020062

PB80-17725 6

USE OF THE STORM MODEL FOR ESTIMATING THE QUANTITY AND QUALITY OF RUNOFF FROM THE METROPOLITAN AREA OF HOUSTON, TEXAS

U.S. GEOLOGICAL SURVEY

Water-Resources Investigations 79-74

Prepared in cooperation with the Texas Department of Water Resources

BIBLIOGRAPHIC DATA SHEET

1. Report No. [illegible]

2.

3. Recipient's Accession No.

4. Title and Subtitle
USE OF THE *STORM* MODEL FOR ESTIMATING THE QUANTITY AND QUALITY OF RUNOFF FROM THE METROPOLITAN AREA OF HOUSTON, TEXAS

5. Report Date
November 1979

6.

7. Author(s)
Kidd M. Waddell, Bernard C. Massey, and Marshall E. Jennings

8. Performing Organization Rept. No. USGS/WRI-79-74

9. Performing Organization Name and Address
U.S. Geological Survey, Water Resources Division
300 E. Eighth Street
Austin, TX 78701

10. Project/Task/Work Unit No.

11. Contract/Grant No.

12. Sponsoring Organization Name and Address
U.S. Geological Survey, Water Resources Division
300 E. Eighth Street
Austin, TX 78701

13. Type of Report & Period Covered
Final

14.

15. Supplementary Notes

Prepared in cooperation with the Texas Department of Water Resources

16. Abstracts The "STORM" model, developed by the U.S. Army Corps of Engineers, was selected from existing models and adapted to use available data to compute runoff from the Houston, Texas, area and to compute the loads and concentrations of biochemical-oxygen demand, dissolved solids, total phosphorus, total organic carbon, total nitrogen, and fecal-coliform bacteria. The water-quality data simulated by the STORM model will be used by the Texas Department of Water Resources to refine and verify a model of the Galveston Bay estuarine system.

Discharge and precipitation data for the 1975 water year and all available water-quality analyses were used to calibrate the model for the Buffalo, Whiteoak, Brays, Sims, Hunting, Greens, and Vince Bayous. Data for the 1974 water year were used to verify the model for discharge. After verification, the calibrations were adjusted to balance the difference between the 1974 and 1975 error predictions for discharge. The adjusted model was used with records of precipitation and evaporation to simulate a 20-year record of the quantity and quality of runoff from the modeled area.

17. Key Words and Document Analysis. 17a. Descriptors
Water quality, Water pollution, Urbanization, Model studies, Rainfall-runoff relationships

17b. Identifiers/Open-Ended Terms
Harris and Galveston Counties, Texas; Urban hydrology

17c. COSATI Field/Group

18. Availability Statement
No restriction on distribution.

[illegible]

19. Security Class (This Report)
UNCLASSIFIED

20. Security Class (This Page)
UNCLASSIFIED

21. No. of Pages
33

22. Price

USE OF THE STORM *MODEL FOR ESTIMATING THE QUANTITY AND QUALITY OF RUNOFF FROM THE METROPOLITAN AREA OF HOUSTON, TEXAS*

By Kidd M. Waddell, Bernard C. Massey, and Marshall E. Jennings

U.S. GEOLOGICAL SURVEY

Water-Resources Investigations 79-74

Prepared in cooperation with the Texas Department of Water Resources

1979

UNITED STATES DEPARTMENT OF THE INTERIOR

Cecil D. Andrus, Secretary

GEOLOGICAL SURVEY

H. William Menard, Director

FOR ADDITIONAL INFORMATION WRITE TO:

U.S. GEOLOGICAL SURVEY
FEDERAL BUILDING
300 EAST 8TH STREET
AUSTIN, TX 78701

CONTENTS

ILLUSTRATIONS

TABLES

USE OF THE *STORM* MODEL FOR ESTIMATING THE QUANTITY AND QUALITY OF RUNOFF FROM THE METROPOLITAN AREA OF HOUSTON, TEXAS

By
Kidd M. Waddell, Bernard C. Massey,
and Marshall E. Jennings
U.S. Geological Survey

ABSTRACT

The "STORM" (storage, treatment, overflow, and runoff) model, developed by the U.S. Army Corps of Engineers, was selected from existing models and adapted to use available data to compute runoff from the Houston, Texas, area and to compute the loads and concentrations of biochemical-oxygen demand, dissolved solids, total phosphorus, total organic carbon, total nitrogen, and fecal-coliform bacteria. The water-quality data simulated by the STORM model will be used by the Texas Department of Water Resources to refine and verify a model of the Galveston Bay estuarine system.

Discharge and precipitation data for the 1975 water year and all available water-quality analyses were used to calibrate the model for the Buffalo, Whiteoak, Brays, Sims, Hunting, Greens, and Vince Bayous. Data for the 1974 water year were used to verify the model for discharge. After verification, the calibrations were adjusted to balance the difference between the 1974 and 1975 error predictions for discharge. The adjusted model was used with records of precipitation and evaporation to simulate a 20-year record of the quantity and quality of runoff from the modeled area.

The difference between the observed and computed concentrations of the water-quality constituents for the 1975 water year ranged from -21 to +8 percent for dissolved solids, -56 to +31 percent for total organic carbon, 0 to +83 percent for biochemical-oxygen demand, -13 to +50 percent for total nitrogen, -40 to +133 percent for total phosphorus, and -33 to +140 percent for fecal-coliform bacteria. The difference between the observed and computed discharge for the 1975 water year ranged from -9 to +5 percent.

The estimated storm-runoff loads of dissolved solids from the eight basins ranged from about 43 to 82 percent of the total estimated loads during the 1975 water year. The percentages of storm-runoff loads for some of the other constituents were higher: 73 to 92 percent for total organic carbon; 77 to 92 percent for biochemical-oxygen demand; 49 to 81 percent for total nitrogen; 51 to 93 percent for total phosphorus; and 84 to 97 percent for fecal-coliform bacteria.

INTRODUCTION

Purpose and Scope of the Study

The Texas Department of Water Resources has developed and is attempting to refine and verify a water-quality model of the Galveston Bay estuarine system. A significant part of the inflow to this estuarine system is runoff from the Houston metropolitan area; therefore, refinement and verification of the model requires definition of the quality of runoff from the Houston area.

The purpose of this study, made in cooperation with the Texas Department of Water Resources, was to adapt an existing model to utilize available streamflow and water-quality data to compute runoff from the Houston area and to compute the concentrations and loads of selected water-quality constituents contained in the inflow to Galveston Bay.

The "STORM" (storage, treatment, overflow, and runoff) model, developed by the Hydrologic Engineering Center of the U.S. Army Corps of Engineers (1976), was selected from available models for use in the Houston area. The model was calibrated independently for each of eight basins and five land-use classifications (fig. 1, table 1) by using observed precipitation, evaporation, runoff, and water-quality data. The flow was calibrated to best fit the observed annual runoff with some emphasis on agreement in monthly volumes. The water-quality constituents were calibrated by using all available analyses to estimate the daily and annual loads of selected constituents and the densities of fecal-coliform bacteria for the 1975 water year. The model calibration was adjusted until the results were near agreement with the independently estimated values of annual loads. A long-term (20-year) simulation was made for each of the eight basins in the Houston area by using hourly precipitation data for the Houston airport as the main block of input data.

The U.S. Geological Survey, in cooperation with State, Federal, and local agencies, has collected data since 1934 on the quantity of runoff in streams that drain the Houston area. In 1964, the Geological Survey, in cooperation with the city of Houston, began a study to determine the effects of urban development on flood peaks and volumes at selected sites on streams (Ranzau, 1976), and in 1969 the study was expanded to include monitoring of selected water-quality constituents on a monthly basis. Consequently, a considerable amount of data are available for calibrating and verifying a model of the quantity and quality of runoff from the Houston area. The water-quality data, however, are limited by the lack of sampling during storms.

Description of the Area

The study area of this report is the drainage basin of Buffalo Bayou, which encompasses 624,000 acres within and adjacent to the metropolitan area of Houston, Texas. Buffalo Bayou is regulated by the Barker and Addicks flood-detention reservoirs near the western limits of Houston. From these reservoirs, Buffalo Bayou meanders east and is fed by six tributaries: Whiteoak, Brays, Sims, Hunting, Vince, and Greens Bayous.

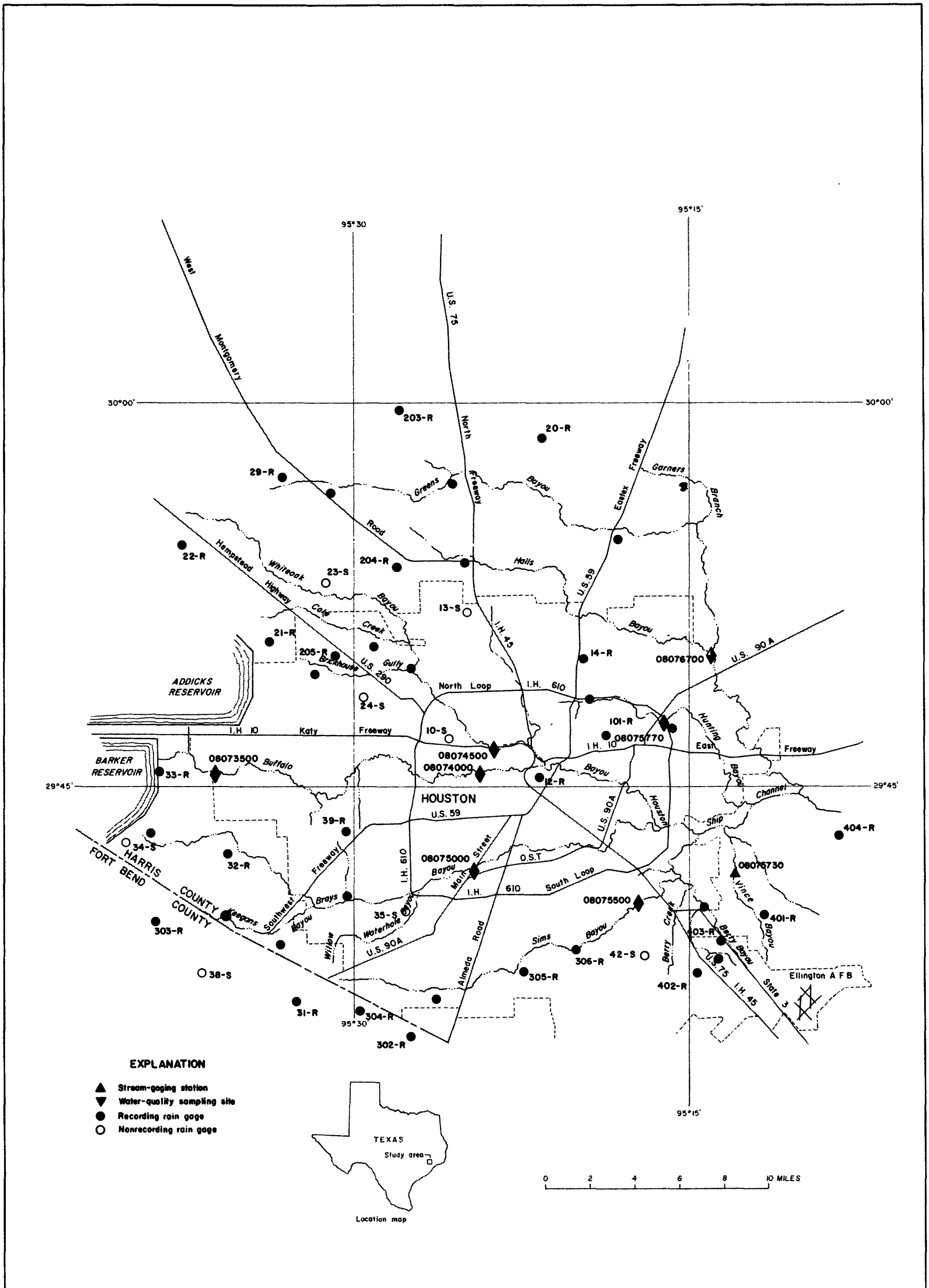


FIGURE 1.-Data-collection sites in the Houston area

The smallest basin modeled in this study was the Vince Bayou basin, which has a drainage area of 9,920 acres. The drainage areas of the other basins range from 22,340 acres to 187,520 acres. Because the Buffalo Bayou basin has a large difference in land use, the basin was subdivided into two parts: Buffalo Bayou basin above site 08073500, which includes two large flood-detention reservoirs, and Buffalo Bayou basin (exclusive of the six major tributary basins) below site 08073500. The drainage area above site 08073500 is 187,520 acres, and the drainage area below site 08073500 is 56,510 acres.

Land use in the basin includes rural areas (55 percent), residential areas (32 percent), and industrial-commercial areas (13 percent). In the residential, commercial, and industrial areas, the original hydrologic characteristics have been altered. Permeable soils have been replaced by varying amounts of impervious structures, such as homes, sidewalks, paved streets, and parking lots. These surfaces become coated with airborne industrial emissions, oil and grease from vehicles, nutrients associated with the care of lawns and gardens, and by many other substances in the urban environment.

The substances that accumulate on the impervious surfaces are subject to being washed off during storms, and the runoff from these storms may cause considerable deterioration of water quality in the receiving waters in Galveston Bay.

The locations of sites included in the data-collection network at the end of the 1975 water year are shown on figure 1. The periods of record for the eight sites (the lowermost sites in each of the respective basins) used in calibration of the model are shown on figure 2.

DESCRIPTION OF THE *STORM* MODEL

The STORM model, as described by the U.S. Army Corps of Engineers (1976), was revised to better serve the needs of this study as follows: (1) A line-printer daily-hydrograph plot was added to assist in calibration; (2) improved water-quality summary tables were added; (3) more ordinates were added to the unit-hydrograph option to improve computed recession flows; and (4) output files from STORM were interfaced with U.S. Geological Survey programs for frequency and duration-curve analyses. A complete documentation of the revised model, which will include a listing of the revised model program and instructions for its use, will be published in a separate report by the U.S. Geological Survey.

The loads and concentrations of six water-quality constituents were computed for selected storms on an hourly basis and then accumulated and averaged, respectively, to daily values. Weighted averages and total loads were computed for each water year of the period of simulation. The loads and concentrations are listed separately for the low-flow and storm-

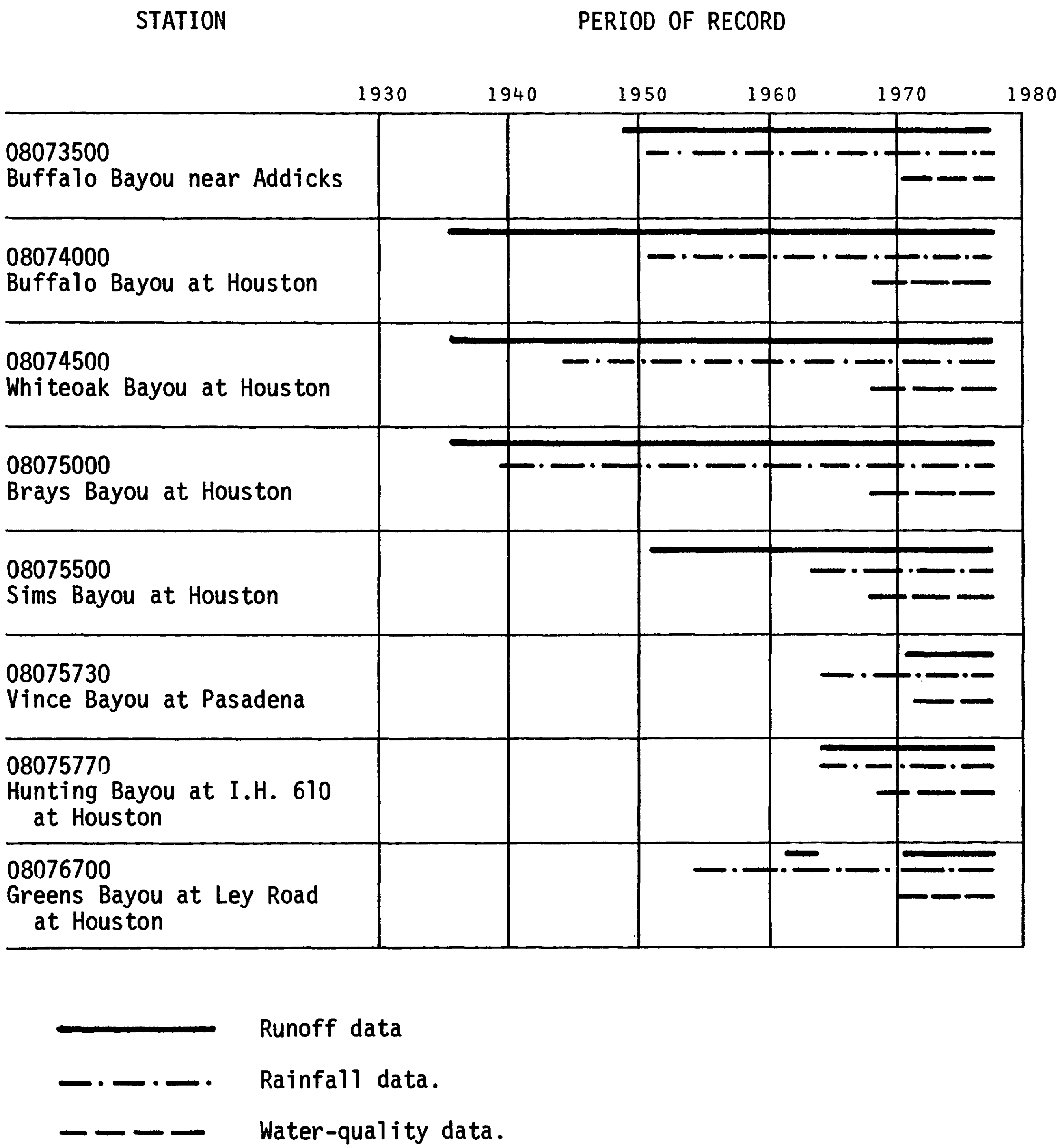


FIGURE 2.-Period of record for data-collection sites in the Houston area

runoff computations. Also a composite of the water quality for both low flow and storm runoff is made for each water year. A generalized flow chart of the procedure used in the model is as follows:

Flow Chart

Initial Conditions
- Low flows
- Antecedent storms
- Concentrations of selected constituents during low flow
- Accumulation rates of selected constituents

↓

Input Data
- Average precipitation (hourly)

↓

Time interval (1 hour)

↓

- Compute discharge (hourly), store daily values
- Compute storm-runoff loads (hourly), store daily values

(loop back to Input Data)

↓

Output
- Annual storm-runoff loads and concentrations (weighted)
- Annual low-flow loads and concentrations
- Annual low-flow loads plus weighted storm-runoff loads
- Hourly constituent-concentration curves for selected storms
- Daily hydrographs of discharge and loads

Storm Runoff

The options in the STORM model permit computation of storm runoff by one of three methods: (1) The U.S. Soil Conservation Service curve-number method; (2) the coefficient method; and (3) a combination of the curve-number and coefficient methods (U.S. Army Corps of Engineers, 1976). The first two methods were used in this study. The curve-number method is more useful in watersheds where losses due to infiltration are relatively high, while the coefficient method is more useful in highly urbanized areas where losses due to infiltration are relatively low.

The U.S. Soil Conservation Service curve-number method uses a rainfall-runoff relationship based on antecedent conditions for each storm. The equation used is:

$$Q = \frac{(P - IA)^2}{P - IA + S}$$

where Q = accumulated runoff, in inches;
P = accumulated precipitation, in inches;
IA = initial abstraction, in inches; and
S = total moisture capacity for storage, in inches.

The value IA (initial abstraction) represents all initial losses from depression storage, interception, and infiltration during the filling of depression storage that occur before runoff begins.

During each storm, soil moisture (S) is adjusted on the basis of infiltration rates and the rate of percolation to the water table. To maintain a continuous assessment of soil moisture (S), the model adjusts the value of S at the beginning of each time increment during periods of no precipitation. The initial abstraction value (IA) is decreased during periods of precipitation and increased during periods of no precipitation.

The coefficient method uses the following equation to compute runoff during each hourly time interval.

$$r = C\ (P - f)$$

where r = runoff, in inches;
C = composite runoff coefficient;
P = rainfall, in inches; and
f = available depression storage.

The values for the runoff coefficients for the pervious and impervious areas of the watershed are specified by the user and subsequently weighted by the model to obtain a composite runoff coefficient (C). This single coefficient is used to compute runoff for every storm regardless of rainfall intensity or soil-moisture conditions. Before the runoff coefficient is applied, however, the available depression storage (f) must be deducted from the rainfall. The depression storage is computed by the model on a continuous basis as a function of past rainfall and evaporation.

Routing

The STORM model uses the triangular unit-hydrograph procedure for routing runoff to the outlets of the basins. This procedure requires the input of variables defining the time of concentration (Tc) and the ratio of the time of recession to the time of the peak of the unit hydrograph (Tp). The equations are as follows:

$$Tp = 0.5 + 0.6\ Tc;$$

$$K = \frac{2}{1 + \frac{T1}{Tp}}\ ;\ \text{and}$$

$$Qp = 1.00833\ \frac{KAQ}{Tp}\ .$$

where Tp = time to peak of the unit hydrograph (hours);
Tc = time of concentration (hours);
T1 = time of recession of the unit hydrograph (hours);
A = drainage area, in acres;
Q = runoff volume, in inches during time step;
Qp = unit hydrograph peak, in cubic feet per second; and
K = runoff-decay coefficient.

Low Flow

Because the low flow is often a major contributor of pollutants to the receiving waters, a provision is included to allow the user to specify the quantity of low flow. The STORM model offers the option of using either hourly or daily variations in low flow.

Quality of Storm Runoff

The STORM model provides two options for determining the quality of storm runoff: (1) An option based on the assumption that the pollutants are all associated with accumulation of dust and dirt in the streets; and (2) an option for input of the accumulation rate of pollutants per day per acre for a given land use.

The second option, which was used in this study, is recommended for areas where a significant part of the land use is nonurban. In using this option, the assumption is made that the rate of accumulation per day is the same throughout the year for a particular constituent. The equations used to compute the hourly rate at which pollutants are washed off the surface are:

$$Mx = P_x \text{ EXPT}$$

where P_x = accumulated pounds of pollutant x; and

$$\text{EXPT} = (1 - e^{-KR_I})$$

where K = runoff-decay coefficient; and
R_I = total storm runoff, in inches.

Quality of Low Flow

Estimates of the concentrations (densities of fecal-coliform bacteria) of each of the six selected constituents during low flow must be entered. In this study, the concentrations were assumed to be constant for the period of simulation and were assumed to represent the combined effects of point sources in the basin above the data-collection sites.

LAND-USE CLASSIFICATION

The land-use maps obtained for this study were prepared by the U.S. Geological Survey (1976) as part of a program to provide land-use and land-cover maps for the entire United States. The land-use classification system was based on previous classification systems that were amenable to the use of data obtained by remote sensing; field surveys were a secondary source of data. The categories of land use and land cover are described in detail by Anderson and others (1976).

For this study, land-use percentages were determined from the U.S. Geological Survey maps for the following categories: (1) Residential; (2) commercial; (3) industrial; and (4) open land. The STORM model requires that the residential land-use category be subdivided according to the percentage of single-family residential and multiple-family residential development. Aerial photographs of the Houston area, taken in 1975, were used to estimate the relative occurrence of single-family to multiple-family residences in each of the basins modeled.

Table 1 lists the percentages of drainage area for the five land-use categories in each basin. These percentages, which were used in the simulation procedure, represent the entire drainage area (extended to mouth) of the respective basins. The percentages used in the calibration procedure represent only the drainage area above each modeled site; therefore, the percentages used in calibration differ slightly from those used in the simulations.

SYNTHESIS OF HYDROLOGIC DATA

Hourly-precipitation data and average monthly-evaporation rates are required for the entire calibration and verification periods. A record of hourly or daily runoff values is also required to adjust the model coefficient to obtain the best fit between observed and computed volumes of runoff.

The 1975 water year was chosen as the calibration period for all basins. Selected hydrologic data for the 1974 water year were used to verify the calibrated model for discharge. After verification, the calibrations were adjusted to balance the difference between the 1974 and 1975 error predictions.

Precipitation

Hourly-precipitation data make up the main block of input data required by STORM, and a basic assumption of the model is that a single rainfall record is representative of rainfall throughout the basin.

Because rainfall patterns in the Houston area are known to have spatial variations, average precipitation records were developed for the six largest basins for the 1974-75 water years. In preparing the average precipitation records for a basin, a centrally located rain gage was selected as the base gage for that basin. An adjustment factor was then determined for each storm by computing the ratio of the rainfall at all gages to the rainfall at the base gage. This adjustment factor was applied to each hourly-rainfall value for that storm at the base gage. For the Vince Bayou basin, a single rain-gage record was considered to be sufficient.

Table 1.--Drainage areas and land-use classification used in the STORM model

Basin	Drainage area (acres)	Land-use classification (percentage of drainage area)				
		Single-family residential	Multiple-family residential	Indus-trial	Commer-cial	Open land
Buffalo Bayou above site 08073500	187,520	1	1	1	1	96
Buffalo Bayou below site 08073500[1]	56,510	35	17	20	20	8
Whiteoak Bayou	71,040	40	8	3	4	45
Brays Bayou	81,920	27	10	3	19	41
Sims Bayou	60,350	28	5	7	9	51
Vince Bayou	9,920	60	23	5	10	2
Hunting Bayou	22,340	50	7	27	9	7
Greens Bayou	134,400	32	13	3	8	44

[1]Exclusive of the six major tributary basins.

Evaporation

Evaporation data are used by STORM for recovery of initial abstraction and as part of the recovery rate for soil-moisture storage. The STORM model requires average daily evaporation values in inches per month. Where the calibration, verification, or simulation period is to exceed 1 year, an average or mean evaporation record is required.

Seven years (1965-71) of pan-evaporation records from the National Weather Service pan-evaporation station at Lake George, approximately 25 miles southwest of downtown Houston (Thompsons 3 WSW) were used to develop an average record of daily evaporation rates. This average record was used for calibration of the model and for the simulation of long-term runoff.

Storm Runoff

Mean daily discharges for the 1974 and 1975 water years were computed for each of the sites listed in table 1 with exception of the two sites on Buffalo Bayou. Modeling of Buffalo Bayou presented a problem because the upper 267 square miles (170,880 acres) of this basin are controlled by two floodwater-detention reservoirs that have a combined capacity of 315,900 acre-feet at the top of the flood pools. The reservoirs are designed and operated for the temporary detention of floodwaters to be released at a rate that will not cause severe flooding. A streamflow station (08073500), located a short distance downstream from the reservoirs, records the floodwater releases.

The most downstream station on Buffalo Bayou (station 08074000) has a drainage area of 358 square miles (229,120 acres) including the area above the reservoirs. To predict inflows to the flood-detention reservoirs, STORM was used to model the drainage area above site 08073500. The record of observed discharge for this site was adjusted to reflect inflow to the reservoirs by accounting for changes in reservoir contents and releases from reservoir storage. A record of daily mean discharges for the downstream station (08074000) was then computed by deducting reservoir releases from the records of observed discharge. Discharge at the downstream station was then modeled by using only that part of the drainage area below station 08073500. A computer program was developed to combine the discharge at the upstream station with the discharge at the downstream station by using the typical reservoir-release patterns as a guide.

Low Flow

STORM requires the user to specify the low flows, which for streams in the Houston area are composed of ground-water seepage and domestic, commercial, and industrial waste-water discharges. For input to STORM, a constant daily value for low flow was estimated for each site on the basis of low-flow records for the 1970-75 water years.

Water Quality
Estimates of the Storm-Runoff Loads

Estimates of the loads of the six water-quality constituents were made for the data-collection sites so that the STORM model could be calibrated. This process involved estimating the daily loads of biochemical-oxygen demand (BOD), fecal-coliform bacteria (FCOL), dissolved solids (DS), total phosphorus (TPH), total organic carbon (TOC), and total nitrogen (TN).

Water-quality data for streams in the Houston area were collected at monthly intervals and during selected storms. Because discharge was continuously monitored at the data-collection sites and because the variability of discharge is often related to the variability of water-quality characteristics, regression equations expressing the relation of constituent concentrations to discharge provided a means of estimating the daily loads of some of the constituents. The correlations of discharge with concentrations of biochemical-oxygen demand, fecal-coliform bacteria, and total organic carbon were poor in most of the basins; therefore, average values were used for the concentrations of these constituents. Table 2 is a summary of the regression equations used to estimate the concentrations.

The standard error of estimate of the dissolved-solids concentrations ranged from 24 percent of the mean at site 08074000 to 69 percent at site 08076700. The standard error of estimate of the concentrations of most other constituents were within a range of about 30 to 80 percent of the mean.

Figure 3 shows the daily concentrations and accumulated loads of dissolved solids as computed by using the regression equations (table 2) and the observed and computed discharges at site 08075000 on Brays Bayou. Although there are significant variations during the year, the accumulated load of dissolved solids as determined by using the computed discharges is only about 12 percent less than the load as computed by using the observed discharges. It is assumed, therefore, that the errors resulting from differences between the observed and computed discharges do not create unreasonable errors in determination of the annual loads. For individual storms, however, the errors may be quite large.

The total load of a constituent (x) passing a data-collection site can be expressed as:

$$TL_x = \sum_{i=1}^{365} Qwi'(Qi) \cdot Qi \qquad (1)$$

in which Qwi'(Qi) represents the concentration of constituents (x) as a function (Qwi') of daily discharge (Qi) for the day (i). If the daily discharges are known, TL_x can be computed by summation of equation (1).

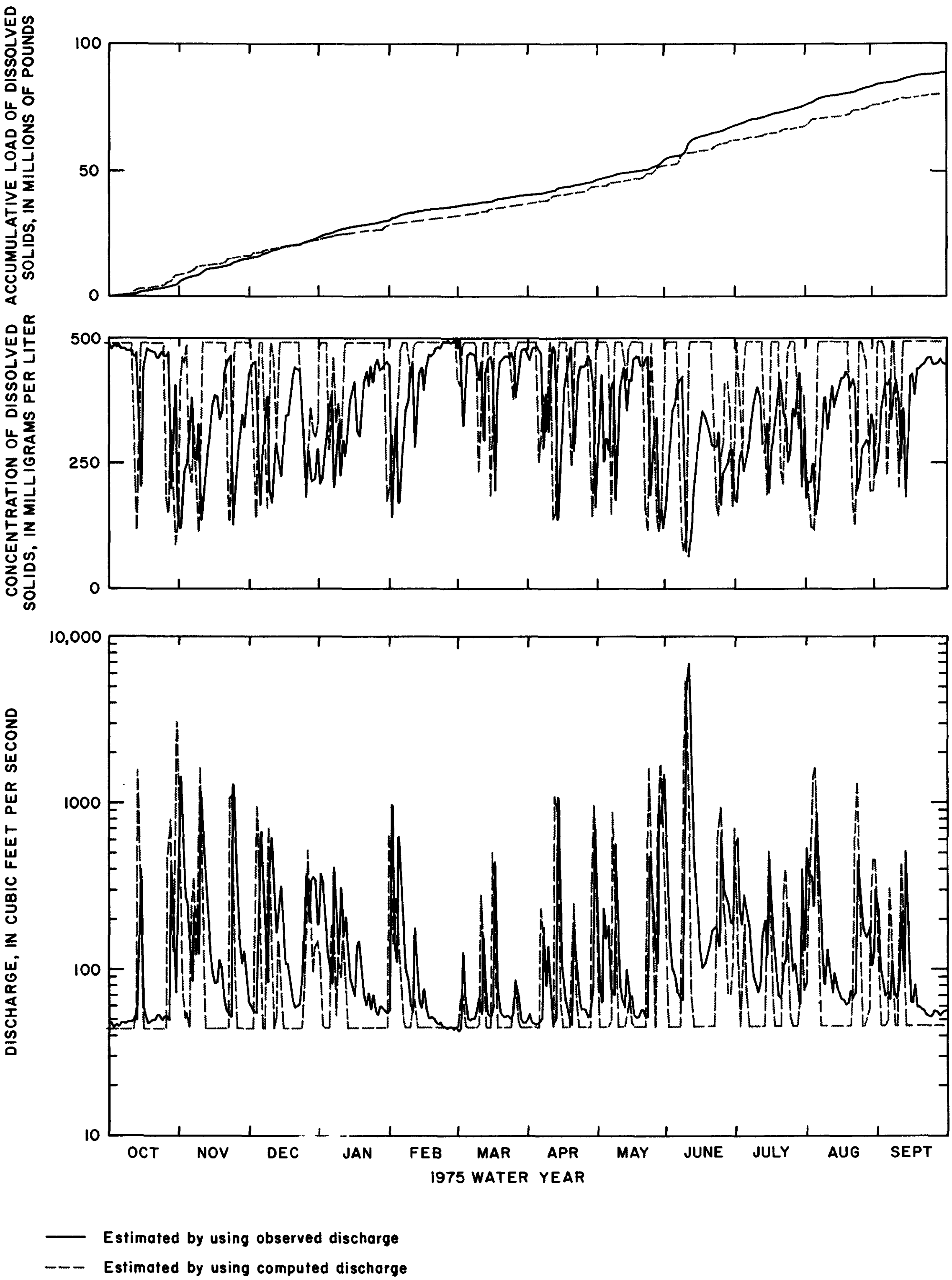


FIGURE 3.-Estimated concentrations and loads of dissolved solids for Brays Bayou (station 08075000) as determined from observed and computed discharges, 1975 water year

Table 2.--Summary of regression equations used for estimating the concentrations of various water-quality constituents

Variables: Q, discharge; BOD, biochemical-oxygen demand; FCOL, fecal-coliform bacteria; DS, dissolved solids; TPH, total phosphorus; TOC, total organic carbon; TN, total nitrogen.

Independent variable	Dependent variable	Number of observations	Regression coefficient	Regression constant	Correlation coefficient	Standard error	
						Log units	Percent of mean
		08073500 Buffalo Bayou near Addicks					
Q	BOD	63	-0.2052	1.0904	-0.42	0.27	66
Q	FCOL	62	.0430	3.0864	.02	.88	377
Q	DS	31	-.4084	3.1124	-.83	.16	38
Q	TPH	63	-.4034	.5192	-.86	.14	33
Q	TOC	51	.0628	1.0179	.14	.26	64
Q	TN	60	-.2594	.7230	-.59	.21	50
		08074000 Buffalo Bayou at Houston					
Q	BOD	91	-.1251	1.1086	-.28	.24	59
Q	FCOL	79	.1522	3.8976	.12	.66	218
Q	DS	60	-.3919	3.2280	-.90	.10	24
Q	TPH	86	-.3427	.8573	-.68	.20	48
Q	TOC	54	.0977	.9153	.27	.18	44
Q	TN	78	-.3451	1.2615	-.71	.18	44
		08074500 Whiteoak Bayou at Houston					
Q	BOD	107	.0608	.7851	.10	.43	118
Q	FCOL	94	.8409	1.8744	.40	1.44	1,389
Q	DS	63	-.3383	3.1078	-.91	.12	29
Q	TPH	101	-.2685	.7264	-.64	.24	60
Q	TOC	63	.0514	1.0186	.11	.31	78
Q	TN	91	-.2069	.9514	-.59	.21	50
		08075000 Brays Bayou at Houston					
Q	BOD	102	.0536	.6667	.08	.42	112
Q	FCOL	66	2.1083	-2.5565	.78	1.07	591
Q	DS	53	-.3984	3.3515	-.90	.12	29
Q	TPH	83	-.5178	1.4563	-.82	.23	56
Q	TOC	52	.0348	.9813	.10	.23	55
Q	TN	67	-.3906	1.5172	-.83	.16	38
		08075500 Sims Bayou at Houston					
Q	BOD	100	-.0647	1.1091	-.20	.21	50
Q	FCOL	87	.1088	4.2908	.10	.62	200
Q	DS	62	-.3514	3.3805	-.87	.14	34
Q	TPH	95	-.4421	1.2185	-.80	.22	54
Q	TOC	60	-.0795	1.3391	-.27	.19	45
Q	TN	85	-.4076	1.5006	-.83	.17	41
		08075700 Hunting Bayou at IH 610, Houston					
Q	BOD	98	.0016	.9399	.00	.32	80
Q	FCOL	85	.7781	2.7406	.49	1.06	577
Q	DS	61	-.2800	2.9434	-.92	.10	23
Q	TPH	93	-.1321	.3920	-.39	.24	58
Q	TOC	54	.0239	1.0508	.05	.33	84
Q	TN	83	-.1132	.8209	-.33	.24	60
		08076700 Greens Bayou at Ley Road, Houston					
Q	BOD	73	-.0793	1.0955	-.24	.30	75
Q	FCOL	73	.3852	3.3134	.44	.75	272
Q	DS	44	-.2926	3.2384	-.76	.28	69
Q	TPH	73	-.3851	1.0906	-.89	.18	45
Q	TOC	50	.0911	.8574	.37	.21	51
Q	TN	73	-.2719	1.1434	-.69	.27	66

The total load $(TL)_x$ is the sum of the low-flow load $(LFL)_x$ and the storm-runoff load $(ROL)_x$, or

$$(TL)_x = (LFL)_x + (ROL)_x. \qquad (2)$$

The low-flow load $(LFL)_x$ can be computed by substituting the estimated low flow (Ql) for (Qi) in equation 1. Because the low flow is assumed to be constant for the year, the low-flow load will be

$$(LFL)_x = Qwi\ (Ql) \cdot Ql \cdot 365. \qquad (3)$$

The storm-runoff load $(ROL)_x$ can be computed as the difference between the total load and the low-flow load, or

$$(ROL)_x = (TL)_x - (LFL)_x. \qquad (4)$$

Load-Accumulation Rates

The STORM model has the option of using a load-accumulation rate in pounds per day per acre. To use this option, the accumulation rates were estimated from observed data by using the expression

$$(AR)_x = (ROL)_x/(365 \cdot \text{area}). \qquad (5)$$

The estimated accumulation rates (table 3) represent the combined effects of all land uses within each of the eight basins, but the model requires that a rate be specified for each land use.

By assuming that the accumulation rates for a given constituent and land use are the same for all basins, the relationships can be described by the equation:

$$C_1 \cdot O_j + C_2 \cdot S_j + C_3 \cdot M_j + C_4 \cdot I_j + C_5 \cdot Cu_j = (AR_x)_j, \qquad (6)$$

Where C_1, C_2, C_3, C_4, and C_5 are unknown accumulation rates that are characteristic of the five land-use categories, and O_j, S_j, M_j, I_j, and Cu_j are the known fractions of total land-use acreages in basin j, where O_j is open land, S_j is single-family residential, M_j is multiple-family residential, I_j is industrial, and Cu_j is commercial.

Equation 6 describes an 8 x 6 matrix with the five unknowns being C_1, C_2, C_3, C_4, and C_5. This matrix has 56 possible solutions.

After obtaining several solutions to equation 6, it was apparent that the data for this study were not sufficient to determine any differences in accumulation rates between commercial and industrial areas or between single-family and multiple-family residential areas. The land-use classification, therefore, was reduced to the three categories of: (1) Residential, (2) commercial-industrial use, and (3) open land. Then, the 8 x 6 matrix was reduced to an 8 x 4 matrix with three unknowns: C_1, C_2, and C_4 and equation 6 rewritten as

$$C_1 \cdot O_j + C_2 \cdot (S_j + M_j) + C_4 \cdot (I_j + Cu_j) = (AR_x)_j.$$

Because of the assumptions used to set up the equation, a unique solution was not expected. The matrix has 56 possible solutions.

Table 3.--Compilation of data used for estimating load-accumulation rates, 1975 water year

Constituents: DS, dissolved solids; TOC, total organic carbon; BOD, biochemical-oxygen demand; TN, total nitrogen; TPH, total phosphorus; FC, fecal-coliform bacteria.

Station number	Drainage area (acres)	Low flow (cubic feet per second)	Total flow for 1975 water year (cubic feet per second per day)	Constituent	Low-flow concentration (milligrams per liter)	Low-flow load (pounds per day)	Weighted-average concentration (milligrams per liter)	Total load (pounds per day)	Storm runoff load (pounds per day)	Accumulation rate (pounds per day per acre)
08073500	187,520	35.6	128,800	DS	299	57,500	95	183,000	126,000	0.67
				TOC	12.0	2,500	16	30,500	28,000	.15
				BOD	6.0	1,150	3.0	6,090	4,940	.026
				TN	2.1	400	1.0	1,900	1,500	.008
				TPH	.8	150	.3	570	420	.002
				FC	[1]14.2	[2]1,240	[1]35	[2]30,000	[2]28,800	[3].15
08074000	[4]41,500	35.9	59,640	DS	534	103,000	205	182,000	79,100	1.9
				TOC	11	2,050	16	14,100	12,000	.29
				BOD	10.3	2,000	11	9,700	7,700	.18
				TN	8.5	1,640	3.8	3,350	1,710	.041
				TPH	3.4	660	1.8	1,590	930	.022
				FC	[1]261	[2]23,000	[1]600	[2]240,000	[2]217,000	[3]5.2
08074500	55,240	17.9	53,130	DS	485	46,800	185	144,000	96,900	1.6
				TOC	11	1,060	14	11,000	9,940	.18
				BOD	7.4	710	7.5	6,050	5,340	.097
				TN	4.7	450	2.3	1,800	1,350	.024
				TPH	2.4	230	1.1	860	630	.011
				FC	[1]23.8	[2]1,040	[1]115	[2]40,900	[2]39,900	[3].72
08075000	60,730	45	68,240	DS	494	120,000	[illegible]	222,000	102,000	1.7
				TOC	8.7	2,100	12	11,600	9,500	.16
				BOD	6.4	1,550	6.5	6,450	4,900	.081
				TN	7.2	1,750	3.4	3,430	1,680	.028
				TPH	3.4	825	1.4	1,400	575	.010
				FC	[1]57.9	[2]6,370	--	--	--	[3]1.6
08075500	40,350	23	40,760	DS	804	99,900	345	208,000	108,000	2.7
				TOC	18	2,270	14	8,430	6,160	.15
				BOD	9.8	1,220	9.0	5,420	4,200	.10
				TN	8.2	1,020	3.9	2,350	1,330	.033
				TPH	3.8	470	1.6	960	490	.011
				FC	[1]204	[2]11,500	[1]260	[2]71,000	[2]59,500	[3]1.5
08075730	5,250	2	7,170	DS	343	3,700	190	20,400	16,700	3.2
				TOC	8.3	90	6.5	690	600	.11
				BOD	4.2	45	5.5	590	545	.10
				TN	2.5	30	1.5	160	130	.025
				TPH	1.0	11	1.5	160	149	.028
				FC	[1]99.4	[2]490	[1]140	[2]6,720	[2]6,230	[3]1.2
08075770	9,400	4	8,530	DS	599	12,900	280	35,600	22,700	2.4
				TOC	13	280	14	1,770	1,490	.16
				BOD	8.5	180	8.0	980	800	.085
				TN	6.9	150	4.6	580	430	.046
				TPH	2.3	50	1.5	190	140	.015
				FC	[1]26.8	[2]260	[1]160	[2]9,140	[2]8,880	[3].94
08076700	116,500	25.1	91,240	DS	673	91,000	255	340,000	249,000	2.1
				TOC	11	1,480	15	20,200	18,720	.16
				BOD	8.3	1,120	7.5	10,100	8,980	.077
				TN	4.9	660	2.4	3,240	2,580	.022
				TPH	2.7	360	1.1	1,480	1,120	.010
				FC	[1]121	[2]7,400	[1]195	[2]120,000	[2]113,000	[3].97

[1]Concentrations are in colonies per liter x 10^{-3}.
[2]Loads are in billions of colonies per day.
[3]Accumulation rates are in billions of colonies per day per acre.
[4]Represents the drainage area at site 08074000 without the drainage area above site 08073500.

Several solutions were obtained for C_1, C_2, and C_4 by selecting different combinations of data from the eight basins. Average values of C_1, C_2, and C_4 were then used as the initial input to the model to begin the calibration. Subsequent adjustments of those parameters were made during the calibration.

Because the model was designed to describe five land-use categories, the accumulation rates for single-family and multiple-family residential areas were used by assuming $C_3 = C_2$, and the accumulation rate for industrial and commercial areas were used by assuming $C_5 = C_4$. During calibration of the model, the accumulation rate for commercial and industrial areas remained approximately equal; but the rate for some of the constituents in multiple-family residential areas was increased to about twice the rate for single-family residential areas. Table 4 shows the estimated accumulation rates after completion of calibration.

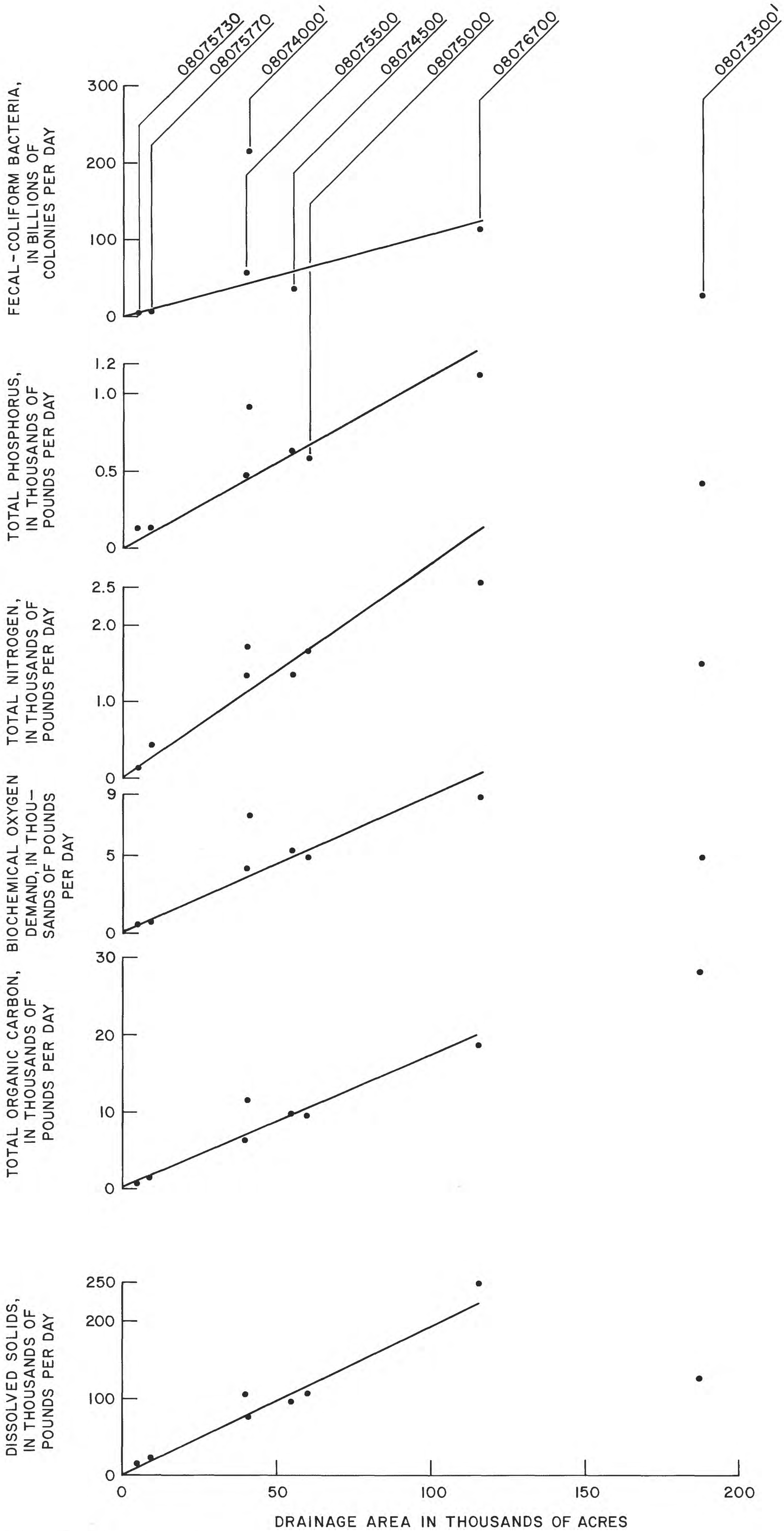
A general relationship between drainage area and the average daily storm-runoff load is shown on figure 4. For the assumptions made in this report regarding the effects of land use on load-accumulation rates, the relationship should be linear only for those sites that have similar land-use classifications. As expected, sites 08073500 and 08074000 show the largest deviation from the general trend because of the differences in land use. The storm runoff and loads from the drainage area above site 08073500, which is 96-percent open land, are small (below the general trend) relative to the size of the drainage area. Conversely, storm runoff and loads from the drainage area above site 08074000[1], which is about 40-percent combined commercial and industrial use, are large (above the general trend) relative to the size of the drainage area. The data points for these sites were not used in construction of the linear relationships shown on figure 4, but are included for comparison.

The estimated storm-runoff loads of dissolved solids from the eight basins ranged from about 43 to 82 percent of the total estimated loads during the 1975 water year. The percentages of storm-runoff loads for some of the other constituents were higher: 73 to 92 percent for total organic carbon; 77 to 92 percent for biochemical-oxygen demand; 49 to 81 percent for total nitrogen; 51 to 93 percent for total phosphorus; and 84 to 97 percent for fecal-coliform bacteria.

Generally, the highest concentrations per unit drainage area for most of the constituents occurred in the lower Buffalo Bayou basin (40-percent commercial and industrial use) and the lowest concentrations occurred in the upper Buffalo Bayou basin (96-percent open land). The estimated storm-runoff loads of dissolved solids at site 08073500 was 0.67 pound per day per acre compared to 1.9 pounds per day per acre for

---

[1]The drainage area for site 08074000 was adjusted so that runoff from the area above site 08073500 was not included.



[1] Data points not used in construction of linear relationships

FIGURE 4.-Relation of drainage area to estimated daily loads of selected water-quality constituents in storm runoff, 1975 water year

Table 4.--Load-accumulation rates as calibrated for the data base

Land-use classification	Dissolved solids (pounds per day per acre)	Total organic carbon (pounds per day per acre)	Biochemical-oxygen demand (pounds per day per acre)	Total nitrogen (pounds per day per acre)	Total phosphorus (pounds per day per acre)	Fecal-coliform bacteria (billions of colonies per day per acre)
Single-family residential	1.8	0.12	0.090	0.023	0.012	1.0
Multiple-family residential	3.1	.22	.16	.042	.019	1.0
Commercial	6.3	.43	.30	.083	.040	7.0
Industrial	6.4	.48	.36	.085	.045	7.0
Open land	1.6	.11	.080	.021	.010	.5

the area below site 08073500 (table 3). The storm-runoff loads per unit drainage area of the other five constituents were from 2 to 35 times greater below site 08073500 than above site 08073500.

CALIBRATION AND VERIFICATION OF THE *STORM* MODEL

The calibration criterion for this study was to achieve the best attainable agreement with the observed and computed annual runoff, with some emphasis on agreement in monthly volumes. Initially, all eight sites were calibrated by using the curve-number technique to compute runoff. After the initial trial at each site, the values estimated for initial abstraction, soil-moisture retention capacity, and infiltration rates were adjusted until the computed runoff agreed closely with the observed runoff for the 1975 water year.

A second calibration was made for each of the eight sites by using the coefficient method of computing runoff. In this method, the factors that require adjustment to achieve agreement between observed and computed annual runoff are the runoff coefficient for pervious areas, the runoff coefficient for impervious areas, and initial abstraction.

The water-quality characteristics were calibrated so that the annual loads had the best attainable agreement with the independently estimated loads at sites nearest the mouth of the basin.

Close agreement between the observed and computed runoff for the calibration year was achieved by both the curve-number method and the coefficient method. Neither of the two methods gave consistently better results, but the coefficient method was less cumbersome to use and required fewer computer runs to achieve calibration. The two calibrations for each site were compared with the discharge records, and the one producing the most accurate monthly volumes was chosen as the final calibration for that site.

Model verification involves the testing of the calibrated model against an independent set of data to determine the model's predictive capability. For this study, hourly rainfall data for the 1974 water year were used to verify the calibrated model for each of the eight sites. A comparison of the computed and observed annual runoff for the 1974 water year showed differences of 2 to 18 percent, with the average being about 10 percent. These differences, which were somewhat larger than anticipated, are attributed to the use of a single rainfall record for basins of up to 187,520 acres.

A comparison of the observed rainfall and runoff data for the 1974 and 1975 water years indicated that both years were equally representative of long-term averages. In an attempt to improve the predictive capabilities of the model, the calibrations were adjusted to balance the differences between the observed and computed discharges for the 1974 and 1975 water years. A comparison of observed annual runoff with values computed by using the adjusted calibrations (table 5) shows differences that range from 2 to 10 percent and average about 5 percent.

A comparison of the average annual concentrations of the six water-quality constituents, as computed by using the STORM model and as estimated by using the regression equations (observed) for the 1975 water year, are given in table 6. The results are in good agreement at some stations but show large differences at other stations.

The percentage of difference between the two independently computed values for the eight sites ranged from 8 to 44 percent for dissolved solids, 0 to 56 percent for total organic carbon, 0 to 83 percent for biochemical-oxygen demand, 0 to 50 percent for total nitrogen, 6 to 133 percent for total phosphorus, and 15 to 140 percent for fecal-coliform bacteria (table 6).

The concentrations of dissolved solids and total nitrogen had the best agreement between the two independently determined values in most of the basins. The percentage of difference exceeded 21 percent for dissolved solids in two of the eight basins and exceeded 20 percent for total nitrogen in one of the eight basins.

The concentrations computed by the STORM model could have been calibrated to agree more closely with those estimated by the regression equations, but this calibration would have required the use of different load-accumulation rates for the same land use in different basins. Because the model was calibrated so that the annual runoff and annual loads have the best attainable agreement with the observed runoff and the independently estimated loads at sites nearest the mouth of the basin, the hourly data produced by the model may be in considerable error and should be used with discretion.

SIMULATION OF DATA

The adjusted STORM models were operated to simulate a 20-year record of runoff and water quality by using the hourly precipitation record at the Houston airport for 1949-66 and 1974-75. The simulations were not intended to reproduce the runoff or the water-quality characteristics that occurred within a given basin during the same period. Changes in land use due to urbanization and industrial development; differences in precipitation intensity, duration, and distribution between the Houston airport and a particular drainage basin; and changes in channel hydraulics make comparisons between the model computations and the field observations during 1949-66 and 1974-75 invalid.

The water-quality characteristics of storm runoff vary primarily because of land use, soil characteristics, and the intensity and duration of the storms. In the simulations made for this report, the 1973 land-

Table 5.--Observed and computed discharges, 1974 and 1975 water years

Station number	Station	Discharge (cubic feet per second per day			
		1974 water year		1975 water year	
		Computed	Observed	Computed	Observed
08073500	Buffalo Bayou near Addicks	117,750	121,500	128,800	123,080
08074000	Buffalo Bayou at Houston[1]	57,440	58,410	59,640	58,790
08074500	Whiteoak Bayou at Houston	47,040	48,000	53,130	51,700
08075000	Brays Bayou at Houston	73,480	67,820	68,240	73,870
08075500	Sims Bayou at Houston	38,580	36,900	38,860	41,410
08075730	Vince Bayou at Pasadena	7,890	7,120	7,170	7,730
08075770	Hunting Bayou at IH 610, Houston	9,570	8,890	8,530	9,330
08076700	Greens Bayou at Ley Road, Houston	84,670	89,320	91,240	88,390

[1]Represents the discharge at site 08074000 without the drainage area above site 08073500.

Table 6.--Observed and computed discharges and concentrations of water-quality constituents, 1975 water year

(Observed concentrations are computed from observed discharges and the regression equations relating concentration to discharge, see table 3.)

Station number	Station	Discharge (cubic feet per second per day)		Percent difference	Dissolved solids (milligrams per liter)		Percent difference	Total organic carbon (milligrams per liter)		Percent difference	Biochemical-oxygen demand (milligrams per liter)		Percent difference	Total nitrogen (milligrams per liter)		Percent difference	Total phosphorus (milligrams per liter)		Percent difference	Fecal-coliform bacteria (1000 colonies per liter)		Percent difference
		Computed	Observed		Computed	Observed		Computed	Observed		Computed	Observed		Computed	Observed		Computed	Observed		Computed	Observed	
08073500	Buffalo Bayou near Addicks	128,800	123,080	5	130	95	37	7.0	16	-56	5.5	3.0	83	1.5	1.0	50	0.7	0.3	133	85	35	140
08074000	Buffalo Bayou at Houston[1]	59,640	58,790	1	295	205	44	14	16	-12	11	11	0	4.2	3.8	11	1.9	1.8	6	400	600	-33
08074500	Whiteoak Bayou at Houston	53,130	51,700	3	200	185	8	11	14	-21	8.0	7.5	7	2.4	2.3	4	1.2	1.1	9	170	115	48
08075000	Brays Bayou at Houston	68,240	73,870	-8	245	220	11	9.5	12	-21	8.0	6.5	23	3.4	3.4	0	1.6	1.4	14	170	--	--
08075500	Sims Bayou at Houston	38,860	41,410	-7	315	345	-9	13	14	-7	9.0	9.0	0	3.6	3.9	-8	1.7	1.6	6	215	260	-17
08075730	Vince Bayou at Pasadena	7,170	7,730	-7	150	190	-21	8.5	6.5	31	6.5	5.5	18	1.8	1.5	20	.9	1.5	-40	170	140	21
08075770	Hunting Bayou at IH 610, Houston	8,530	9,330	-9	305	280	9	14	14	0	13	8.0	62	4.0	4.6	-13	1.8	1.5	20	345	160	116
08076700	Greens Bayou at Ley Road, Houston	91,240	88,390	3	215	255	-16	11	15	-27	8.5	7.5	13	2.5	2.4	4	1.2	1.1	9	165	195	15

[1] *Computations are adjusted to represent the discharge without the drainage area above site 08073500.*

use distribution was assumed to be constant for the simulation period. Therefore, the variability of runoff and water-quality characteristics, as well as the intensity and duration of the storms, was controlled by the precipitation record. The distribution percentages of the five land-use classifications can be changed, however, so that the user of the model may evaluate the effects of various land-use distributions for a common simulation period.

The ranges of annual loads and discharge-weighted concentrations of six water-quality constituents in storm runoff and the associated discharge for each of the basins during the simulation period are shown on figure 5.

The ranges of concentrations of the constituents in the simulated storm runoff reflect the effects of the various combinations of land use in the basins. The largest differences occur in the basins that have the more extreme combinations of land use. For example, the two basins exhibiting the highest range of concentrations for most of the constituents are Buffalo Bayou below site 08073500 and Hunting Bayou. These two basins have the highest combined percentages of commercial and industrial land uses, and these land uses result in the highest load accumulation rates.

The minimum loads occurred during the 1956 water year, when runoff was the lowest of the simulation period. The maximum loads occurred during the 1957 water year, when runoff was about double that of the 1956 water year. Because very little runoff occurred during 1956, much of the accumulated loads of chemical constituents were flushed during 1957. This flushing resulted in the highest loading value for the simulation period, even though the runoff was not the maximum.

SUMMARY AND RECOMMENDATIONS

The purpose of this study was to adapt an existing model to utilize available streamflow and water-quality data to compute runoff from the Houston area and to compute the concentrations and loads of selected water-quality constituents contained in the inflow to Galveston Bay.

The STORM model, developed by the Hydrologic Engineering Center of the U.S. Army Corps of Engineers was selected from available models and calibrated independently for each of eight basins and five land-use classifications by using observed precipitation, evaporation, runoff, and water-quality data. The flow was calibrated to best fit the observed annual runoff with some emphasis on agreement in monthly volumes. The water-quality constituents were calibrated by using all available analyses to estimate the daily and annual loads of selected constituents and the densities of fecal-coliform bacteria for the 1975 water year. The model calibration was adjusted until the results were near agreement with the independently estimated values of annual loads. A long-term (20-year) simulation was made for each of the eight basins in the Houston area by using hourly precipitation data for the Houston airport as the main block of input data.

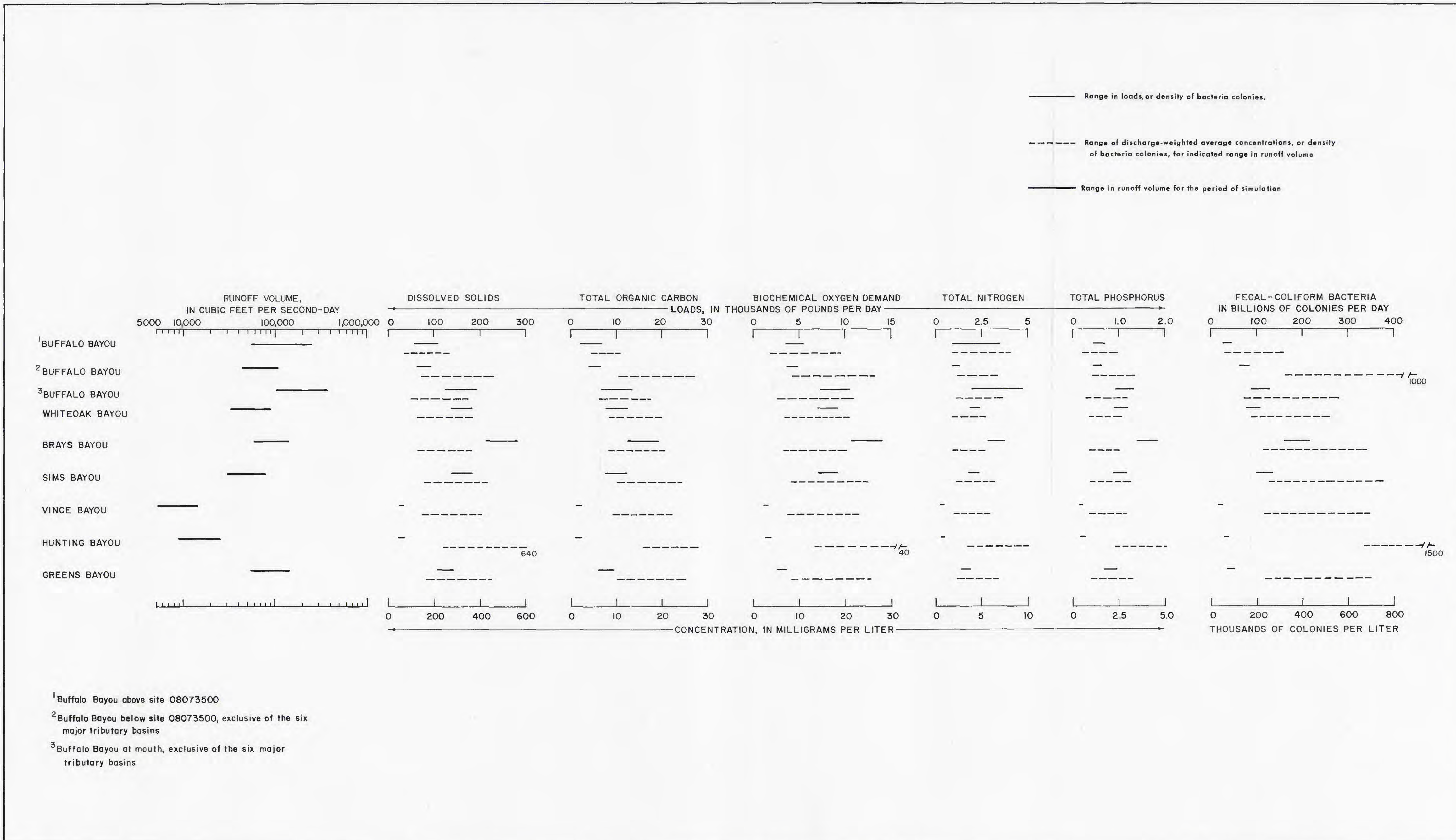


FIGURE 5.-Ranges of annual weighted-average concentrations and loads of selected water-quality constituents in storm runoff and associated discharge for the period of simulation

The STORM model was revised to better serve the needs of this study as follows: (1) A line-printer daily-hydrograph plot was added to assist in calibration; (2) improved water-quality summary tables were added; (3) more ordinates were added to the unit-hydrograph option to improve computed recession flows; and (4) output files from STORM were interfaced with U.S. Geological Survey programs for frequency and duration-curve analyses.

The loads and concentrations of six water-quality constituents were computed for selected storms on an hourly basis and then accumulated and averaged, respectively, to daily values. Weighted averages and total loads were computed for each water year of the period of simulation. The 1975 water year was chosen as the calibration period for all basins. Selected hydrologic data for the 1974 water year were used to verify the calibrated model for discharge. After verification, the calibrations were adjusted to balance the difference between the 1974 and 1975 error predictions.

Estimates of the loads of the six water-quality constituents were made for the data-collection sites so that the STORM model could be calibrated. This process involved estimating the daily loads of biochemical-oxygen demand (BOD), fecal-coliform bacteria (FCOL), dissolved solids (DS), total phosphorus (TPH), total organic carbon (TOC), and total nitrogen (TN).

Water-quality data for streams in the Houston area were collected at monthly intervals and during selected storms. Because discharge was continuously monitored at the data-collection sites and because the variability of discharge is often related to the variability of water-quality characteristics, regression equations expressing the relation of constituent concentrations to discharge provided a means of estimating the daily loads of some of the constituents. The correlations of discharge with concentrations of biochemical-oxygen demand, fecal-coliform bacteria, and total organic carbon were poor in most of the basins; therefore, average values were used for the concentrations of these constituents.

The standard error of estimate of the dissolved-solids concentrations ranged from 24 percent of the mean at site 08074000 to 69 percent at site 08076700. The standard error of estimate of the concentrations of most other constituents were within a range of about 30 to 80 percent of the mean. The estimated storm-runoff loads of dissolved solids from the eight basins ranged from about 43 to 82 percent of the total estimated loads during the 1975 water year. The percentages of storm-runoff loads for some of the other constituents were higher: 73 to 92 percent for total organic carbon; 77 to 92 percent for biochemical-oxygen demand; 49 to 81 percent for total nitrogen; 51 to 93 percent for total phosphorus; and 84 to 97 percent for fecal-coliform bacteria.

The calibration criterion for this study was to achieve the best attainable agreement with the observed and computed annual runoff, with some emphasis on agreement in monthly volumes. Initially, all eight sites were calibrated by using the curve-number technique to compute runoff. After the initial trial at each site, the values estimated for initial abstraction, soil-moisture retention capacity, and infiltration rates were adjusted until the computed runoff agreed closely with the observed runoff for the 1975 water year.

A second calibration was made for each of the eight sites by using the coefficient method of computing runoff. In this method, the factors that require adjustment to achieve agreement between observed and computed annual runoff are the runoff coefficient for pervious areas, the runoff coefficient for impervious areas, and initial abstraction. The water-quality characteristics were calibrated so that the annual loads had the best attainable agreement with the independently estimated loads at sites nearest the mouth of the basin.

A comparison of the average annual concentrations of the six water-quality constituents, as computed by using the STORM model and as estimated by using the regression equations (observed) for the 1975 water year are in good agreement at some stations but show large differences at other stations. The percentage of difference between the two independently computed values for the eight sites ranged from 8 to 44 percent for dissolved solids, 0 to 56 percent for total organic carbon, 0 to 83 percent for biochemical-oxygen demand, 0 to 50 percent for total nitrogen, 6 to 133 percent for total phosphorus, and 15 to 140 percent for fecal-coliform bacteria.

The concentrations of dissolved solids and total nitrogen had the best agreement between the two independently determined values in most of the basins. The percentages of difference exceeded 21 percent for dissolved solids in two of the eight basins and exceeded 20 percent for total nitrogen in one of the eight basins.

The concentrations computed by the STORM model could have been calibrated to agree more closely with those estimated by the regression equations, but this calibration would have required the use of different load-accumulation rates for the same land use in different basins. Because the model was calibrated so that the annual runoff and annual loads have the best attainable agreement with the observed runoff and the independently estimated loads at sites nearest the mouth of the basin, the hourly data produced by the models may be in considerable error and should be used with discretion.

To refine the urban data-collection program and to facilitate the synthesis and analysis of data, the following items should be included in future studies:

1. Runoff and the concentrations of selected water-quality constit-

uents should be monitored at additional sites that are characterized by a particular land use so that the associated water quality is definitive.

2. Sites below small drainage areas should be included within the larger network of data-collection sites to facilitate more accurate calibration of the precipitation-runoff hydrograph and the associated water quality.

3. Data-collection programs should emphasize sampling throughout several storms each year by using either automatic or manual techniques. The samples should be distributed throughout the hydrograph, but multiple samples should be taken on the rising and falling limbs. The analyses should include, but not necessarily be limited to: (1) Specific conductance; (2) suspended sediment; (3) nutrients; (4) bacteria; (5) organic carbon; and (6) biological-oxygen demand. Other constituents or characteristics should be selected to serve the needs of a particular study.

4. Detailed land-use maps should be constructed for each drainage basin.

5. A data-management program that is formulated for computer processing and that is compatible with current modeling efforts should be adopted.

6. The STORM model should be refined to reproduce storm hydrographs more accurately at hourly time intervals.

7. A more detailed urban model, calibrated by the use of storm data, should be adapted for use in smaller drainage areas.

REFERENCES CITED

Anderson, J. R., Hardy, E. E., Roach, J. T., and Witmer, R. E., 1976, A land use and land cover classification system for use with remote sensor data: U.S. Geological Survey Professional Paper 964, 28 p., 4 figs.

Ranzau, C. E., Jr., 1976, Hydrologic data for urban studies in the Houston, Texas, metropolitan area, 1974: U.S. Geological Survey open-file report, 228 p., 16 figs.

U.S. Army Corps of Engineers, 1976, Storage, treatment, overflow, runoff model "STORM": Corps of Engineers, Davis, California, computer program users manual, 45 p., 4 app.

U.S. Geological Survey, 1976, Land use and land cover and associated maps for Houston, Texas: U.S. Geological Survey Open-File Report 76-647, 4 sheets.