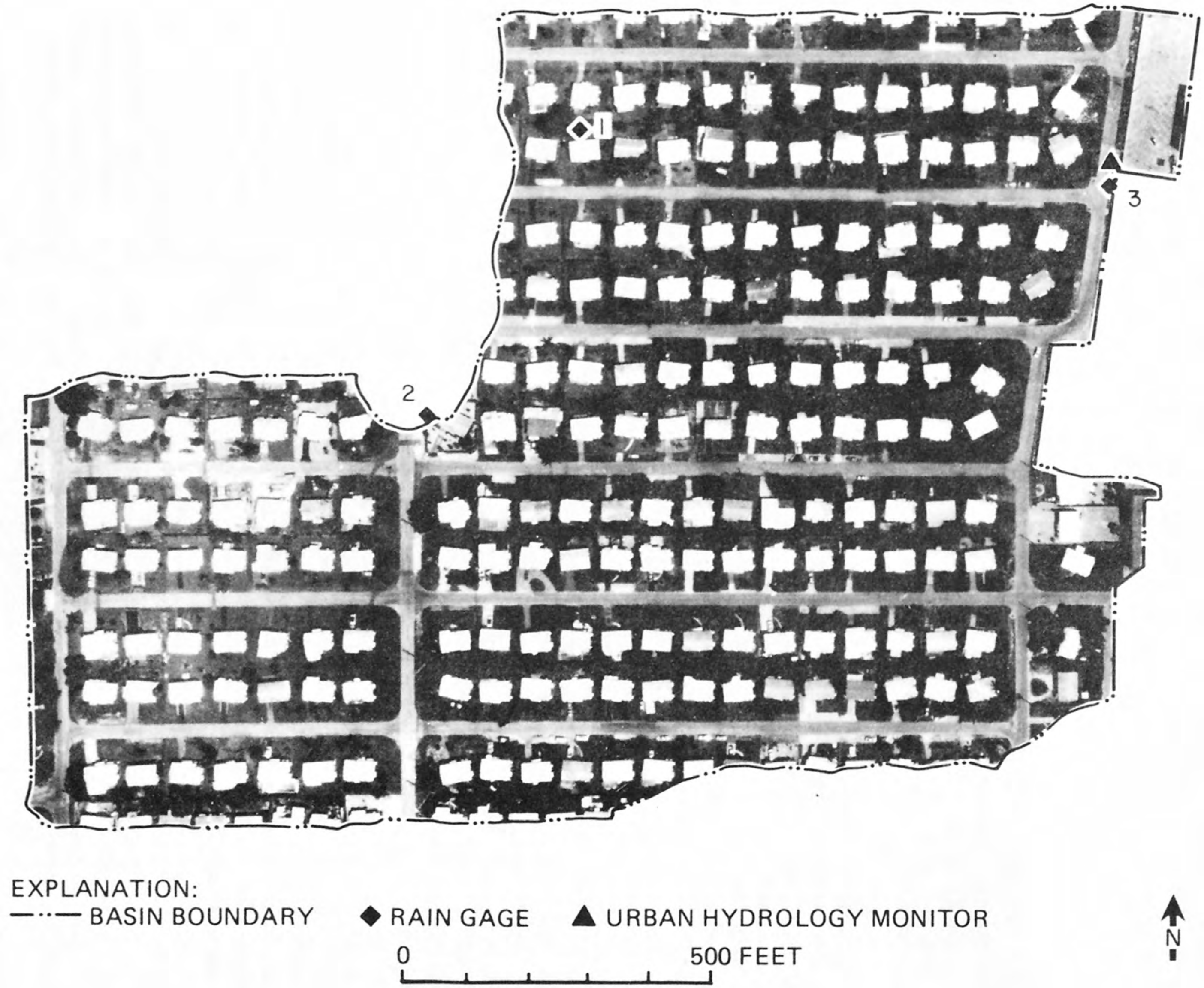

Figure 2.--Single-family residential area near Pompano Beach.

The highway watershed comprises 58.3 acres and includes a 3,000-foot long segment of Sample Road (fig. 3), a six-lane divided highway with curb and gutters. Approximate traffic flow is 20,000 vehicles per day. Data were collected in the basin between April 1975 and June 1977.

Roadside development is sparse with large areas of unimproved sand soil that rainfall readily infiltrates. Thirty-five individual inlets feed the main sewer, which drains to an infiltration pond at the west end of the area. The discharge is gaged in a 42-inch diameter section of pipe 150 feet from the outfall. Hardee and others (1978) summarized the rainfall-runoff, water-quality, and storm-load information.

Commercial Watershed

The commercial watershed is part of a 28.4-acre regional shopping mall, Coral Ridge Shopping Center, located in downtown Fort Lauderdale, Fla. The mall is located at the northeast corner of the intersection of Oakland Park Boulevard and U.S. Highway 1 (fig. 4). Data were collected between May 1975 and June 1977.

The entire shopping center is impervious roof or parking-lot pavement, except for several small tree islands which are pervious. The northern part of the parking lot drains to an infiltration gallery. The remaining 20.4 acres of roof and parking lot are drained through two collector systems, which join near the southwest corner of the basin. Tidal water stands in the 36-inch diameter pipe, necessitating submergence corrections to low-flow computations. Miller and others (1979) published a summary of rainfall-runoff, water-quality, and storm-load data.

EQUIPMENT AND OPERATION

An automated monitoring system was developed by the U.S. Geological Survey (Smoot and others, 1974; Hardee, 1979) to measure stormwater quantity and quality in sewers. The instrumentation system records rainfall and runoff data and activates the water-sampling equipment. All functions of the system, shown in figure 5, were recorded on a six-channel analog recorder at 36-second intervals.

Rainfall was recorded by as many as three, commercially available, tipping-bucket rain gages with a measuring resolution of 0.01 inch. Data from remote gages were relayed by commercial telephone lines. Successive tips of the bucket in the raingage were accumulated on a sliding-wire potentiometer and transferred to the recorder chart at the 36-second sampling interval.

Flow in the storm drains was computed from the continuous records of water pressure at a piezometer in the storm drain upstream of a U-shaped Venturi-type constriction and a piezometer in the throat of the constriction. The pressure from the piezometers was converted to an electrical response by pressure transducers and then recorded on the analog chart.

Rainfall and stage records were converted to a digital form and entered into the data-management system on a 1-minute interval. Computations of flow were calculated from the head, or difference in head, of the two piezometers depending on the flow conditions.

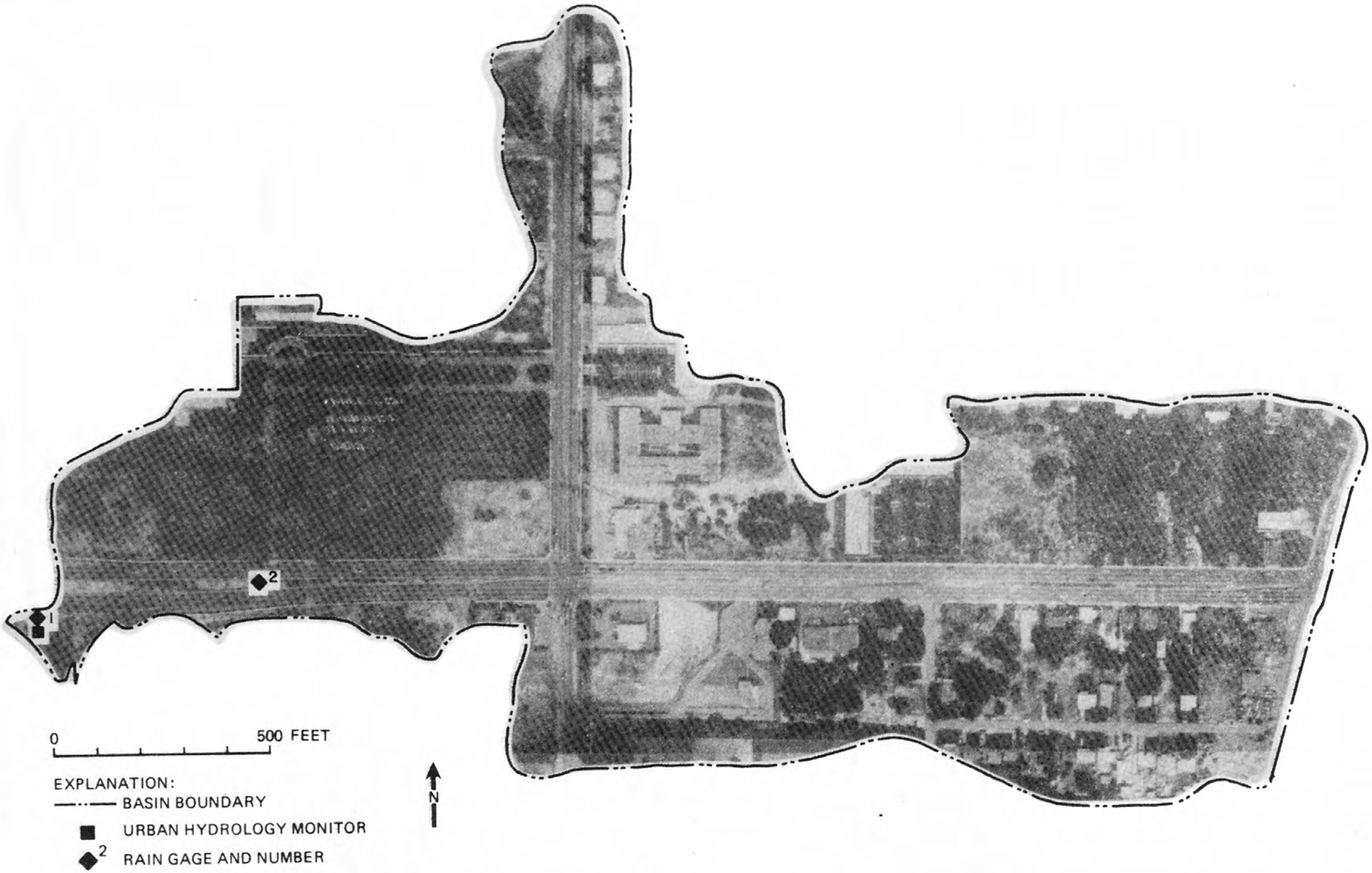

Figure 3.--Sample Road highway area.

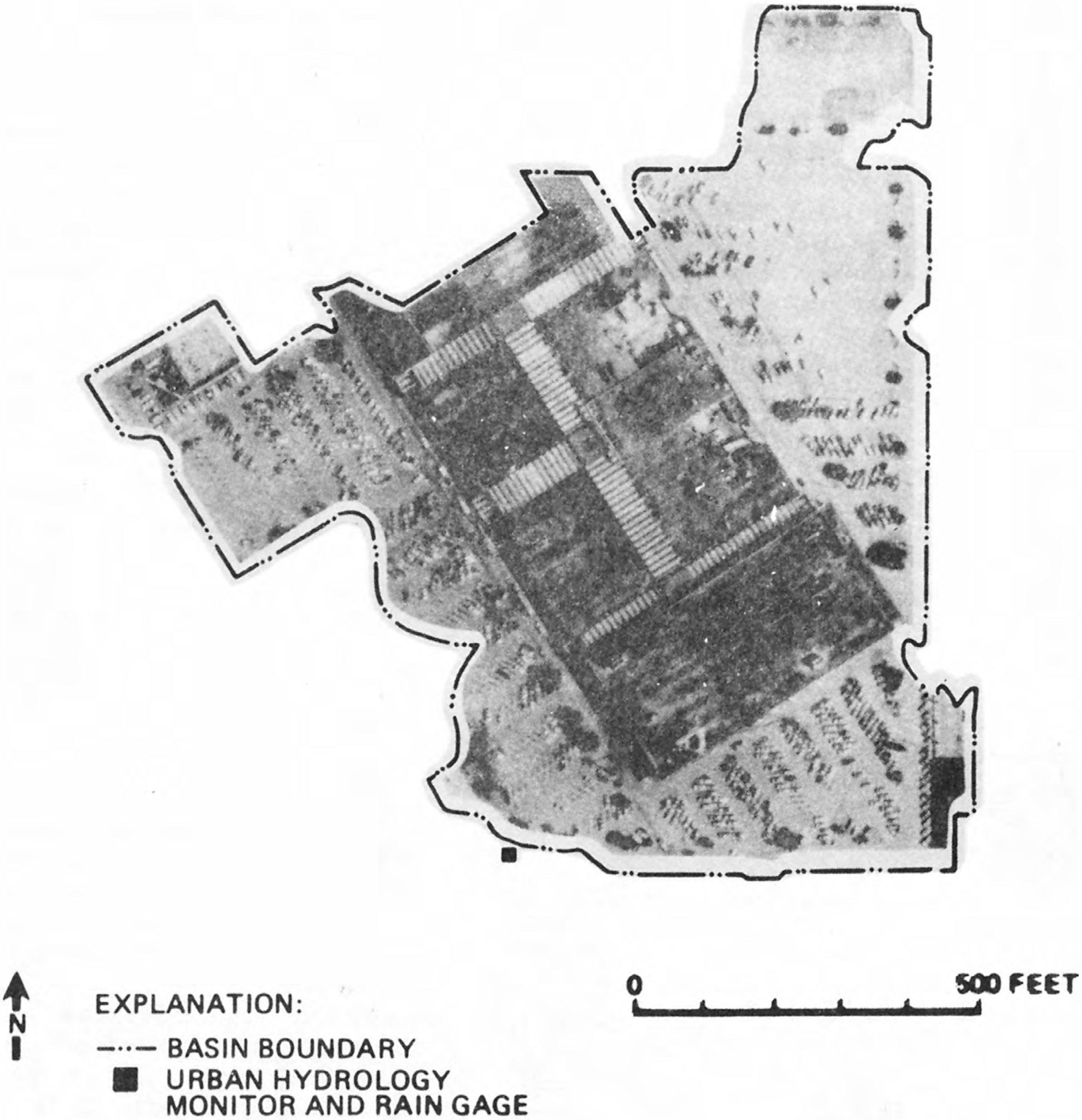

Figure 4.--Coral Ridge Shopping Center in Fort Lauderdale.

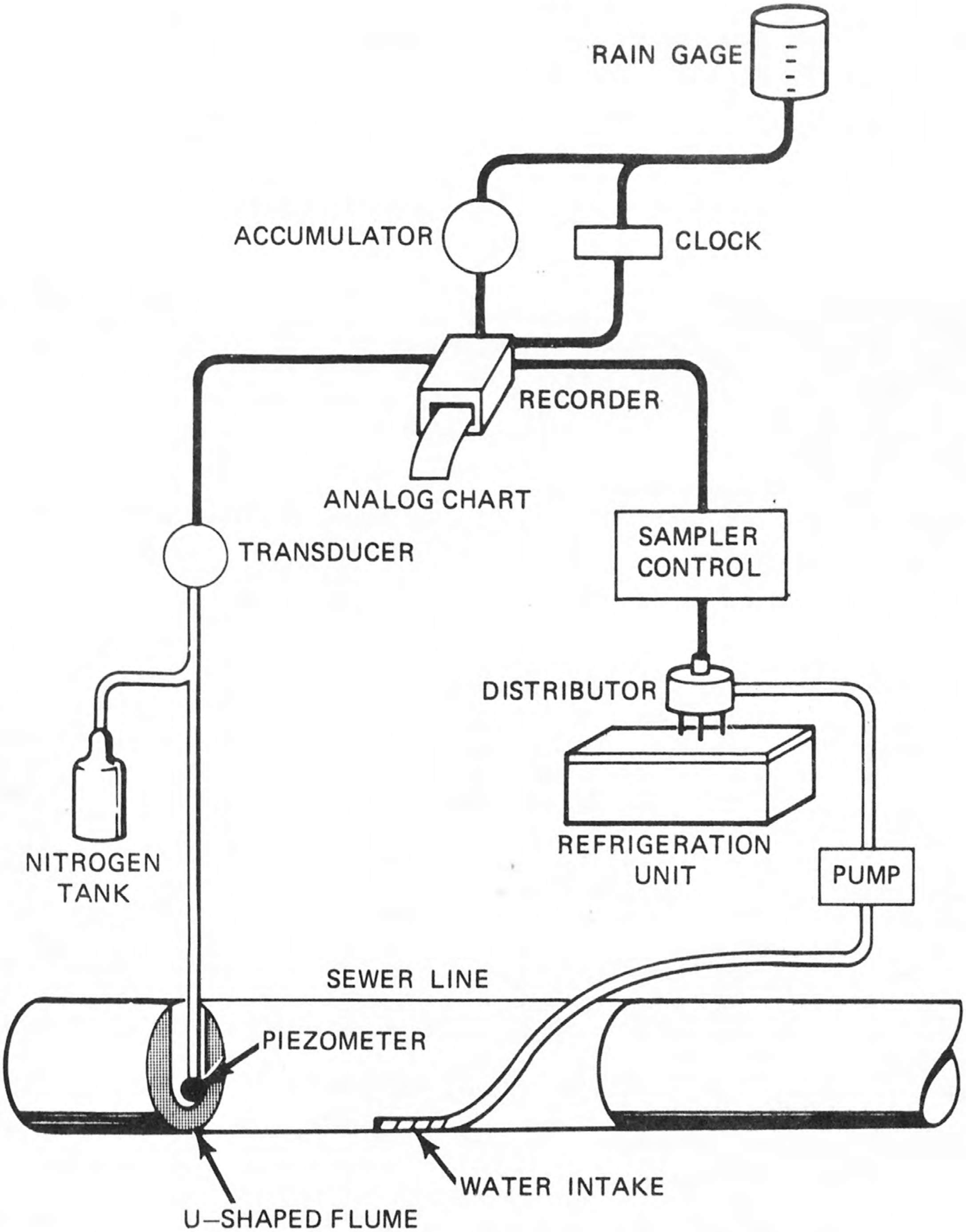

Figure 5.--Instrumentation configuration.

The continuous flow water-quality sampler collected 24 (2-liter) samples on a preset time interval, usually between 2 and 7 minutes. Sampling was initiated by a preselected water stage on the upstream piezometer. Stormwater was continuously pumped through the distribution system, and at preset times filled a 2-liter bottle in 10 seconds. Water pumped between sample collection periods was wasted back to the storm sewer. When the sample distributor had cycled through the 24 samples, a trip switch shut off the pump. The polypropylene sample bottles were housed in a refrigeration unit maintained at 4°C. Samples were later retrieved and delivered to the laboratory for chemical analyses. Results of the chemical analyses were stored in the data-management system.

Bulk precipitation (dry fallout and rainfall) were collected at the highway and commercial sites for approximately one-third of the investigative period. The samples were obtained with two 11-inch diameter polypropylene funnels on the roof of the instrumentation shelter, approximately 9 feet above the land surface. During a storm the rainfall washed the collected dry fallout through polyethylene tubing into the refrigerated collection bottle.

More specific information on the equipment design is described by Hardee and others (1978). Subsequent modifications to the monitor resulted in large part from the experience gained during the investigation.

DATA-MANAGEMENT SYSTEM

A FORTRAN written, direct-access, data-management system was created to store, retrieve, and manipulate basic data collected at the three sites (Wilson and others, 1978; Miller and others, 1979). Rainfall and water-stage data were digitized from the analog chart and entered into computer storage with two programs, STORM and UPDATE (fig. 6). A program, DISCHARG, was used to compute flow which was then stored in the data base. Water-quality analyses were entered by the program QUALIN using cards that had been retrieved from the U.S. Geological Survey Water-Quality File, WATSTORE (Hutchinson, 1975). Two summary programs, RRSUMRY and QSUMRY, were used to print the tables used in the basic-data reports. LOAD used the water-quality and discharge data to calculate loads for runoff periods with adequate sampling. Several interface programs were used to make data matrices available for statistical analyses and deterministic modeling.

RAINFALL-RUNOFF PROCESS

Several factors influence the amount of rainfall that flows off an urbanized basin. The amount of impervious area and its hydraulic connection to a sewer system are the two most important factors in south Florida. An impervious area that is hydraulically connected to a sewer system has been termed the hydraulically effective impervious area (Miller, 1978). Only a relatively minor contribution of runoff is observed from pervious areas in the three watersheds studied because of the extremely shallow slopes and highly permeable soils. Detailed drainage maps for the three study areas were published by Miller (1979). Table 1 summarizes the total area, impervious area, and hydraulically effective impervious area for the three watersheds.

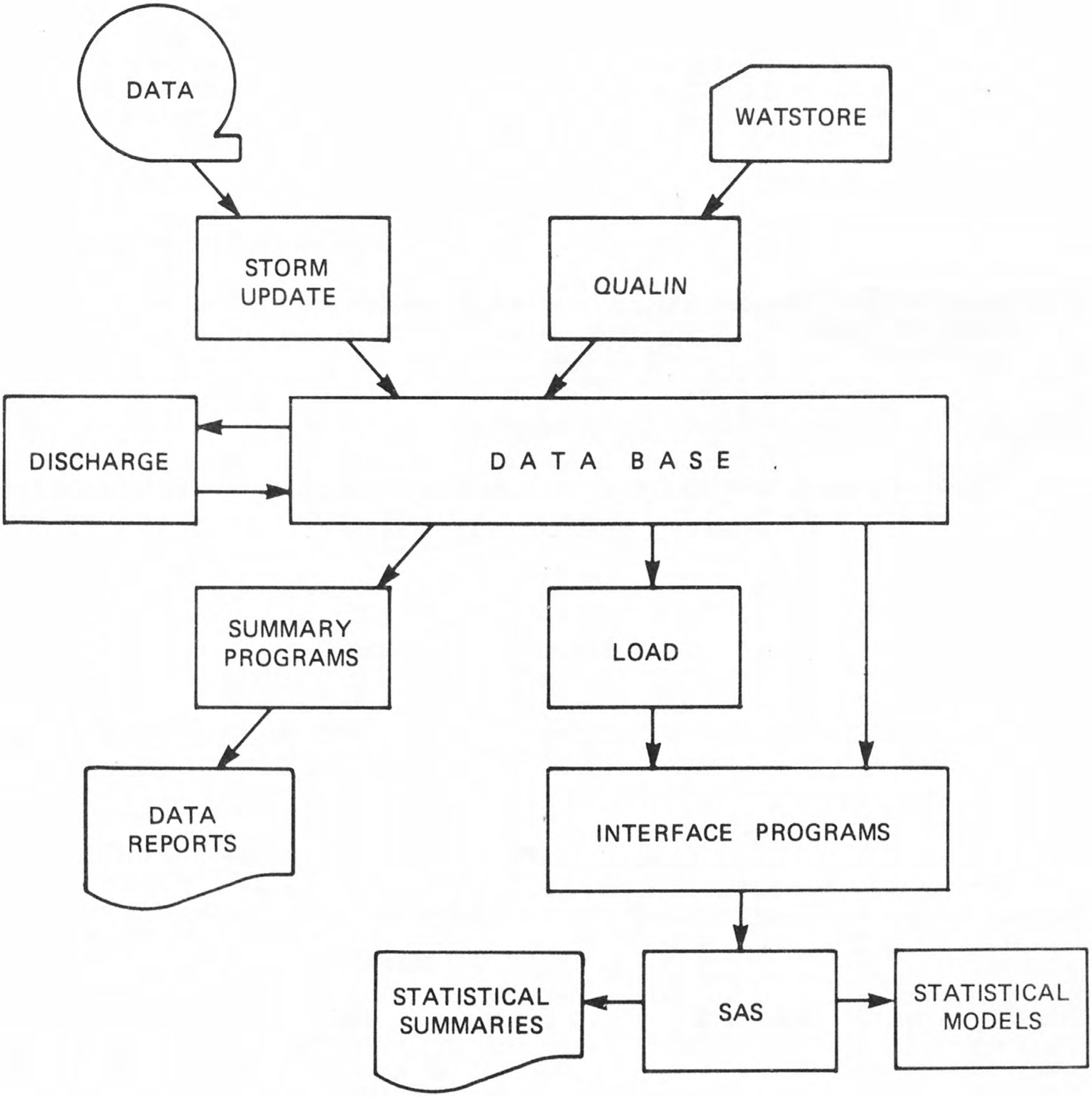

Figure 6.--Data-management system.

Table 1.--Summary of contributing drainage areas for the three watersheds

Watershed	Total area (acres)	Impervious area (acres)	Hydraulically effective impervious area (acres)	Hydraulically effective impervious area (percent)
Residential	40.8	17.9	2.4	5.88
Highway	58.3	21.1	10.5	18.0
Commercial	20.4	20.0	20.0	98.0

Residential Area

Figure 7 presents the rainfall-runoff data for the 40.8-acre residential area. Storms having less than 0.2 inch or more than 2 inches precipitation were not included in the plot. In general, the runoff was between 5 and 10 percent of the observed rain. A simple linear regression analysis for the 31 storms that had associated quality data produced the equation:

$$\text{RUNOFF} = 0.103\ \text{RAIN} - 0.017 \tag{1}$$

where both RUNOFF and RAIN are in inches.

Equation 1 states that about 10.3 percent of the rainfall, less a small portion, runs off. This equation, however, does not fit the data very well and explains only 73 percent of the variation in RUNOFF. A better representation of runoff for the 31 storms is given by the equation:

$$\text{RUNOFF} = 0.0078\ \text{PEAK} + 0.024\ \text{RAIN} \tag{2}$$

This representation includes the peak discharge for each storm (in cubic feet per second) and total rainfall (in inches). Ninety-seven percent of the variation in the data is represented by this equation.

The relatively small hydraulically effective impervious area (5.9 percent) and the shallow slope of the residential area account for the low runoff. The importance of peak discharge in the runoff regression model, equation 2, suggests that proportionally more runoff may result from previous areas during storms of high intensity. The data also indicate that saturation of pervious soils plays a significant role in producing runoff after a rainfall depth of approximately 0.8 inch has been accumulated.

Highway Area

Rainfall-runoff data for the 58.3-acre highway area are presented in figure 8. The relation is expressed by the following regression model (equation 3) based on 42 storms which had water-quality data.

$$\text{RUNOFF} = 0.19\ \text{RAIN} \tag{3}$$

The rainfall coefficient, 0.19, is extremely close to the 18.1 percent hydraulically effective impervious area noted in table 1. The regression model explained 90 percent of the variation in the runoff data for the 42 storms.

A more extensive use of the 108 digitized rainfall-runoff periods was reported by Jennings and Doyle (1978). The deterministic modeling approach they used was able to simulate runoff volumes to an average error of 12.5 percent during the verification phase. Simulations of peak flow were useable for even complex rainfall-runoff periods.

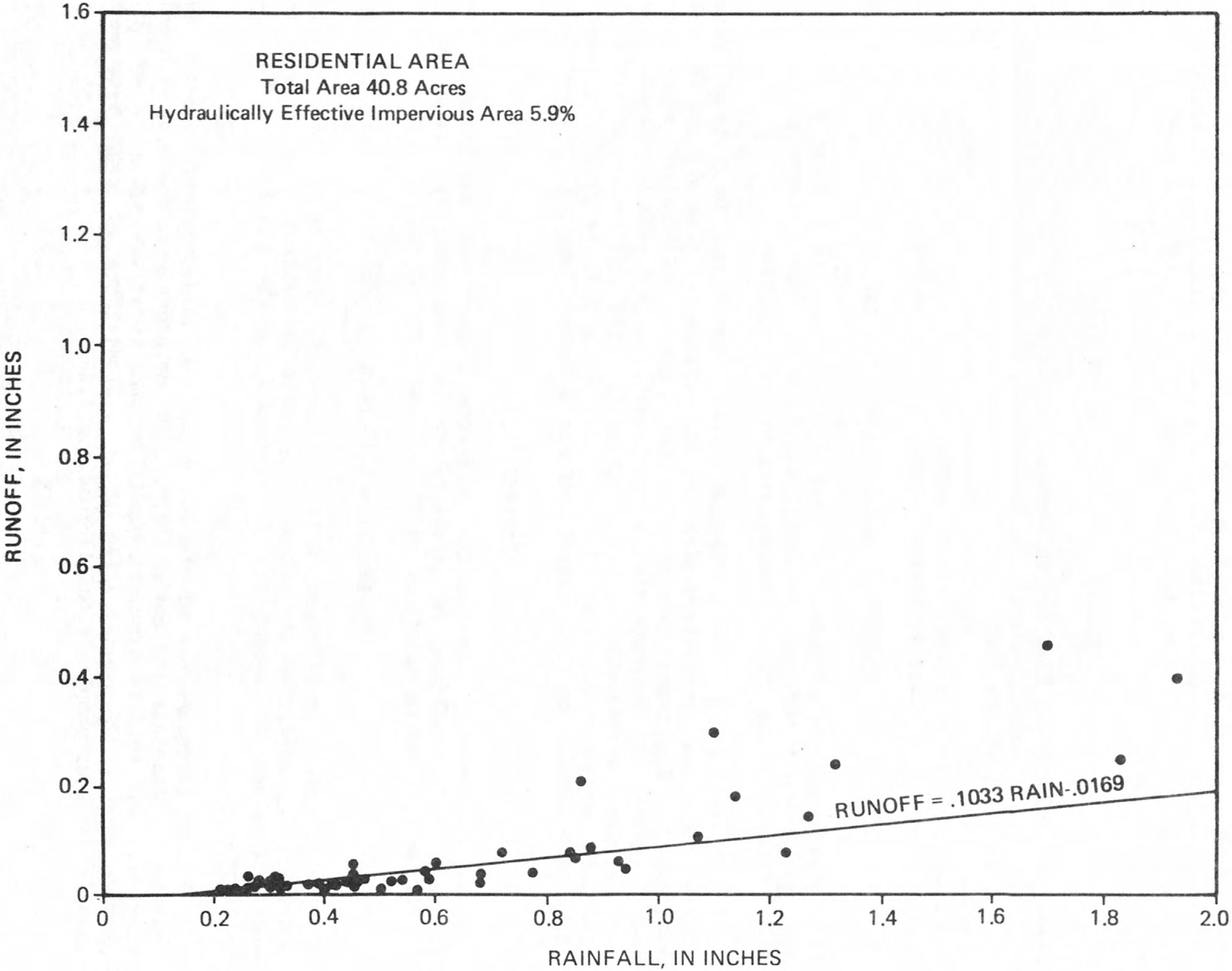

Figure 7.--Rainfall-runoff for the residential area.

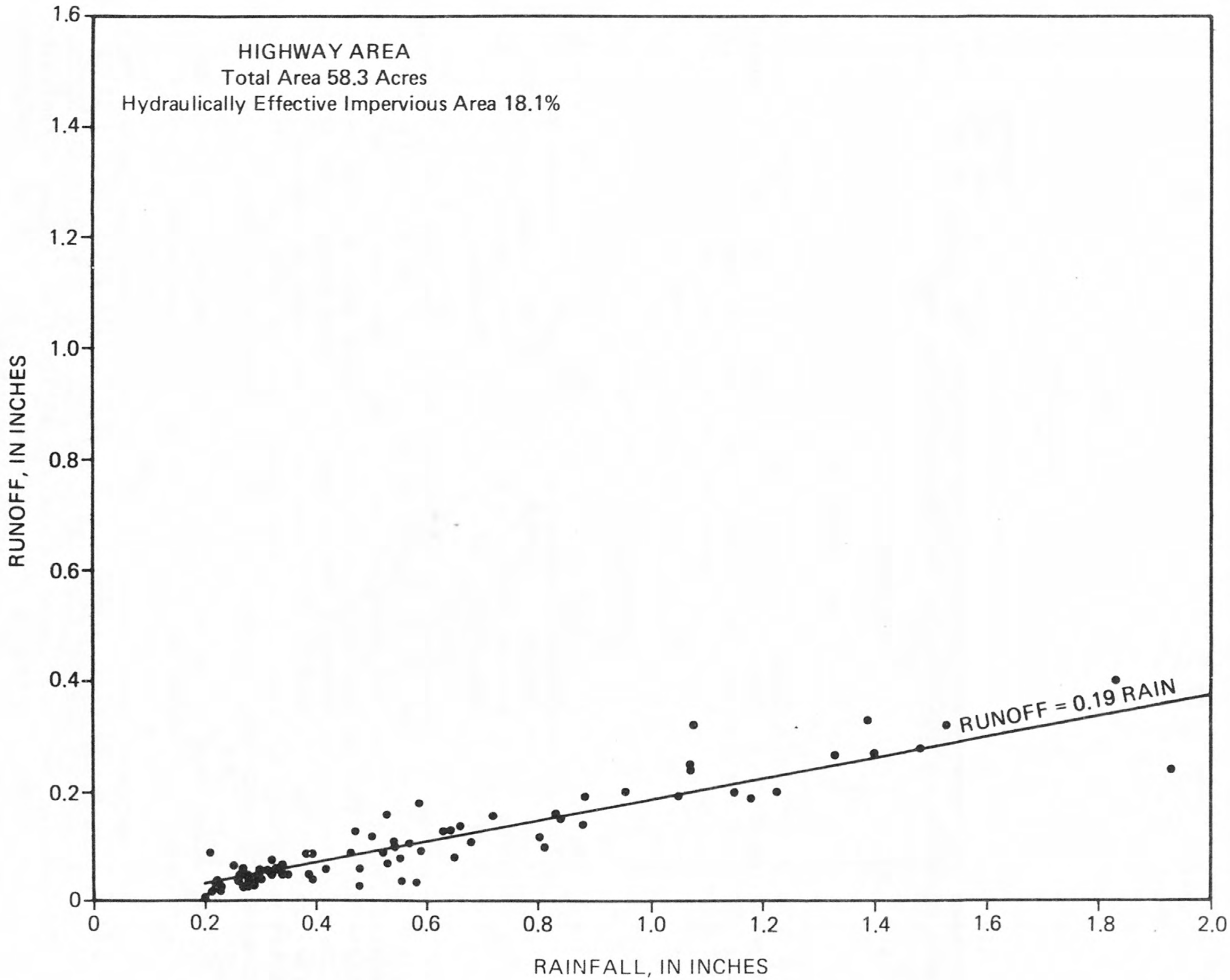

Figure 8.--Rainfall-runoff for the highway area.

Commercial Area

Figure 9 is a plot of the rainfall-runoff relationship for the commercial area. Only 0.4 acre (table 1) is pervious. The regression model for the runoff based on 31 storms which had associated water-quality data, is explained entirely by rainfall in the equation:

$$RUNOFF = 0.977\ RAIN \qquad (4)$$

The high rainfall coefficient is indicative of how well the area is paved and sewered. The coefficient is very close to the hydraulically effective impervious area, 98.4 percent, (table 1). Small-diameter roof drains connect directly into the storm-sewer system located under the parking lot. Ninety-six percent of the variation ($R^2 = 0.96$) in the runoff were explained for the 31 storm periods used in the model.

WATER-QUALITY PROCESSES

Constituent Selection

The potentially large list of water-quality constituents that could be sampled during the investigation was reduced to 29. The 29 constituents were chosen to define the concentrations and loads that may have potentially deleterious impacts on the surface-water system. Total analyses rather than filtered sample analyses were chosen in order to obtain the total loads.

Concentration Statistics

Tables 2, 3, and 4 list the number, range, average, and standard deviation for the constituents sampled at the residential, highway, and commercial sites. The number of samples collected was large in order to compute storm loads accurately for a variety of storm sizes, seasons, and antecedent dry conditions characteristics of south Florida.

A meaningful comparison of concentration between the three land-use areas is not possible due to three factors, storm size (rainfall depth), season, and point on the hydrograph during which the sample was collected. These three factors introduce a sample bias that must be understood and accounted for before making a direct comparison with other land-use areas. For example, the residential area has the highest average concentration of total nitrogen, 2.0 mg/L, and this might coincide with our expectations considering lawn fertilization and a higher incidence of domestic animals.

The storm size is important because a finite amount of total nitrogen is available to be washed off the basins. A smaller storm would have higher concentrations of total nitrogen because less rainfall is available to dilute the material being washed off the basin. The average sampled storm sizes for the residential, highway, and commercial sites are 0.51, 0.68, and 0.85 inches, respectively. Confirmation of the inverse relatonship between storm size and observed concentration was obtained by finding a statistically significant negative correlation between almost all 29 constituent concentrations and the storm size at the time of sampling.

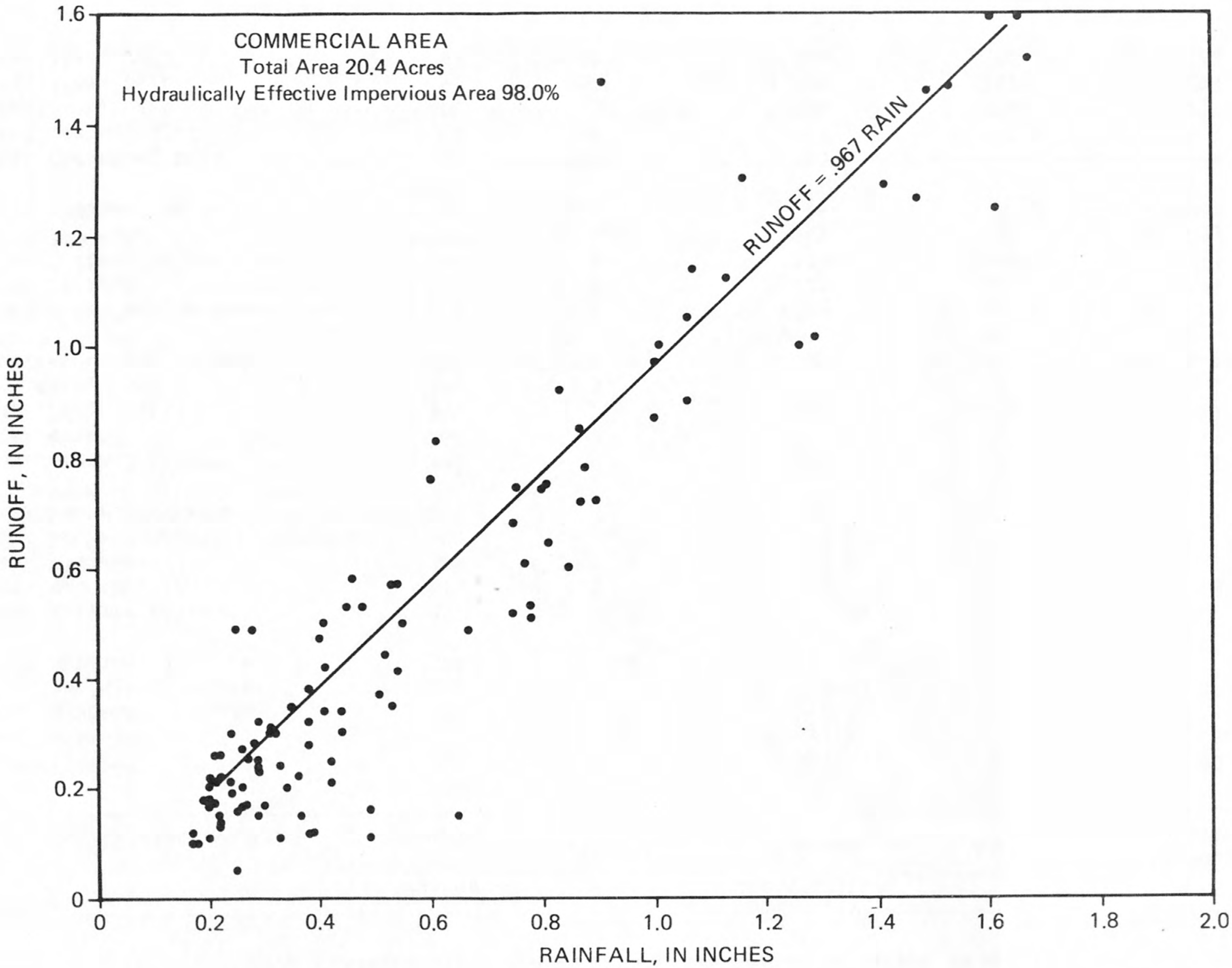

Figure 9.--Rainfall-runoff for the commercial area.

Table 2.--Water-quality constituents sampled at the residential site

[All concentrations are in milligrams per liter except as noted]

Constituent, units	Number of samples	Concentration			Standard deviation
		Minimum	Maximum	Average	
Conductivity[1]	452	34	350	96	56
Total nitrogen	380	.29	11.5	2.0	1.8
Total organic nitrogen	379	.14	9.4	1.2	1.1
Total ammonia nitrogen	379	.00	2.60	.33	.50
Total nitrite nitrogen	380	.00	1.49	.05	.12
Total nitrate nitrogen	380	.00	2.09	.46	.34
Dissolved chloride	118	1	48	8.8	6.6
Total phosphorus	380	.06	2.4	.31	.28
Total orthophosphate phosphorus	380	.03	1.8	.21	.21
Total inorganic carbon	366	1	17	5.8	2.9
Total organic carbon	366	0	104	14	14
Total carbon	366	3	120	20	16
Color, P-C units[2]	348	5	160	31	27
Turbidity, Jtu[3]	380	3	70	13	9.3
Chemical oxygen demand	377	2	289	41	41
Biochemical oxygen demand, mg/L[4]	213	2	20	7.9	3.8
Total residue	367	9	625	113	76
Total filterable residue	367	9	574	87	58
Suspended solids	367	0	249	26	30
Total cadmium, μg/L	96	0	6	.8	1.0
Total chromium, μg/L	94	<10	20	-------------	-------------
Total copper, μg/L	96	0	41	8.0	6.0
Total iron, μg/L	300	0	5,300	298	405
Total lead, μg/L	96	30	1,100	167	158
Total zinc, μg/L	96	10	560	86	72

Table 2.--Water-quality constituents sampled at the residential site--Continued

[All concentrations are in milligrams per liter except as noted]

Constituent, units	Number of samples	Concentration			Standard deviation
		Minimum	Maximum	Average	
Fecal coliform[5]	57	1,000	486,000	120,000	160,000
Fecal streptococci[5]	58	5,000	125,000	58,000	37,000
Total coliform[5]	62	24,000	1,770,000	274,000	300,000

[1] Micromho per centimeter.
[2] Platinum-cobalt units.
[3] Jackson turbidity units.
[4] 5-day biochemical oxygen demand.
[5] Cells per 100 mL of sample.

Table 3.--Water-quality constituents sampled at the highway site

[All concentrations are in milligrams per liter except as noted]

Constituent, units	Number of samples	Concentration			Standard deviation
		Minimum	Maximum	Average	
Conductivity[1]	520	25	450	104	72
Total nitrogen	440	.09	6.48	0.96	1.0
Total organic nitrogen	441	.05	3.30	.53	.53
Total ammonia nitrogen	441	.00	2.70	.13	.36
Total nitrite nitrogen	441	.00	.41	.02	.03
Total nitrate nitrogen	441	.00	1.60	.28	.24
Dissolved chloride	58	1	62	12	7.8
Total phosphorus	440	.00	.80	.08	.09
Total orthophosphate phosphorus	440	.00	.31	.04	.03
Total potassium	128	.40	3.8	1.25	.73
Total inorganic carbon	426	0	35	18	23
Total organic carbon	426	0	149	6.3	4.8
Total carbon	426	3	158	26	51
Color, P-C units[2]	440	5	240	29	39
Turbidity, Jtu[3]	441	2	85	9.6	8.0
Chemical oxygen demand	435	0	440	55	59
Biochemical oxygen demand, mg/L[4]	84	1.3	36	9.0	8.4
Total residue	438	9	658	113	97
Total filterable residue	439	4	642	99	88
Suspended solids	430	0	241	15	25
Total cadmium, µg/L	427	0	8	.7	.1
Total chromium, µg/L	247	<10	70	----------	----------
Total copper, µg/L	428	0	51	6.5	6.1
Total iron, µg/L	432	0	3,100	207	294
Total lead, µg/L	428	18	2,700	282	258

Table 3.--Water-quality constituents sampled at the highway site--Continued

[All concentrations are in milligrams per liter except as noted]

Constituent, units	Number of samples	Concentration			Standard deviation
		Minimum	Maximum	Average	
Total zinc, µg/L	428	0	1,000	90	117
Fecal coliform[5]	18	150	30,700	6,200	8,200
Fecal streptococci[5]	18	800	8,700	2,900	2,000
Total coliform[5]	11	800	25,000	8,000	8,000

[1] Micromhos per centimeter.
[2] Platinum-cobalt units.
[3] Jackson turbidity units.
[4] 5-Day biochemical oxygen demand.
[5] Cells per 100 mL of sample.

Table 4.--Water-quality constituents sampled at the commercial site

[All concentrations are in milligrams per liter except as noted]

Constituent, units	Number of samples	Concentration Minimum	Concentration Maximum	Concentration Average	Standard deviation
Conductivity[1]	372	32	6,200	131	330
Total nitrogen	319	.07	11.1	1.1	0.96
Total organic nitrogen	320	.00	11.0	.81	.91
Total ammonia nitrogen	320	.00	.34	.03	.04
Total nitrite nitrogen	320	.00	.40	.02	.03
Total nitrate nitrogen	320	.00	1.30	.21	.17
Dissolved chloride	49	4	118	32	27
Total phosphorus	320	.01	1.00	.10	.10
Total orthophosphate phosphorus	320	.00	.73	.05	.07
Total potassium	93	.20	4.5	.90	.57
Total inorganic carbon	308	0	60	10	11
Total organic carbon	308	0	99	5.8	4.8
Total carbon	308	1	116	16	13
Color, P-C units[2]	317	0	140	15	11
Turbidity, Jtu[3]	317	0	140	14	14
Chemical oxygen demand	308	10	2,200	71	151
Biochemical oxygen demand, mg/L[4]	69	1.4	10.8	5.4	2.3
Total residue	305	31	4,170	154	268
Total filterable residue	313	17	3,450	105	202
Suspended solids	318	1	720	45	72
Total cadmium, μg/L	287	0	7	.9	1.2
Total chromium, μg/L	210	<10	2,300	------------	------------
Total copper, μg/L	287	0	500	15	32
Total Iron, μg/L	289	0	8,400	334	607
Total lead, μg/L	295	6	7,000	387	603

Table 4.--Water-quality constituents sampled at the commercial site--Continued

[All concentrations are in milligrams per liter except as noted]

Constituent, units	Number of samples	Concentration			Standard deviation
		Minimum	Maximum	Average	
Total zinc, µg/L	295	0	1,900	128	170
Fecal coliform[5]	19	200	127,000	19,000	35,000
Fecal streptococci[5]	18	3,800	78,000	20,000	20,000
Total coliform[5]	17	6,000	116,000	43,000	29,000

[1] Micromhos per centimeter.
[2] Platinum-cobalt units.
[3] Jackson turbidity units.
[4] 5-Day biochemical oxygen demand.
[5] Cells per 100 mL of sample.

Seasonal rainfall pattern causes varied periods of antecedent dry conditions, and as a result greater accumulations of contaminants and higher concentrations to be observed during the dry season, October through May. Figure 10 shows higher observed nitrogen concentration for the residential area during the dry season. Approximately 20, 33, and 41 percent of the samples from the residential, highway, and commercial areas, respectively, were collected during the dry season.

A third factor that may introduce a bias is the distribution of samples over the hydrograph. Samples collected during the initial phases of a runoff event typically have the highest concentration. Because of automatic sampling equipment, more samples were often collected during the early part of most runoff events. The main point, however, is that average concentrations of constituents should not be directly compared between different areas without an adjustment for seasonal or antecedent condition, storm sample size, and collection frequency considerations.

Two approaches obviate these pitfalls, flow-weighted average concentrations, and annual loads. Annual loads are calculated in this report and land-use affects will be discussed in that part of the report.

Correlation of Concentration and Hydrologic Variables

Constituent concentrations are a complex function of the amount of material available to be washed off the basin and the washing-off process.

A matrix of the 29 water-quality constituents and hydrologic variables conceptually thought to affect concentrations was constructed to provide correlations. With the potentially large number of concentrations available (300-400) for testing, good statistical practices were assured. In general, correlations were poor, probably because the amount of material available for washoff varied from storm to storm, thereby controlling the observed concentrations.

Some of the hydrologic variables which may affect the washoff process and, therefore, have an effect on the observed concentration are summarized in table 5. The basic factors listed in table 5 include time of the year, time into the storm event, instantaneous discharge, the accumulated runoff, and the rainfall intensity for some time increment prior to the sample collection. In general, water-quality constituents showed little dependence on these hydrologic variables. Month versus concentration typically had the best correlation ($r = 0.4$). This is reasonable because the significant decreases in concentration occur during May and June due to the seasonal rainfall pattern (fig. 10). Season is significant, but decreases in concentration occur abruptly in months 5 (May) and 6 (June), while in months 12 (December) and 1 (January) concentrations probably differ little.

Accumulated rainfall (RF) at the time of sample collection exhibited an even lower correlation. As the washoff process proceeds in response to rainfall, the concentration decreases as accumulated rainfall increases. This inverse relationship was observed for most of the constituents at all three sites. Although the independent variable, accumulated rainfall, accounts for a certain amount of within-storm variation it does not include the important seasonal component.

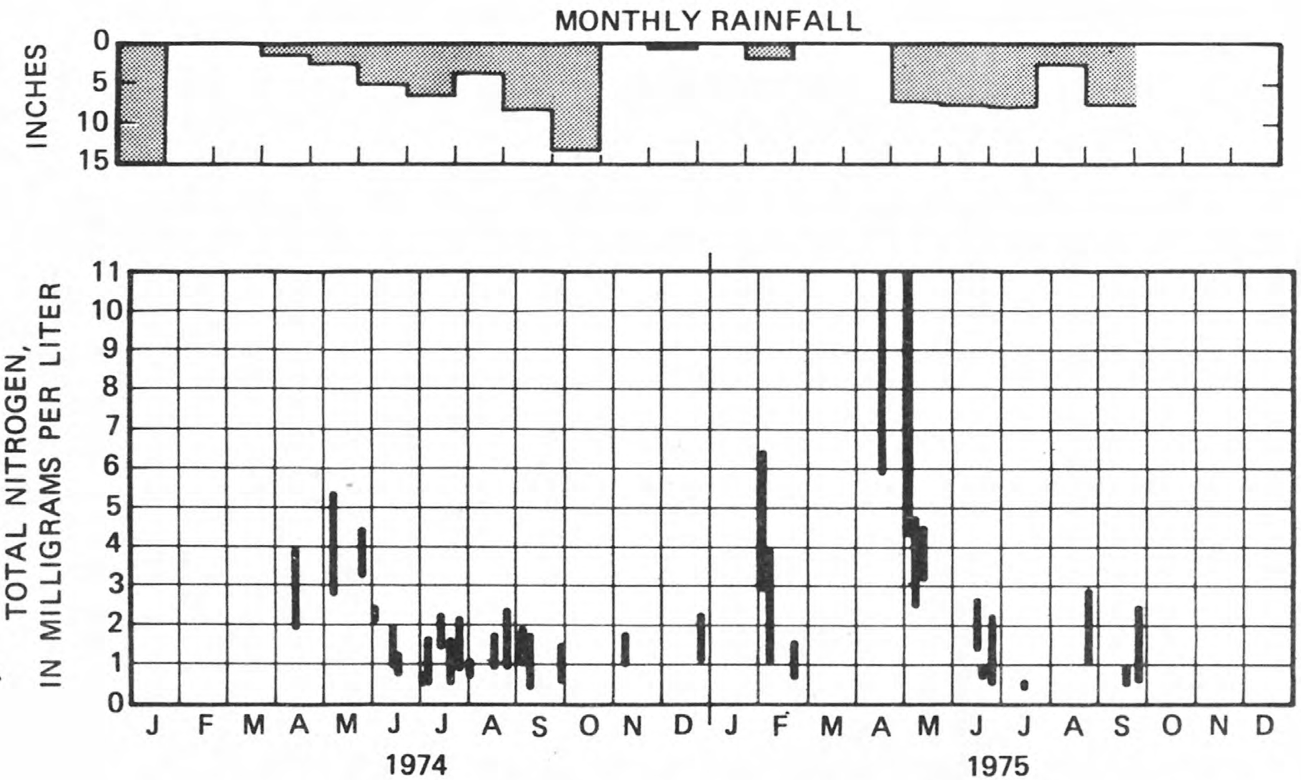

Figure 10.--Observed range of total nitrogen at the residential area.

Table 5.--Variables used in the concentration matrix

Dependent Variables

The 29 water quality variables in concentration units.

Independent Variables

TIMERO	- Time since start of runoff, in minutes.
ACCRO	- Accumulated runoff at the time of sample collection in inches.
INSTQ	- Instantaneous discharge at the time of sample collection, in cubic feet per second.
MON	- Month when sample collected, that is, January=1, December=12.
TSS	- Time since the start of storm (rainfall).
RF	- Accumulated rainfall at the time of sample collection in inches.
RI2	- Two-minute rainfall intensity 2 minutes prior to sample collection, in inches per minute.
RI5	- Two-minute rainfall intensity 5 minutes prior to sample collection, in inches per minute.
RI10	- Two-minute rainfall intensity 10 minutes prior to sample collection, in inches per minute.
RI15	- Two-minute rainfall intensity 15 minutes prior to sample collection, in inches per minute.

Accumulated runoff (ACCRO) is another independent variable that is highly correlated with accumulated rainfall. Use of accumulated runoff to describe the concentration variation might be expected to be more useful since the runoff lag of the basin is built into the runoff variable. Runoff will continue for an appreciable time after rainfall ceases, depending on the basin shape and size. Although runoff would appear to be better than rainfall for describing concentration variation, they appear to be equally, but weakly, significant for explaining concentration variation.

Two similar variables commonly used in describing stormwater runoff quality are TIMERO (time of runoff) and TSS (time since start of storm). Both consistently had lower correlation with the quality constituent concentrations than did accumulated runoff and accumulated rainfall. TIMERO and TSS ignore rainfall intensity and basin lag factors and consequently are less preferred for describing the concentration variation process.

An entirely different type of independent variable was the suite of rainfall intensity factors. A suite of 2-minute interval rainfall intensity measurements, at 2, 5, 10, 15, and 30 minutes prior to sample collection, was tested. The hypothesis is that a very short burst of high-intensity rainfall could dislodge additional particulate matter and cause increases in concentration. This independent variable might also be expected to decrease the observed concentration because more dilution water is available per unit time if the amount of material available for transport does not signficantly increase.

In the case of the commerical site evidence can be seen of the two mechanisms operating simultaneously. Typically the accumulated rainfall variable (RF) correlation coefficient is negative while the short-term rainfall intensity (particularly RI2) correlation coefficient is positive. This implies the opposing effects of dilution of concentration by rainfall and increased transportation of constituents by intense rainfall. When these two opposing mechanisms are operating, it is not surprising that the resulting correlation for either variable is not particularly high.

While the correlations between concentration and any one variable are not strong, it is likely that a good multiple regression expression may result when several variables are entertained. Concentration multiple regression expressions have not been developed since their principal use is the estimation of loads. Multiple regression expressions for observed load data are included in a subsequent portion of this report.

Concentration Decay Across the Hydrograph

Previous investigations of storm-water quality have shown a decrease in the concentration of various constituents after the onset of the storm. The rapid decrease in the initial part of the storm-runoff period results from the readily transported fraction in areas adjacent to the storm sewer being washed into the sewerage system. The materials remaining on the hydraulically effective impervious area are reduced, and the concentration of portions flowing from more distant impervious areas is diluted by the continuing rainfall. Sample concentrations observed at a point in the storm-drain system are complex mixtures of runoff into nearby inlets, and runoff occurring at an earlier portion of the storm from upstream inlets. The basin size and configuration and rainfall depth and duration all have an important bearing on the observed concentration-decay rate.

Concentration curves have conventionally been plots of concentrations versus time. Marsalek (1975) has suggested that the decay function is exponential and of the form:

$$C = C_0 e^{(-K_1, t)} \qquad (4)$$

where:

C = pollutant concentrations,

C_0 = the pollutant concentration at the beginning of runoff,

K_1 = decay constant in 1/minute, and

t = time from beginning of storm in minutes

e = natural logarithm

The representation is illustrated in figure 11 for lead from the residential area storm of June 17, 1975. Although the exponential decrease of lead concentration as a function of time for this particular runoff period has a high correlation coefficient, r = 0.96, the use of time to describe the concentration curve ignores the rainfall intensity and drainage pattern.

Figure 12 illustrates the plot of lead concentration versus accumulated rainfall. The basin response (rainfall-runoff response) time is ignored in this function. A number of samples were collected after rainfall ceased causing significant scatter in the data.

Figure 13 illustrates concentrations of lead versus runoff for the June 17, 1975 runoff period. This representation has a high correlation (r = 0.96) and takes the time-varying rainfall pattern and the response time of the basin into account. The equation is represented by:

$$C = C_0 e^{(-K_2 RO)} \qquad (5)$$

where:

C = the variable lead concentration,

C_0 = the lead concentration at the beginning of runoff,

K_2 = lead decay constant from the residential area, in 1/inches of runoff, and

RO = the runoff, in inches.

e = natural logarithm

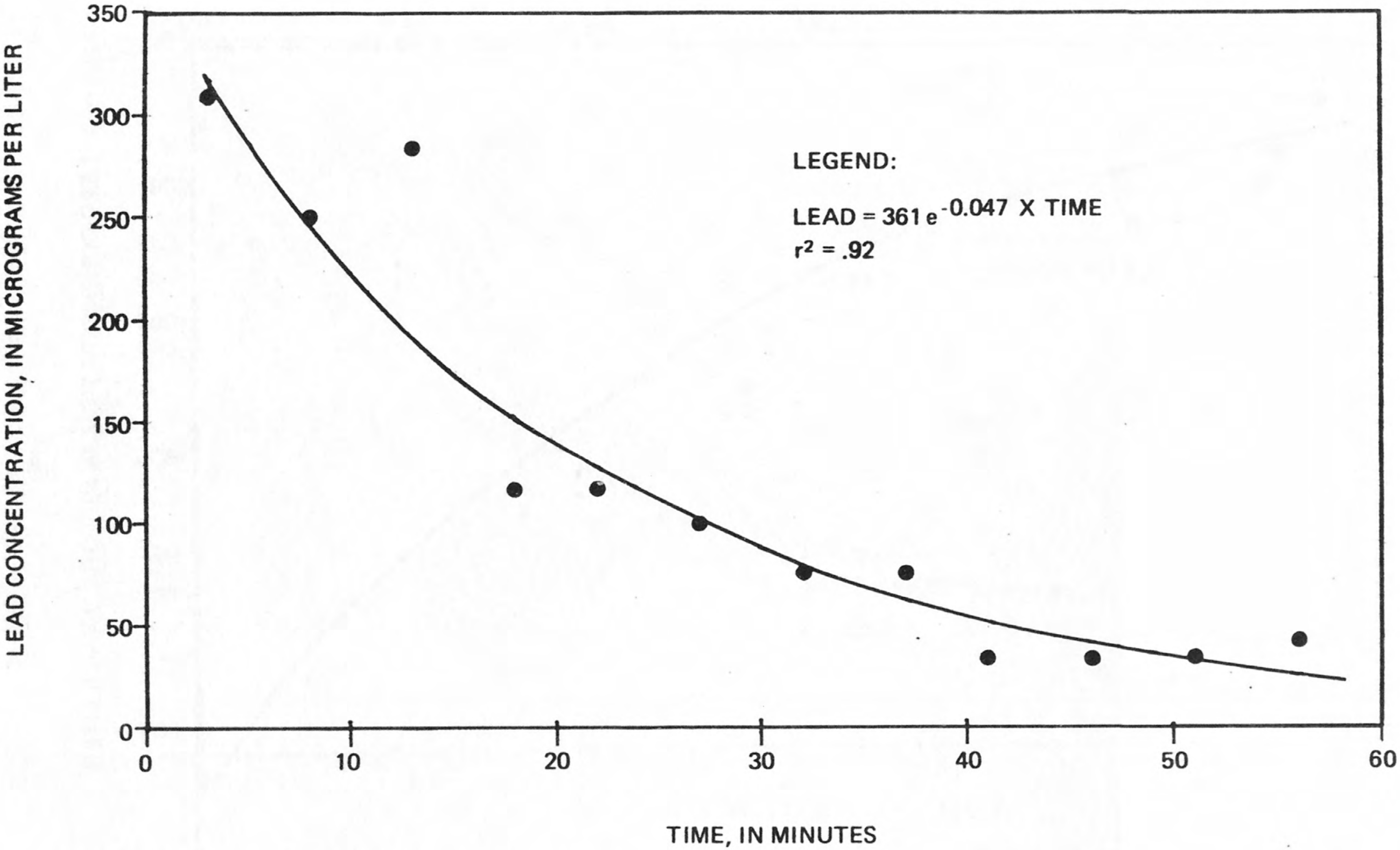

Figure 11.--Concentration decay curve for lead versus time at the residential area on June 17, 1975.

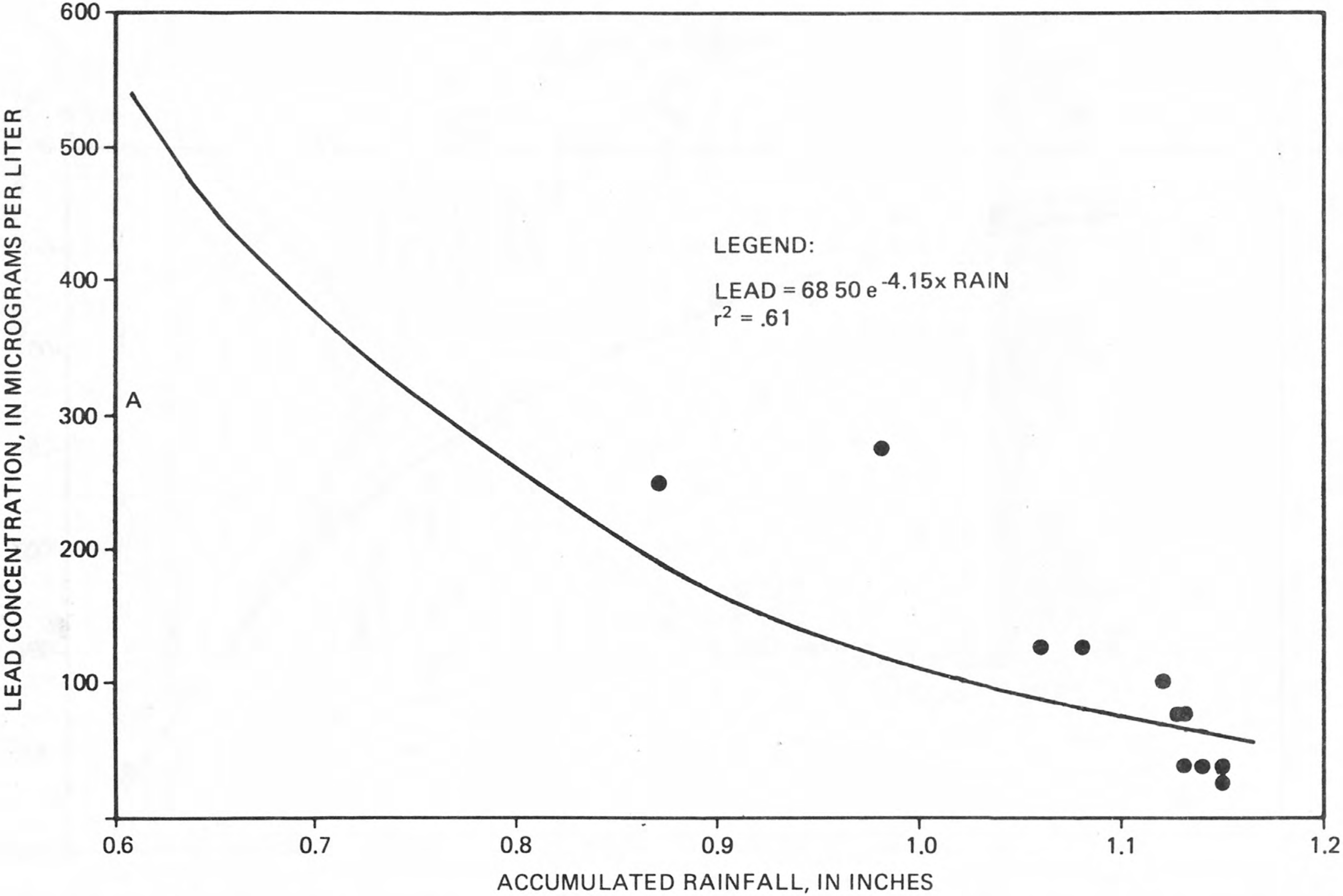

Figure 12.--Concentration decay curve for lead versus rainfall at the residential area on June 17, 1975.

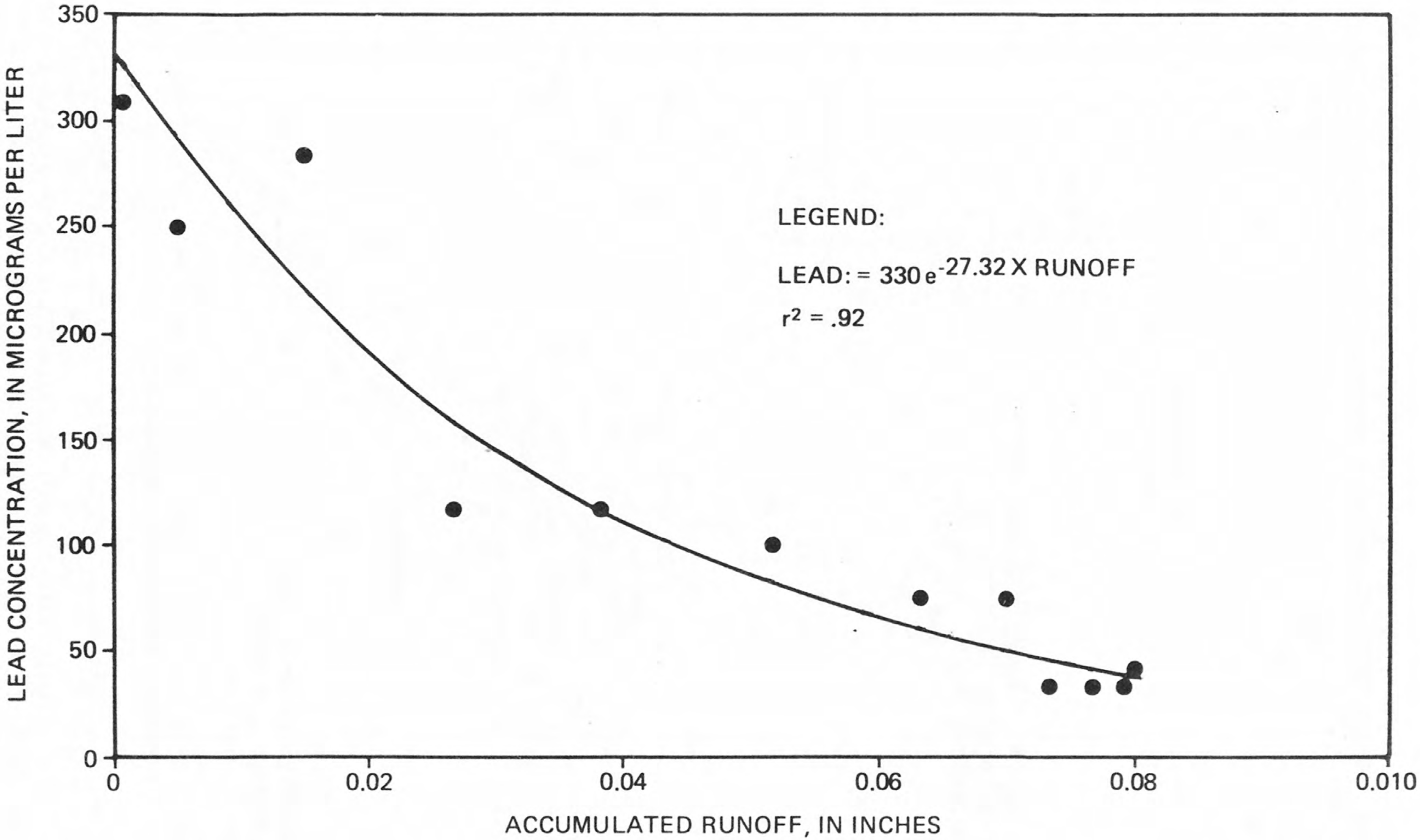

Figure 13.--Concentration decay curve for lead versus runoff at the residential area on June 17, 1975.

Solving the equation for runoff equal to zero gives an initial or beginning concentration of 330 μg/L lead. The value of K_2 depends partly on the nature of the basin. If only 5.9 percent of the residential area is hydraulically interconnected and the runoff inches is assumed to come from the hydraulically interconnected area rather than total drainage area, K_2 decreases from 27.32 to 1.62. K_2, however, does not vary as a function of the number of hydraulically effective impervious acres because the runoff in inches is implicitly tied to the number of acres. A larger basin may show a time lag before the maximum concentration is reached, but the use of runoff to describe the concentration decay curve incorporates the lag. Large and small basins should be directly comparable.

Two other types of curves, linear and second degree, are readily suited to describing changes in concentration. The three mathematical forms--linear, second degree, and exponential--were fitted for two storms for each of the three sites to determine what type of mathematical curve would best fit the concentration decay data. The independent variables were time, accumulated runoff, and accumulated rainfall. The correlation coefficient was arbitrarily used as the indicator of best fit.

The better correlations with their associated curve form and independent variable are shown in table 6. The highest correlation for each constituent is 0.88 or better. The independent variable which appears most often is runoff, while the curve form appearing most often is the second degree.

The success of the second-degree curve is due to its fitting capability near the end of the runoff event when, for numerous storms, constituent concentrations would increase slightly. This concentration increase is probably associated with the loss of dilution water due to termination of rainfall. It must be remembered that the second-degree curve is not as parsimonious as the exponential curve, requiring three parameters instead of two. An example of the second-degree equation for total lead as a function of runoff for the residential area storm of June 17, 1975, is:

$$\text{Lead} = 305 - 5792 * \text{ACCRO} + 30757 * \text{ACCRO}^2 \qquad (6)$$

STORMWATER CONSTITUENT LOADS

Computation of Loads

Constituent loads were calculated on a 1-minute time interval utilizing the discharge and water-quality data. Constituent concentrations for times between actual samples were interpolated linearly between the measured values. Concentrations prior to the first sample and after the last sample were assumed equal to the appropriate adjacent value. A conversion factor was used to convert the result to pounds.

Total storm loads for seven water-quality constituents are listed in tables 7, 8, and 9 for the residential, highway, and commercial sites, respectively. These values are the basis for the construction of multiple regression models. Additional constituent loads are published in the basic-data reports for each of the three sites (Mattraw and others, 1978; Hardee and others, 1978; and Miller and others, 1979).

Table 6.--Summary of analysis of fitting mathematical curves to constituent concentration decay

Constituent	Curve form	Independent variable	Correlation coefficient	Curve form	Independent variable	Correlation coefficient
Total nitrogen	Exponential	Time	0.88	Second degree	Runoff	0.86
Total phosphorus	Second degree	Runoff	.94	Second degree	Runoff	.89
Total carbon	Exponential	Runoff	.89	Linear	Runoff	.85
Chemical oxygen demand.	Exponential	Runoff	.91	Second degree	Time	.91
Total iron	Linear	Rainfall	.95	Second degree	Time	.93
Total residue	Exponential	Runoff	.95	Linear	Runoff	.91
Total lead	Second degree	Runoff	[1].93	Second degree	Time, rainfall	.93

[1] Occurred for three out of six storms.

Table 7.--Rainfall, runoff, and constituent loads for storms sampled from the residential area

Storm date	Rainfall in inches	Runoff in inches	Number of samples	Total nitrogen in pounds	Total phosphorus in pounds	Total carbon in pounds	Chemical oxygen demand in pounds	Total residue in pounds	Total lead in pounds	Total zinc in pounds
4-15-74	0.60	0.059	9	1.3	0.32	20	55	--	--	--
5-7-74	.40	.011	10	.31	.046	3.0	4.9	13	--	--
5-28-74	.14	.001	16	.050	.0049	.50	1.1	1.7	--	--
6-3-74	.21	.003	21	.070	.0079	.73	1.7	3.2	--	--
6-15-74	.54	.030	15	.40	.075	4.0	9.9	27	--	--
6-16-74	1.14	.185	12	1.6	.35	8.3	13	120	--	--
7-2-74	.47	.034	12	.26	.042	2.4	5.1	25	--	--
7-15-74	.42	.018	8	.27	.047	2.3	5.9	15	--	--
7-18-74	.85	.072	10	.52	.13	4.8	4.9	42	--	--
7-21-74	.32	.016	12	.20	.026	2.5	6.6	12	--	--
7-31-74	.15	.004	12	.029	.0064	.46	1.0	1.8	--	--
8-17-74	.68	.043	12	.51	.13	6.0	13	39	--	--
8-23-74	.32	.031	12	.27	.065	3.9	6.1	26	--	--
9-5-74	.11	.007	12	.090	.014	1.7	3.8	8.2	--	--
9-6-74	.24	.013	12	.077	.013	1.3	1.9	7.4	--	--
9-30-74	.99	.099	10	.70	.078	5.0	9.3	39	--	--
12-26-74	.14	.010	11	.13	.021	--	4.3	11	--	--
2-5-75	.14	.009	12	.38	.066	3.2	9.3	23	--	--
2-10-75	.37	.018	10	.26	.052	2.6	3.3	22	--	--
2-24-75	.45	.035	10	.26	.086	2.7	7.4	27	--	--
4-12-75	.14	.017	12	1.3	.20	11	24	56	--	--
5-5-75	.26	.038	12	1.9	.21	15	21	84	0.15	0.057
5-7-75	.31	.041	12	1.2	.13	10	8.4	55	--	--
5-9-75	.22	.013	12	.42	.040	2.5	3.4	16	.015	.012
6-17-75	1.24	.084	12	1.4	.19	8.6	18	170	.11	.056

Table 7.--Rainfall, runoff, and constituent loads for storms sampled from the residential area--Continued

Storm date	Rainfall in inches	Runoff in inches	Number of samples	Total nitrogen in pounds	Total phosphorus in pounds	Total carbon in pounds	Chemical oxygen demand in pounds	Total residue in pounds	Total lead in pounds	Total zinc in pounds
6-19-75	0.10	0.002	6	0.013	0.0020	0.21	0.53	2.4	---------	---------
6-24-76	.94	.047	12	.37	.035	2.9	5.7	17	0.051	0.026
7-14-75	.24	.010	12	.055	.0062	.89	1.5	4.9	.0088	.0040
8-23-75	.93	.065	12	.29	.068	3.0	8.4	40	.051	.026
9-17-75	.50	.014	12	.11	.023	2.0	3.2	9.6	.016	.0083
9-26-75	.73	.083	11	.85	.18	6.4	12	53	.12	.067

Table 8.--Rainfall, runoff, and constituent loads for storms sampled from the highway area

Storm date	Rainfall in inches	Runoff in inches	Number of samples	Total nitrogen in pounds	Total phosphorus in pounds	Total carbon in pounds	Chemical oxygen demand in pounds	Total residue in pounds	Total lead in pounds	Total zinc in pounds
4-15-75	0.06	0.008	11	0.48	0.03	12	27	36	---------	---------
5-5-75	.23	.007	8	.46	.02	8.5	16	24	0.043	0.029
5-9-75	.38	.005	12	.24	.01	3.3	7.1	15	.037	.012
5-22-75	.11	.011	12	.30	.02	8.6	14	43	.073	.041
5-29-75	.88	.052	12	.32	.03	3.7	6.0	81	.11	.027
7-14-75	.22	.029	12	.14	.01	5.2	9.3	29	.032	.0094
8-29-75	.27	.038	12	.27	.03	9.0	18	54	.099	.022
9-17-75	.45	.090	12	.78	.07	22	40	85	.28	.073
10-22-75	.36	.029	9	.22	.09	2.2	5.2	24	.072	.035
10-31-75	.38	.051	12	.37	.02	4.5	7.4	36	.098	.023
1-5-76	.30	.057	12	1.0	.07	18	31	85	.18	.058
5-5-76	.63	.134	12	1.2	.11	30	117	140	.34	.059
5-17-76	.30	.057	12	.80	.04	13	29	60	.12	.023
5-21-76	.63	.134	12	.83	.09	22	42	120	.28	.072
5-28-76	2.09	.365	12	2.1	.26	37	100	220	1.2	.19
6-4-76	.38	.088	24	.64	.05	14	43	70	.26	.10
6-7-76	.65	.137	12	1.0	.09	26	58	200	.34	.12
6-16-76	.08	.011	8	.07	.02	3.4	9.6	12	.053	.015
6-19-76	1.36	.269	11	1.1	.16	36	200	92	.67	.10
6-23-76	.95	.202	5	1.0	.15	46	69	230	.72	.098
6-25-76	.58	.086	4	.24	.04	8.9	33	42	.16	.040
6-27-76	.20	.087	4	.39	.04	15	27	140	.22	.066
7-6-76	.18	.018	6	.41	.02	20	44	67	.18	.087
7-7-76	.53	.160	5	.77	.08	23	68	150	.89	.15
7-13-76	.12	.026	3	.59	.02	17	34	56	.14	.063

Table 8.--Rainfall, runoff, and constituent loads for storms sampled from the highway area--Continued

Storm date	Rainfall in inches	Runoff in inches	Number of samples	Total nitrogen in pounds	Total phosphorus in pounds	Total carbon in pounds	Chemical oxygen demand in pounds	Total residue in pounds	Total lead in pounds	Total zinc in pounds
7-22-76	1.92	0.244	12	2.8	0.19	48	91	200	0.90	0.21
8-16-76	1.39	.325	11	2.8	.28	54	120	340	.83	.32
8-8-76	.56	.108	5	.59	.08	19	40	120	.21	.087
10-9-76	.37	.090	9	1.6	.09	30	170	110	.39	.13
11-2-76	2.42	.594	6	2.2	.49	93	130	360	1.0	.39
11-17-76	1.07	.244	12	1.4	.16	38	99	170	.72	.17
12-13-76	2.50	.499	11	4.1	.34	73	100	410	1.8	.29
2-8-77	.71	.163	8	1.6	.12	42	100	-----------	1.0	.24
4-10-77	.32	.052	23	.73	.06	20	32	110	.15	.19
4-12-77	.27	.030	8	.34	.03	13	26	52	.093	.044
4-13-77	1.14	.170	8	1.1	.11	42	85	180	.091	----------
4-24-77	.16	.016	22	.21	.01	7.5	20	35	.098	.028
5-9-77	.88	.138	8	.64	.08	21	48	92	.35	.067
5-10-77	1.04	.190	13	1.8	.13	17	46	150	.46	.072
7-1-77	.29	.064	7	.83	.06	--------------	76	350	.26	.072

Table 9.--Rainfall, runoff, and constituent loads for storms sampled from the commercial area

Storm date	Rainfall in inches	Runoff in inches	Number of samples	Total nitrogen in pounds	Total phosphorus in pounds	Total carbon in pounds	Chemical oxygen demand in pounds	Total residue in pounds	Total lead in pounds	Total zinc in pounds
5-29-75	0.53	0.352	12	1.5	0.055	10	27	160	0.56	0.19
6-3-75	1.29	1.015	12	5.0	.31	27	84	340	2.0	.68
6-17-75	.54	.569	12	3.2	.36	36	76	413	1.1	.44
6-23-75	1.74	1.776	12	8.4	.31	44	106	378	.82	.45
8-7-75	.35	.346	12	1.4	.094	22	24	137	1.0	.25
9-7-75	.33	.241	12	1.0	.081	17	30	156	.82	.27
2-1-76	.38	.385	12	2.1	.33	32	185	252	--	--
2-25-76	.87	.720	6	1.8	.37	33	105	312	.56	.37
2-28-76	.73	.682	14	1.5	.11	37	122	239	.96	.27
4-6-76	.42	.245	12	3.2	.41	44	152	267	.90	.37
6-7-76	1.65	1.601	12	5.2	.44	58	323	782	1.5	.48
6-23-76	1.13	1.122	9	2.7	.21	62	110	604	1.3	.38
7-7-76	1.67	1.519	12	4.2	.35	80	306	695	3.0	.78
7-9-76	.48	.530	12	1.7	.10	23	103	295	.96	.13
7-25-76	.17	.125	4	1.2	.12	27	98	150	.45	.13
8-11-76	.21	.174	6	1.6	.11	24	190	262	.63	.30
8-18-76	1.47	1.266	8	3.4	.27	49	145	838	1.8	.67
9-10-76	.38	.121	8	.86	.076	21	67	103	.52	.15
9-14-76	1.06	1.050	12	5.3	.68	52	199	490	1.5	.56
10-9-76	.44	.336	11	4.6	.18	41	470	2010	2.2	.65
11-17-76	.38	.278	11	1.7	.10	35	191	244	.61	.24
12-13-76	1.93	1.981	8	4.1	.20	102	421	790	2.3	.83
1-15-77	.78	.552	11	3.4	.34	36	468	699	1.3	.40
1-29-77	.29	.315	5	4.3	.44	32	442	474	2.2	.58
1-31-77	.28	.491	6	4.0	.28	63	295	408	1.3	.35

Table 9.--Rainfall, runoff, and constituent loads for storms sampled from the commercial area--Continued

Storm date	Rainfall in inches	Runoff in inches	Number of samples	Total nitrogen in pounds	Total phosphorus in pounds	Total carbon in pounds	Chemical oxygen demand in pounds	Total residue in pounds	Total lead in pounds	Total zinc in pounds
2-8-77	0.85	0.805	8	5.8	0.36	49	325	------------	3.2	0.82
4-13-77	1.41	1.295	8	7.7	1.1	108	332	1590	2.5	0.94
4-24-77	.32	.296	24	2.1	.36	85	113	229	.80	.20
5-9-77	1.00	.876	7	6.2	.81	44	367	645	2.4	.60
5-20-77	1.16	1.305	11	5.3	.65	102	575	997	2.7	.87
6-9-77	2.16	2.251	9	2.4	.48	--------------	465	1010	1.7	.73

Load Model Variables

The hydrologic variables used in the regression analysis for predicting total load are peak discharge, depth of rainfall, a suite of maximum intensities, and storm duration (table 10). The antecedent-conditions variables used are a suite of rainfall histories (depth of rainfall for various time periods) and a suite of antecedent dry hours (the number of hours prior to the storm in which various depth of rainfall accumulated). The season variables include various sine and cosine functions utilizing Julian day of the year. Cross products of some of the hydrologic variables and antecedent-conditions variables were also formed and used as independent variables.

Regression Methodology

SAS 76, Statistical Analysis System, developed at North Carolina State University (Barr and others, 1976) was used to perform stepwise multiple regression and associated calculations. The SAS 76 stepwise regression procedure was used in the analysis of the load matrices for the three sites. This procedure examines the contribution made by each independent variable at every step. A variable once a part of the regression may exit later due to its relationship with remaining variables in the regression (Draper and Smith, 1966).

The following criteria were used to establish acceptable regression results:

1. The square of the multiple correlation coefficient >0.8,

2. Standard error of estimate <50 percent,

3. Variables significant at 10 percent level,

4. No patterns in residuals, and

5. Number of independent variables ≤ 3.

Residential Basin Load Models

Seven water-quality total load equations representing the primary statistical modeling results for the residential area are presented in table 11. Peak discharge appears in five of the seven regression equations. This is expected because of the strong correlation between peak discharge and runoff, coupled with the fact that runoff multiplied by concentration gives storm load. ADH025, the number of hours prior to the storm in which 0.25 inch of rainfall accumulated, or a cross product of this variable with rain or intensity appears in six of the seven load models listed in the table. Antecedent dry hours is a variable that would be expected to occur in most models due to the accumulation of constituents. The significance of the time to accumulate 0.25 inch appears to be related to the 0.2 inch of rainfall required to produce significant runoff. Rainfall depths smaller than 0.2 inch appear unable to wash accumulated constituents from the basin.

Table 10.--Variables used in the load matrix

Dependent variables

RUNOFF	-	runoff, in inches
TNIT	-	total nitrogen, in pounds
TPHOS	-	total phosphorus, in pounds
TCAR	-	total carbon, in pounds
COD	-	chemical oxygen demand, in pounds
TRES	-	total residue, in pounds
TLEAD	-	total lead, in pounds
TZINC	-	total zinc, in pounds

Independent variables

RHIST1	-	depth of rainfall falling 1 day before storm, in inches
RHIST3	-	depth of rainfall falling 3 days before storm, in inches
RHIST7	-	depth of rainfall falling 7 days before storm, in inches
RHIST14	-	depth of rainfall falling 14 days before storm, in inches
RHIST30	-	depth of rainfall falling 30 days before storm, in inches
ADH005	-	number of hours antecedent to storm in which 0.05 inch of rain fell
ADH010	-	number of hours antecedent to storm in which 0.10 inch of rain fell
ADH025	-	number of hours antecedent to storm in which 0.25 inch of rain fell
ADH050	-	number of hours antecedent to storm in which 0.50 inch of rain fell
ADH100	-	number of hours antecedent to storm in which 1.00 inch of rain fell
RAIN	-	depth of rainfall for storm, in inches

Table 10.--Variables used in the load matrix--Continued

Independent variables--Continued

PEAK	-	peak discharge, in cubic feet per second
DUR	-	duration of storm in which 90 percent of rainfall fell in minutes
INT5	-	maximum 5 minute intensity rainfall, inches per hour
INT10	-	maximum 10 minute intensity rainfall, inches per hour
INT15	-	maximum 15 minute intensity rainfall, inches per hour
INT30	-	maximum 30 minute intensity rainfall, inches per hour
INT60	-	maximum 60 minute intensity rainfall, inches per hour
INTAVG	-	average intensity rainfall for storm, inches per hour
RNXH3	-	cross product of RAIN, RHIST3
RNXH14	-	cross product of RAIN, RHIST14
RNXA10	-	cross product of RAIN, ADHO10
RNXA25	-	cross product of RAIN, ADHO25
H3XDUR	-	cross product of RHIST3, DUR
H14XDU	-	cross product of RHIST14, DUR
H3XRO	-	cross product of RHIST3, RUNOFF
H14XRO	-	cross product of RHIST14, RUNOFF
A10XDU	-	cross product of ADHO10, DUR
A25XDU	-	cross product of ADHO25, DUR
A10XDU	-	cross product of ADHO10, DUR
A10XRO	-	cross product of ADHO10, RUNOFF
A25XRO	-	cross product of ADHO25, RUNOFF
INXRH3	-	cross product of INTAVG, RHIST3
INXH14	-	cross product of INTAVG, RHIST14

Table 10.--Variables used in the load matrix--Continued

Indepenent variables--Continued

INXA10	-	cross product of INTAVG, ADH010
INXA25	-	cross product of INTAVG, ADH025
RNXINT	-	cross product of RAIN, INTAVG
SINHAR	-	sine harmonic of Julian day
COSHAR	-	cosine harmonic of Julian day
SINLAG	-	sine harmonic lagged 1/2 period
COSLAG	-	cosine harmonic lagged 1/2 period
SINPD	-	sine harmonic with period halved
COSPD	-	cosine harmonic with period halved
SNLGPD	-	sine harmonic lagged 1/4 period with period halved
CSLGPD	-	cosine harmonic lagged 1/8 period with period halved

Table 11.--Load regression equations for the residential area

Mean of dependent variable[1]	Number of items	Dependent variable	Intercept	Independent variable 1	Independent variable 2	Independent variable 3	R^2	Standard error of estimate (as percent)
0.037	32	1 RUNOFF	-0.017	0.109 RAIN	----------	----------	0.724	66.8
.037	32	2 RUNOFF	.0039	.0092 PEAK	----------	----------	.959	25.8
.037	32	3 RUNOFF	-.0028	.0078 PEAK	0.024 RAIN	----------	.971	22.1
.525	32	4 TNIT	.106	.073 PEAK	.00084 ADH025	-0.22 SNLGPD	.790	48.4
.093	32	5 TPHOS	.008	.014 PEAK	.00058 RNXA25	----------	.857	41.1
5.30	31	6 TCAR	1.192	.041 RNXA25	.93 PEAK	-5.05 RAIN	.811	50.9
9.67	32	7 COD	3.81	.16 RNXA10	-.00043 A10XDU	----------	.798	54.0
34.8	31	8 TRES	-4.154	29.48 RNXINT	3.03 PEAK	.23 RNXA25	.795	52.9
.065	8	9 TLEAD	.009	.00031 INXA25	----------	----------	.798	40.1
.032	8	10 TZINC	.001	.0071 PEAK	.000025 ADH025	----------	.957	18.7

[1] Runoff in inches, other variables in pounds.

The regression model for total nitrogen load contains peak discharge (PEAK), ADH025, and a seasonal factor (SNLGPD). SNLGPD is defined as a sine curve, fitted to Julian days, which begins on April 1 and has two periods per year. Use of this independent variable causes a maximum nitrogen load on approximately May 15 and decreasing to a minimum load about August 15. Figure 10 shows the range of total nitrogen concentrations between April 1974 and September 1975 (Mattraw and Sherwood, 1977). The rapid decrease in nitrogen concentration after the start of the rainy season in May is readily apparent for both years. Data between September and April are generally sparse, due to less frequent rainfall and generally smaller storms. The halved period of the sine function is a surrogate for the rapid dieoff of nitrogen concentrations that occurs during May.

Regression models for total phosphorus, total carbon, and total residue all contain peak discharge and the cross product of rainfall and antecedent dry hours for 0.25 inch of rain (RNXA25). The similarity of regression results reflects the fact that chemical analyses for these constituents include the total contribution (particulate plus dissolved components). It seems reasonable that these constituents should accumulate on the basin as a function of antecedent dry period and wash off in a response to the amount of rainfall. Total residue also shows a large positive response to the cross product of rainfall depth and the rainfall intensity (RNXINT). A more intense rainfall can be envisioned as capable of dislodging coarse-grained particulate matter, thereby increasing the total residue load. The regression equation for zinc shows a strong relationship with peak discharge and an antecedent dry-period parameter (ADH025).

Highway Basin Load Models

Table 12 lists eight load models for the highway area. Rainfall (RAIN) is the most significant variable for six of the seven load equations listed in table 12. Rainfall appears to act as a surrogate for runoff, which is strongly involved in the load calculation. Peak discharge (PEAK) is similar to rainfall, but occupies a position of secondary importance in explaining runoff loads for the highway site. Peak discharge appears in the total nitrogen, total residue, total lead, and total zinc regression models. This tends to reiterate the importance of runoff and the near total dominance of hydrologic factors on runoff loads for the highway basin.

The phosphorous and total carbon models contain the cross product of rainfall and antecedent dry hours for the accumulation of 0.10 inch of rainfall. The smaller antecedent precipitation quantity for the highway site suggests that the efficient sewer-collection system which had caused the rainfall/runoff intercept to be zero is also efficient in collecting washoff from storms in the 0.10-inch rainfall range.

Antecedent condition variables did not appear in four of the seven load equations. This implies that constituents do not accumulate on the highway-site contributing areas as a function of time. One explanation for this lack of build-up may be the activity and velocity of vehicular traffic. The 3,000-foot segment does not have any traffic-control devices, and the speed limit is 45 miles per hour. Constituent accumulations may be readily removed from the highway area by traffic and accumulate on pervious and nonhydraulically connected impervious areas, thus becoming unavailable to the surface runoff process, except for large storms.

Table 12.--Load regression equations for the highway area

Mean of dependent variable[1]	Number of items	Dependent variable	Intercept	Independent variable			R^2	Standard error of estimate (as percent)
				1	2	3		
0.202	42	1 RUNOFF	-0.01	0.19 RAIN	------------	------------	0.902	32.1
1.02	42	2 TNIT	.093	.76 RAIN	0.033 PEAK	------------	.803	39.1
.103	42	3 TPHOS	.007	.096 RAIN	.00025 RNXA10	------------	.879	38.0
26.5	41	4 TCAR	3.752	14.9 RAIN	.045 RNXA10	0.066 DUR	.801	41.3
60.0	42	5 COD	17.0	58.3 RAIN	------------	------------	.558	58.4
132	41	6 TRES	28.8	83.6 RAIN	3.73 PEAK	------------	.665	48.8
.450	41	7 TLEAD	-.038	.50 RAIN	.0098 PEAK	------------	.756	53.2
.113	41	8 TZINC	.018	.0000026 A10XDU	.0054 PEAK	------------	.750	47.2

[1] Runoff in inches, other variables in pounds.

Commercial Basin Load Models

Regression models for water-quality loads at the commercial area are summarized in table 13. In every case, PEAK is the most important variable in accounting for the loads. When the stepwise procedure was allowed to include runoff as a possible variable, it only included runoff for total carbon. Since runoff is used directly in the computation of load, a higher, but spurious, correlation is expected between runoff and the dependent variable. Therefore, the assumption that PEAK is acting as a surrogate for runoff on this basin may not be substantiated.

Every load model contains one or more variables relating to antecedent dry hours. Total nitrogen, total residue, and total zinc all have ADH100, which is the antecedent hours during which 1.0 inch of rainfall accumulated. The total carbon model contained ADH050, and the chemical oxygen demand model contained ADH005. The total lead regression model contained RHIST3 which is the amount of rain in the previous 3 days. The variability of the antecedent conditions variable included in the commercial area load models contrasts with the residential area which primarily reflected the last one quarter of an inch of rain. The antecedent conditions variable may be sensitive to the type of constituent. For example, chemical oxygen demanding materials may be more readily washed off the impervious areas of the commercial area. Total nitrogen, total residue, and total zinc may be more resistant to flushing and, therefore, require more rainfall to reduce the accumulation of these contaminants.

Three different sine functions of Julian day, SINHAR, SNLGPD, and SINLAG, appear in the total phosphorus, total carbon, and chemical oxygen demand load models. They all attempt to account for the seasonal rainfall/water-quality concentration variation. The critical time period is the end of dry season, April, and the beginning of the rainy season, May and June. Measures of antecedent conditions, ADH050 and RHIST30, to a certain extent address the same overall factor for total phosphorus and chemical oxygen demand. The small amount of variation accounted for by the sine functions results.

The commercial site should be an excellent location for testing some of the basic assumption of SWMM (Metcalf and Eddy, Inc., 1971). The contaminant accumulation as a function of time appears in the regression equations. Exponential washoff functions for the various loads appear to show considerable variation and may depend on several factors rather than solely on pavement properties (Amy and others, 1974). Further exploration of the washoff function would appear to be a fruitful area of research.

TOTAL LOAD ESTIMATES

Total loads for the seven water-quality constituents were compiled for the three watersheds. Storm-runoff loads fall into three categories:

1. Measured loads - for the residential site, loads were measured during 32 rainfall-runoff periods (table 7);

Table 13.--Load regression equations for the commercial area

Mean of dependent variable[1]	Number of items	Dependent variable	Intercept	Independent variable 1	Independent variable 2	Independent variable 3	R^2	Standard error of estimate (as percent)
0 .741	30	1 RUNOFF	-0.06	0.967 RAIN	------------------	------------------	0.958	15.5
3.28	30	2 TNIT	-.569	.103 PEAK	0.0027 ADH100	--------------	.706	30.8
.325	30	3 TPHOS	-.107	.0108 PEAK	.00044 ADH050	0.0886 SINHAR	.672	43.9
46.6	29	4 TCAR	24.9	29.4 RAIN	-8.19 SNLGPD	--------------	.431	44.4
227	30	5 COD	-16.46	5.67 PEAK	28.5 RHIST30	118 SINLAG	.614	45.9
537	29	6 TRES	-344	19.2 PEAK	1.24 DUR	.557 ADH100	.662	50.5
1.48	29	7 TLEAD	.172	.0423 PEAK	-.436 RHIST3	.0016 DUR	.651	34.1
.471	29	8 TZINC	-.015	.0149 PEAK	-.1155 RHIST3	.00027 ADH100	.784	25.7

[1] Runoff in inches, other variables in pounds.

2. Loads estimated by multiple regression - 30 of the residential site measured loads were used to construct multiple linear regression models (table 11). Rainfall, runoff, and other data for 45 additional storm events were stored in the data-management system. The load models were applied to the 45 storms and loads calculated; and

3. Loads estimated by simple regression - rainfall data for 172 additional small storms were not included in the data-management system. Simple linear regressions between rainfall and load for the 30 measured storms were developed, and the loads for storms greater than 0.15 inch of rainfall (30 storms) were estimated.

The cutoff of 0.15 inch of rainfall for the residential site is the zero intercept obtained from the rainfall runoff equation (equation 1). The same calculation for the highway and commercial rainfall runoff equations exclude storms smaller than 0.05 and 0.07 inch, respectively. Table 14 lists the measured, estimated, and total loads for the observation period at the three land-use areas.

A rough comparison of loads among the three watersheds can be obtained by dividing the total estimated load by the collection period in days. Table 15 lists the daily loads for the three land-use areas. This comparison can be improved by dividing the daily load by the number of hydraulically effective impervious acres (table 1). This procedure produces the "loading" which permits a direct comparison for different sized areas. Loadings for seven quality constituents in the three watersheds are also given in table 15.

The total nitrogen and total phosphorus loadings are considerably higher in the residential area. Although the loading is computed on the basis of the hydraulically effective impervious area, it is likely that a substantial portion of these nutrients are derived from lawn fertilization or pet wastes. The role of pet wastes in the residential area is substantiated by the high concentrations of bacteria in the runoff (table 2).

Total carbon loadings were remarkably similar for the three land-use areas.

Loadings of chemical oxygen demand were approximately 2 times higher in the commercial area. The relatively large, hydraulically effective impervious area for the commercial basin, 20 acres, is fairly symmetrical and vehicular speeds are low. These factors may be important in retaining chemical oxygen demanding materials on the parking surface. The true role of the parking lot in retaining chemical oxygen demand might be even larger if the runoff from the 8 acres of roof were isolated.

Loadings of total residue were greatest in the residential area and least in the highway area. Total residue includes both dissolved solids (total filterable residue) and suspended solids. The dissolved component was dominant at all three sites.

Table 14.--Estimated loads, in pounds, at the three land-use areas

Variable	Measured load	Estimated multiple regression load	Estimated simple regression load	Total
		Residential - 562 Days		
Storms	32	45	172(30)[1]	249
Rain (in inches)	15.70	42.61	19.44(13.10)[2]	77.75
TNIT	16.8	32.6	12.3	61.7
TPHOS	2.99	6.74	2.40	12.13
TCAR	164.	279.	124.	567.
COD	310.	413.	227.	950.
TRES	1079.	3297.	946.	5322.
TLEAD	.590	1.70	1.09	3.38
TZINC	.296	2.64	.560	3.46
		Highway - 886 Days		
Storms	42	61	331(173)[1]	434
Rain (in inches)	30.96	49.40	36.12(32.93)[2]	116.48
TNIT	42.7	66.5	41.6	150.8
TPHOS	4.33	5.81	4.74	14.88
TCAR	1086.	1603.	1080.	3769.
COD	2519.	3917.	2342.	8778.
TRES	5422.	8545.	5093.	19060.
TLEAD	18.5	29.4	19.8	67.7
TZINC	4.63	6.38	4.51	15.52
		Commercial - 765 Days		
Storms	31	82	285(112)[1]	398
Rain (in inches)	25.91	52.92	26.57(21.95)[2]	105.40
TNIT	101.	181.	70.24	351.8
TPHOS	10.2	13.8	7.29	26.3
TCAR	1373.	3672.	1105.	6150.
COD	6989.	15684.	4952.	27625.
TRES	15868.	27616.	12171.	55655.
TLEAD	43.3	76.8	31.5	152.
TZINC	13.8	22.9	10.4	47.1

[1] Number of storms with measurable runoff (in parenthesis).
[2] Inches of rain occurring in storms with measurable runoff.

Table 15.--Daily loads and loadings for three land-use areas

	Land-use areas		
	Residential	Highway	Commercial
Daily loads in pounds per day			
Total nitrogen	0.109	0.170	0.460
Total phosphorus	.0216	.0168	.0344
Total carbon	1.01	4.25	8.04
Chemical oxygen demand	1.69	9.91	36.1
Total residue	9.47	21.5	72.7
Total lead	.0060	.0764	.199
Total zinc	.0062	.0175	.0616
Loadings in pounds per day per acre			
HEIA[1]	2.4	10.5	20.0
Total nitrogen	.046	.016	.023
Total phosphorus	.0090	.0016	.0017
Total carbon	.42	.41	.40
Chemical oxygen demand	.70	.94	1.8
Total residue	3.9	2.0	3.6
Total lead	.0025	.0073	.0099
Total zinc	.0026	.0017	.0031

[1] Hydraulically effective impervious area (in acres).

Lead loading was highest at the commerical site. The shopping center in downtown Fort Lauderdale has approximately 100,000 cars per day passing on the two adjacent streets. The highway site has approximately 20,000 cars per day with only a 25 percent reduction in lead loading (table 15). Apparently, a major fraction of the lead from car exhaust is deposited on the roadway surface.

Total zinc loading was similar for the residential and commerical areas and approximately half that value for the highway area.

THE ROLE OF ATMOSPHERIC INPUT IN STORMWATER RUNOFF QUALITY

Bulk-precipitation samples, a combination of dry fall and wet fall, were collected at the highway and commercial areas for time periods that permit estimates of the role of atmospheric input. Using the observed concentration, the inches of rainfall, and the hydraulically effective impervious acres, the atmospheric load of each constituent to the hydraulically effective impervious area can be calculated. Table 16 lists the measured atmospheric loads for the seven constituents. An estimate of the total atmospheric load for each area was obtained by scaling the number of collection hours represented by the measured loads to the total number of hours for the investigation period. Collection hours and the estimated atmospheric loads for the two areas are listed in table 16.

The potential role of the atmospheric load, as represented by the bulk-precipitation samples, can be gained by comparing "load-in" to the estimated runoff "load-out." This comparison is simplified by calculation of the load-in/load-out ratio (table 16).

The atmospheric loadings input to the hydraulically effective impervious of the transportation site exceed the runoff loads (load-out) of total nitrogen, total phosphorus, and total zinc. One possible explanation for the low apparent runoff loads is the resuspension of dry fallout particles by vehicular traffic and deposition on noncontributing pervious areas. An alternate suggestion that has been advanced is that the funnel collector has a trapping efficiency of over 100 percent. Although the atmospheric loading process is not well understood, measurements of atmospheric fallout (both dry fall and wet fall) are essential to thoroughly evaluate stormwater runoff quality. An additional inference is the desirability of reducing the hydraulically effective impervious area in urban architectural design since even a clean impervious area will be susceptible to atmospheric loading.

Total residue and chemical oxygen demand loads in the highway area also appear to result in large part from atmospheric input. Total lead and total carbon runoff loads are estimated to contain nearly a 50 percent contribution from atmospheric sources in the highway area.

Total carbon load-in/load-out ratio for the commercial area was identical to that observed for the highway area. Total carbon is approximately two-thirds inorganic (tables 3 and 4) at both sites, suggesting soil materials and concrete as sources.

Table 16.--Atmospheric input versus runoff

Constituent	Measured atmospheric load in pounds	Collection hours	Ratio Total hours / Collection hours	Estimated atmospheric load in pounds	Estimated runoff load in pounds	Ratio Load-in / Load-out
			Highway Total days = 886 = 21,264			
Total nitrogen	95.2	7,714	2.75655	262.42	150.8	1.74
Total phosphorus	5.59	7,714	2.75655	15.41	14.88	1.04
Total carbon	643.8	7,388	2.87818	1,853.	3,769.	.49
Total residue	6,157.6	7,590	2.80158	17,251.	19,060.	.905
Chemical oxygen demand.	3,166.2	9,590	2.21731	7,020.	8,778.	.80
Total zinc	11.65	9,155	2.32267	27.06	15.52	1.74
Total lead	13.93	8,706	2.44245	34.02	67.7	.50
			Commercial Total days = 765 = 18,360 hours			
Total nitrogen	90.6	6,918	2.65295	240.45	351.8	0.68
Total phosphorus	4.94	6,919	2.65356	13.11	26.3	.50
Total carbon	967.4	5,943	3.08935	2,988.6	6,150.	.49
Total residue	14,450.	6,918	2.65395	38,350.	55,655.	.69
Chemical oxygen demand.	7,306.	6,952	2.64097	19,295.	27,625.	.70
Total zinc	30.1	8,288	2.21525	66.7	47.1	1.42
Total lead	65.2	8,173	2.24642	146.5	152.	.92

The atmospheric contribution of total nitrogen, total phosphorus, total residue, and chemical oxygen demand were all in excess of 50 percent of the observed runoff load. They were also proportionally lower than the observed load-in for the transportation area.

Atmospheric contributions of total zinc exceeded the load-out. Either an undetected contamination source exists in the bulk precipitation sampling apparatus or zinc that falls out on the parking lot reacts and forms an insoluble complex which fails to run off. A third possibility is that the bulk precipitation sampler is close to a source of zinc.

This third possibility is a likely explanation for the high atmospheric input of total lead at the commercial area. The bulk-precipitation collector is less than 20 feet from Oakland Park Boulevard (40,000 cars per day) and less than 150 feet from the intersection with U.S. Highway 1. Many vehicles per day stop and start at the traffic light, so that the lead in the bulk precipitation is probably unrepresentative of the shopping center as a whole.

SUMMARY

Three land-use areas representative of sewered urban areas in south Florida were selected for an intensive investigation of stormwater-runoff quality. A U.S. Geological Survey automated instrumentation package designed to measure and record rainfall, stage, and collect water-quality samples across the storm hydrograph was used during the investigation. The large volume of data collected at the residential, highway, and commercial sites was placed in a computerized data-management system to facilitate storage, retrieval, and manipulation. Statistical models of the stored rainfall-runoff data indicated that most of the runoff came directly from the hydraulically effective impervious area.

Twenty-nine water-quality constituents were collected over the hydrograph with enough frequency to compute loads and test washoff process variables. Seven constituents were selected for concentration-decay analysis. Linear, second-degree, and exponential curves were fitted to observed time, accumulated rainfall, and accumulated runoff data for two storms at each of the three sites. The second-degree fit to runoff appears to work best for the limited sample tested.

Loads for 30 or more storms were computed for each of the three land-use areas. The loads were regressed against a suite of accumulation and washoff variables. Multiple linear regression load models were developed for seven constituents. Load models were used to estimate loads for unsampled storms stored in the data-management system. Loads for small storms not in the data-management system were estimated by simple linear regressions between rainfall and the measured storm loads. Combining the measured and estimated loads produced estimates for the collection period. Loadings (pounds per day per acre of hydraulically effective impervious area) were calculated for the three land-use areas. Total nitrogen, total phosphorus, and total residue were highest in the residential area. Chemical oxygen demand and total lead were highest in the commercial area.

Bulk-precipitation quality samples collected at the highway and commercial sites were used to estimate atmospheric loads into the two areas. Atmospheric loads exceeded the runoff loads for total nitrogen, total phosphorus, and total zinc at the highway area. Total zinc from bulk precipitation exceeded load-out at the commercial site. Atmospheric contributions to runoff loads were 49 percent or greater for all seven constituents at the two sites.

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