PREDICTION AND CONTROL OF URBAN STORMWATER QUALITY— A CASE STUDY

by Philip B. Bedient, Jeff L. Lambert, Chris B. Amandes, and David P. Smith

INTRODUCTION

Urban stormwater runoff has become the major source of stream pollution in many urban areas, since point source effluents have been largely controlled through improved treatment. However, there appears to be a severe lack of information on the general effects of urban stormwater runoff because of the site-specific nature of the runoff process.

The Environmental Protection Agency has expended large sums of research money on the characterization, definition, control, and ultimate management of nonpoint loads from urban runoff. Experience has indicated that in order to develop a management methodology, comprehensive monitoring and modeling of urban runoff is prerequisite until predictive tools are significantly improved. To address this problem, a coordinated research study by the Department of Environmental Science and Engineering at Rice University and the City of Houston Health Department was undertaken in May 1977.

Past data collection programs for water quality in the City of Houston emphasized low-flow "grab sampling" to define point source effects. Such information represents only a rough index of overall water quality. The study group designed a comprehensive stormwater quality and low-flow quality sampling program for the Brays Bayou watershed (figure 1), based on experience and information developed in previous stormwater management programs (Characklis et al., 1976; Bedient et al., 1978). The study area was selected for convenient location, available stream gauging, repre-

Mr. Bedient is Assistant Professor of Environmental Engineering at Rice University. Mr. Lambert is research scientist in the Dept. of Environmental Science and Engineering at Rice University. Mr. Amandes and Mr. Smith are graduate students at Rice University.

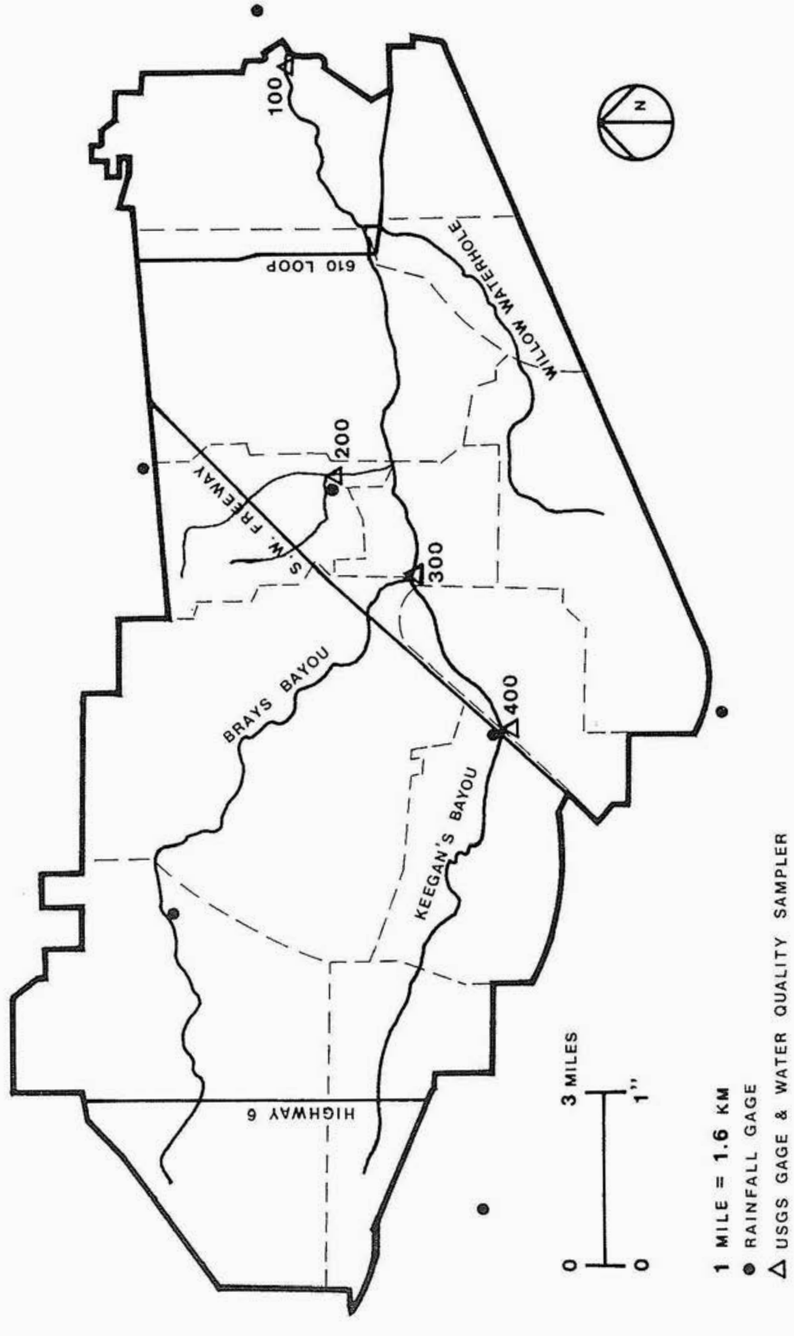

FIG. 1. WATER QUALITY AND FLOW MONITORING SITES AND RAINFALL RECORDERS IN BRAYS BAYOU

sentative urban land use, uniform soils, and an extensive existing collection of information.

STORMWATER CHARACTERISTICS

In order to design a stormwater sampling system, it is necessary to understand the temporal and spatial dynamics of storms in general. Differences in storm response are largely due to watershed size, slope, land use, soils, imperviousness, drainage density, and available storage. These factors must be considered for each sampling site in order to isolate significant parameters. For example, selection of two sites with similar size, slope, drainage pattern, and soil type can be used to distinguish effects of land use and imperviousness on stormwater quality. It is preferable to sample from small, single land-use areas as well as from large watersheds, however, so that storage and routing effects can be determined.

Temporal variations in stormwater depend on rainfall intensity and duration, watershed storage characteristics, and channel hydraulics. Three types of curves are used to define a storm event: the hydrograph, the concentration curve, and the mass flow curve. A hydrograph is characterized by the time to peak, t_p, the peak flow, Q_p, and the recession rate, all of which depend on the particular watershed and rainfall event under study. The shape of the hydrograph is largely affected by urban development, which can cause more rapid runoff from adjacent sewered areas and concrete-lined channels (figure 2e).

The concentration curve is a plot of pollutant concentration (mg/l) vs. time during a storm. Concentration curves exhibit the general patterns shown in figures 2a through 2d. The first flush is most frequently observed in urban watersheds for total suspended solids (TSS) and occasionally for nutrients (nitrogen and phosphorus), while the dilution pattern of figure 2b is often recorded for nutrients where wastewater is the greater part of low flow.

The mass flow curve is the product of flow (l/sec) and concentration (mg/l) at corresponding points in time, and represents a graph of pollutant load (mg/sec) vs. time. Mass flow curves typically resemble the shape of the hydrograph, with the timing of the peak dependent on the shape of the concentration curve and hydrograph. Integration of the mass flow curve gives the total pollutant load passing a sampling site during a given storm.

STORMWATER MONITORING PROGRAM

Four sites were selected for the initial sampling program in Brays Bayou watershed in an effort to differentiate effects of land use and urban drainage (figure 1). The watershed is located in rapidly-developing southwest Houston. More than 50% of the 86.8-square-mile study area has been

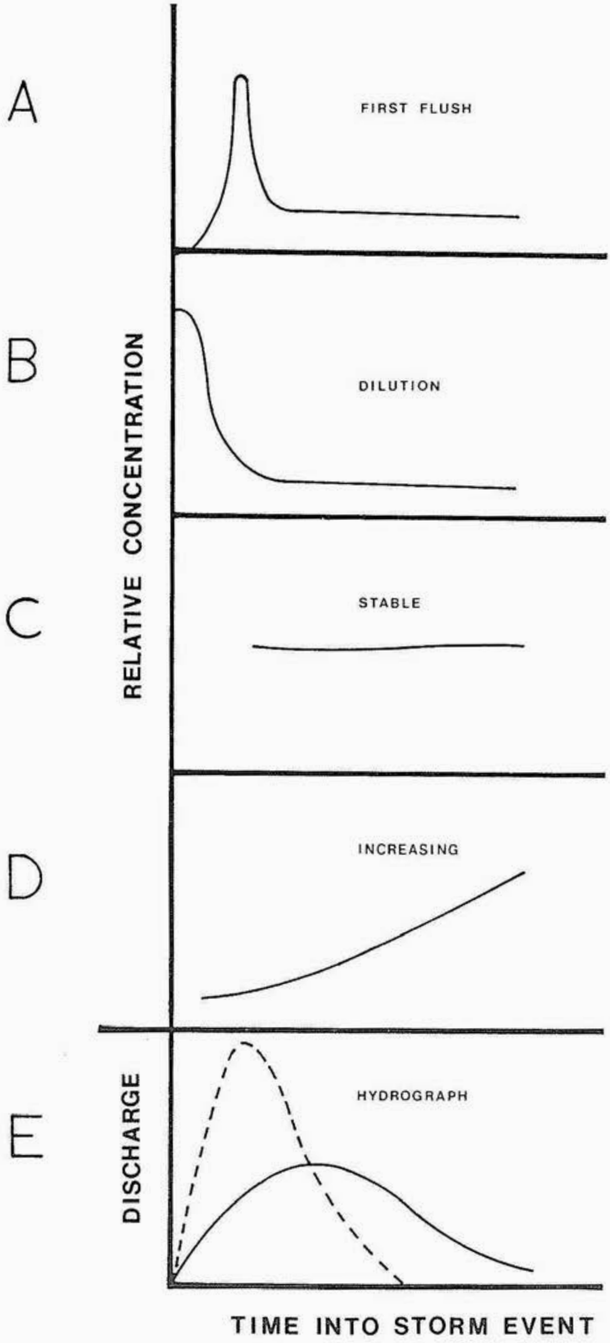

FIG. 2. TEMPORAL VARIATIONS OF STORMWATER (Characklis et al., 1976)

fully urbanized with residential and associated strip commercial development. Automatic stormwater quality sampling sites are located beside USGS stream gauges at major bridge crossings at Main St. (100) and Gessner Rd. (300) along the main stream channel. The major developing tributary, Keegan's Bayou, is sampled at the Southwest Freeway (400) and a small residential/commercial area, Bintliff Ditch, is monitored before it joins Brays Bayou (200). The upper part of Brays Bayou is developing agricultural and open land, and its runoff is sampled at Gessner Rd. (300). The Main St. site (100) collects the total load from all areas in the watershed. City of Houston personnel maintain the sites, and the City Health Department Laboratory performs all chemical analyses.

Water quality data have been collected on 27 storms at four sites in the Brays Bayou watershed since the beginning of the program. Chemical parameters are analyzed for samples taken at 15 to 30 minute intervals throughout a storm, and include total suspended solids (TSS), total phosphorus (TP), nitrogen species (TKN, NO_3, NO_2, NH_3), biochemical oxygen demand (BOD), dissolved oxygen (DO), and conductivity. A brief storm summary is presented in table 1.

DEVELOPMENT OF LOAD-RUNOFF RELATIONSHIPS

One of the major findings of the earlier Woodlands Project at Rice University was the importance of relating storm pollutant loads (lbs/acre) to total storm runoff (inches). Resulting regression lines from the study produced reasonable fits to the data for four different watersheds and eight water-quality parameters. However, data were lacking on fully urbanized sites because of slow construction at the Woodlands.

Load-runoff relationships were derived for three water-quality parameters, total suspended solids (TSS), total Kjeldahl nitrogen (TKN), and total phosphorus (TP), for the Brays Bayou watershed (Main St.), Bintliff (200), and Keegan's Bayou (400) (figure 3). Each data point represents the total load from a single storm. Urban land uses represent approximately 37%, 70%, and 20% of the three watershed areas, respectively. The slope of the regression line represents an average watershed concentration for a given pollutant, and differences should be explained on the basis of differences in watershed characteristics, especially land use.

A ranking of the three sites along with the Woodlands sites is presented in table 2. It is interesting to note that Main St. yields the highest load of TSS by a large margin, with Keegan's and Bintliff close together, although the percentage of urbanization is much higher in the Bintliff area (70%) than in Keegan's (20%). Construction activity and recent channelization work in Keegan's Bayou most likely account for difference. TSS levels in Brays Bayou are, on the average, more than twice the levels found in the Woodlands watersheds or Hunting Bayou. Note that the forested site (P-10)

TABLE 1

Storm Summary

Date	Rainfall (inches)	Runoff (inches)	Peak Q (cfs)	Load (lbs/acre) TSS	TP	TKN
MAIN ST.						
8 Jul 1977	.18	.06	1180	10.80	0.025	0.055
28 Jul 1977	.11	.03	410	5.70	0.014	0.039
11 Aug 1977	1.24	.01	245	1.33	0.010	0.006
6 Sep 1977	.52	.07	680	19.14	0.047	0.059
1 Nov 1977	1.24	.15	1457	13.66	0.056	0.096
8 Nov 1977	1.11	.18	1724	19.78	0.042	0.098
21 Nov 1977	.66	.15	1106	23.71	0.091	0.123
13 Dec 1977	1.05	.26	2940	43.99	0.061	0.171
11 Jan 1978	1.54	.60	5130	72.70	—	—
12 Feb 1978	.81	.39	3572	58.25	0.118	0.198
BINTLIFF						
1 Nov 1977	1.16	.69	571	46.18	0.110	0.080
1 Nov 1977	.69	.42	345	26.09	0.039	0.118
13 Dec 1977	1.20	.67	295	64.89	0.070	0.183
11 Jan 1978	1.74	.98	889	58.78	0.127	0.201
12 Feb 1978	1.05	.70	540	83.26	0.097	0.199
29 May 1978	1.56	.83	875	97.41	0.094	0.244
7 Jun 1978	1.80	1.12	1020	99.42	0.198	0.480
GESSNER						
12 Feb 1978	.81	.25	1130	46.21	0.072	0.161
2 May 1978	.23	.03	186.9	4.95	0.025	0.015
29 May 1978	.64	.08	713.7	20.45	0.015	0.034
KEEGAN'S						
30 Jan 1977	.15	.07	125	7.40	0.050	—
10 Feb 1977	1.38	.48	270	50.00	—	—
6-7 Sep 1977	1.45	.12	190.5	13.01	0.052	0.041
21 Nov 1977	.33	.06	61.5	6.41	0.045	0.015
11 Jan 1978	1.12	.41	470	28.14	0.167	0.217
29 May 1978	.64	.02	81.0	4.84	0.010	0.015
7 Jun 1978	2.16	.38	469.5	73.07	0.149	0.138

yielded the lowest level of TSS, a finding consistent with a greater potential for retention of suspended solids in natural areas.

TP is highest in Keegan's, possibly because of construction and sewage effluents. Bintliff has relatively high levels, though no sewage effluents are discharged into the channel. Stormwater runoff from impervious areas is the main source of TP in Bintliff. Finally, the Woodlands watersheds again produce much lower levels for TP, with the forested P-10 site yielding the minimum.

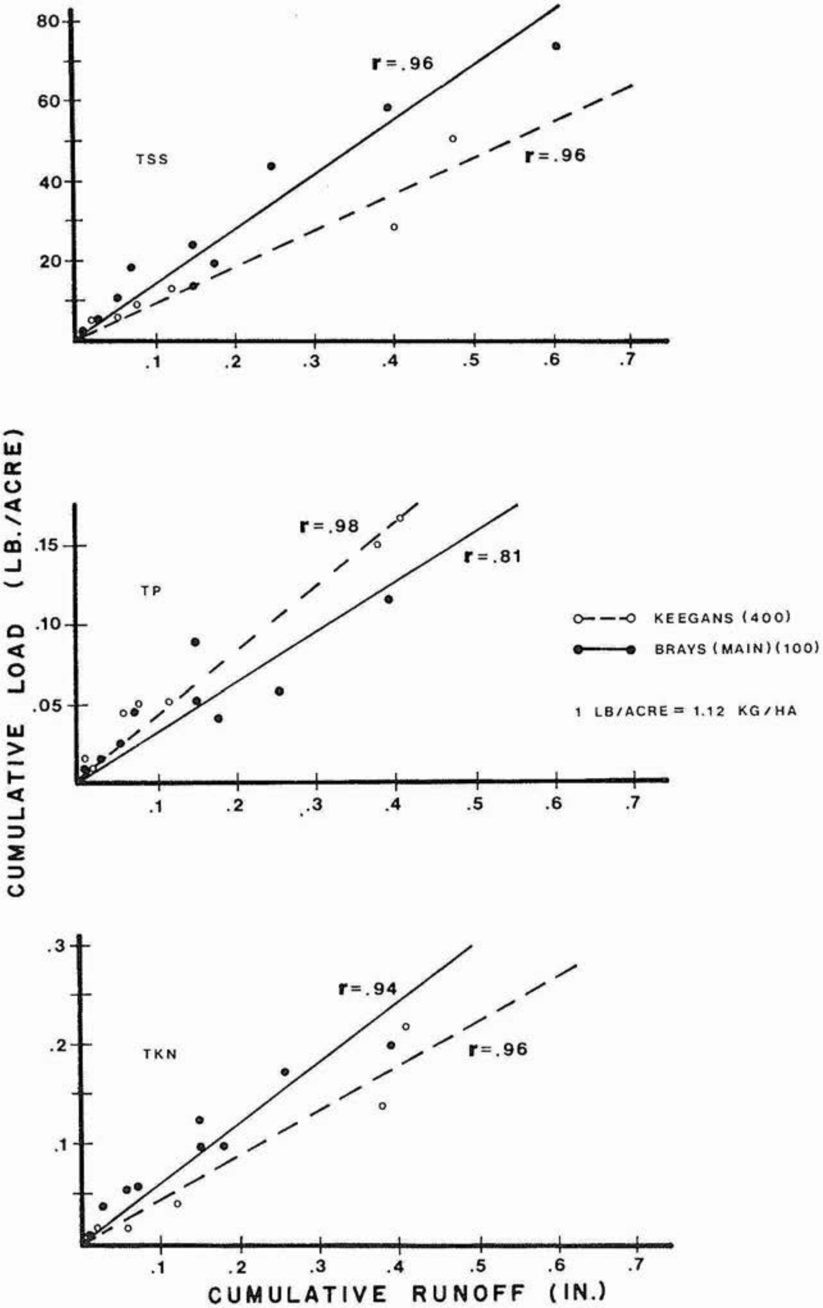

FIG. 3. LOAD-RUNOFF RELATIONSHIPS FOR KEEGAN'S AND BRAYS AT MAIN

TABLE 2

COMPARISON OF AVERAGE LOAD-RUNOFF SLOPES

SITE	Urbanized (%)	TSS (mg/l)	TP (mg/l)
Main	37	592	3.58
Keegan's	20	398	4.33
Bintliff	70	388	3.36
Woodlands (P-30)	10	191	.09
Hunting	94	156	1.24
Woodlands (P-10)	1	37	.06

In general, the more heavily urbanized sites produced the greatest loads of TSS and TP. Construction activity significantly affected the results. Bintliff, which had the most stable urban land use, however, yielded high values for both parameters.

The load-runoff relations that were developed from sampled storms can be extended to estimate mass flows during individual or sequential storms. A water quality model (HLOAD) was developed for the Woodlands project and has been adopted for the City of Houston study. The model uses runoff values and time-varying load-runoff relationships for each water-quality parameter to be measured, in order to calculate mass flows during storms. The range over which the slopes of the load-runoff curves vary is determined by the spread in pollutant concentrations observed in the stormwater sampling program (Harned, 1977).

The load-runoff relations can also be used to calculate total annual loads for selected pollutants. A measured or predicted annual streamflow hydrograph is required, along with average low-flow concentration values. During storms, the load-runoff relation is used to predict the mass flow, while during intermittent low flows, mass flow is estimated as the product of streamflow and average low-flow concentration.

The Rice research group used the load-runoff relations to calculate total annual loads for two sites. Storms for the water-year 1976 (August 1975—July 1976) were analyzed, and a total volume of storm flow expressed as inches of runoff over the watershed was calculated. Annual storm loads were calculated by using the load-runoff curve. The results show that 2046 lbs/acre/year of solids were washed off the surface of the watershed and carried downstream by the bayou. Storm flow loads represent 88% of the solids load transported by the bayou on an annual basis. A similar calculation for the less-developed Keegan's watershed for the same period indicated a total annual solids load of 1039 lbs/acre/year, of which 96% represented storm loads.

SIMULATION OF NONPOINT SOURCE LOADS

Over the past several years, urban runoff has been intensively investigated. Increased data bases have led to better understanding of the processes involved, and then to the development of sophisticated modeling techniques. However, the prediction of stormwater volume has met with far greater success than the prediction of stormwater quality. The water quality subroutines of both the STORM (U.S. Army Corps of Engineers, 1975) and SWMM (EPA, 1971) models require extensive data collection and careful calibration for each new application. Results from use of the SWMM model in the Woodlands Project indicated that some accuracy problems existed with the original water quality prediction method (Diniz and Characklis, 1976). In fact, the water quality subroutine of the SWMM model was specifically modified as a result of the Woodlands project. In the present study, an attempt was made to restrict the modeling techniques to simplified procedures that correspond to the accuracy of the sampling program.

The following sections describe in detail various modeling approaches used to simulate historical events and to predict responses to various control strategies. Results for Brays Bayou (Main St.) and Keegan's Bayou are presented below to show management approaches for the entire watershed and for the subwatershed level.

HEC-1 RESULTS FOR BRAYS BAYOU

The relationship between the factors of increasing land development, impervious area, and drainage patterns, and the resultant changes in hydrologic response, is of critical importance to water resources planning. Generally, as a watershed is urbanized, the total runoff and peak flow increase, causing potential problems with stormwater pollutant loads and flooding. Hydrologic computer models are used to simulate expected future land use and watershed characteristics, and to predict the resulting flows. Models that could be used include HEC-1 (U.S. Army, 1973), STORM (U.S. Army, 1975), and SWMM (Environmental Protection Agency, 1971). The selection of the best model for simulating the overall response of Brays Bayou depended largely on the availability of precipitation data, land-use data, and flood routing coefficients. On the basis of its previous applications to large watersheds and the availability of unit hydrograph data, HEC-1 was chosen as the model for preliminary investigation of flood response.

Brays Bayou was divided into six subwatersheds (upper Brays, upper Keegan's, lower Keegan's, middle Brays, Willow Waterhole, and lower Brays) for the HEC-1 modeling. The latter three subwatersheds are almost completely developed. Our objective was to determine the effect of continuing development in the watershed up to an expected ultimate level.

HEC-1 generates a hydrograph using Snyder's unit hydrograph characteristics (Chow, 1964). Peak flow, Q_p, is related to the time-to-peak, t_p, and to the storage coefficient C_p, by the following equation:

$$Q_p = \frac{640\, C_p A}{t_p}$$

where Q_p is expressed in cubic feet/second, t_p is in hours, and A is the watershed size in square miles. Once the hydrograph is computed, it is routed downstream and combined with flows from the other subwatersheds until the final outflow hydrograph is developed for the Main St. site.

The model was calibrated (based upon 1975 land use) for two observed storm hydrographs, those of June 9, 1975, and June 15, 1976 (figure 4). The calibration procedure adjusts the values for t_p, C_p, depression storage, and infiltration rates until the computed flows approximate the actual flows. Results are shown in table 3. The 1-hour and 2-hour unit hydrographs were derived by setting the loss rate to zero and distributing one inch of rainfall uniformly over the watershed. Both of these current unit hydrographs have peak discharges that exceed the figure of 6000 cfs, which VanSickle (1969) said was the ultimate value for Brays Bayou (table 4). This illustrates the critical relationship between development and the peak discharge.

To simulate future land-use conditions, which we assumed to be the most complete development possible, the t_p, C_p, and percentage of infiltration of the upper subwatersheds were adjusted to correspond to the already developed lower subwatershed. The unit hydrographs predicted under these ultimate conditions have peak discharges that approximately double Van Sickle's predicted values (table 4), assuming that all of the runoff can reach the main channel.

The predicted characteristics of ultimate development were also applied to the events against which the HEC-1 was calibrated, the June 9, 1975, and the June 15, 1976, storms. Flows for the 6-hour—25-year and the 6-hour—100-year frequency storms with uniform rainfall over the watershed were also compared to those projected for ultimate land-use conditions (table 4). Note that even under present land use, both the 25-year and the 100-year frequency storms will have peak discharges exceeding the capacity of the channel (about 30,000 cfs). This preliminary analysis assumes that all stormwater runoff is able to reach the channel, and neglects any backwater effects.

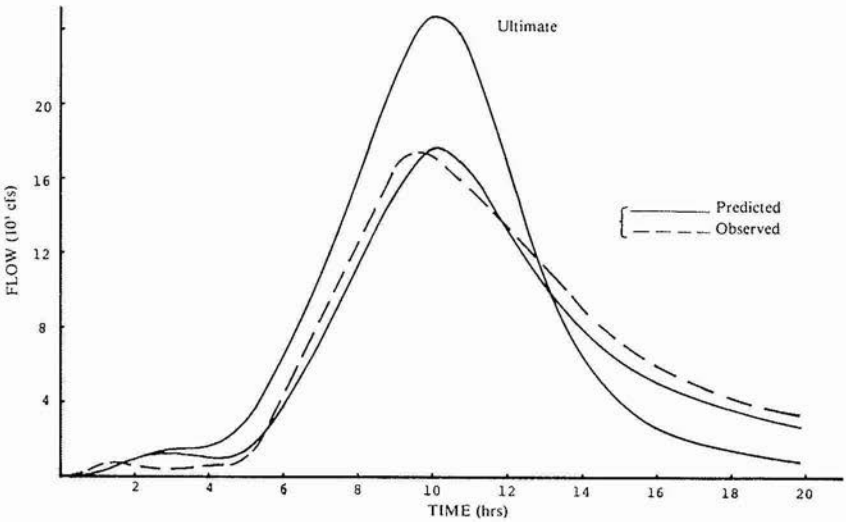

FIG. 4a. HEC-1 SIMULATIONS OF JUNE 9, 1975, STORM.
1 cfs = .028 m^3/s

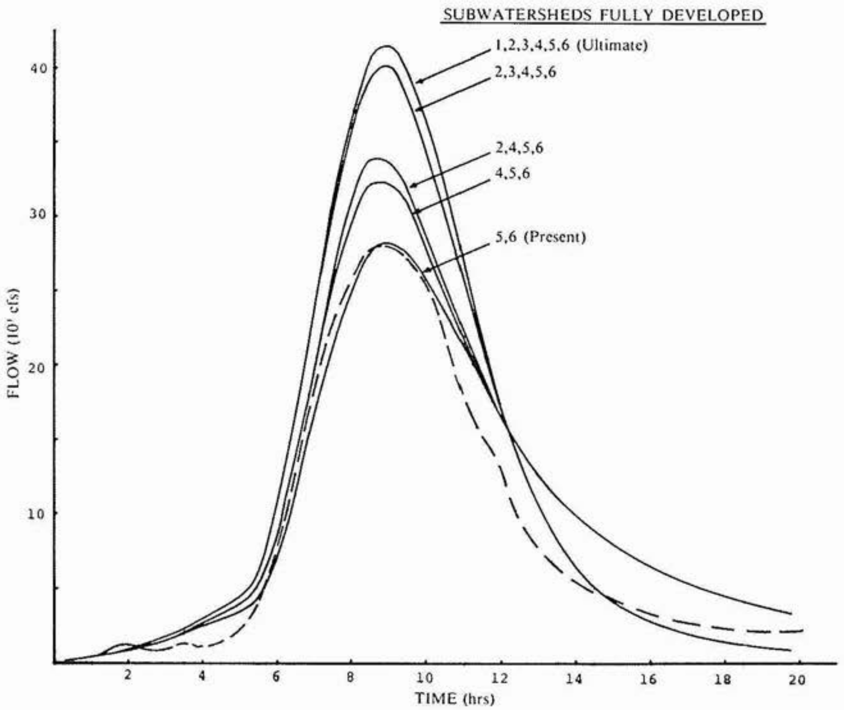

FIG. 4b. HEC-1 SIMULATIONS OF JUNE 15, 1976, STORM.
1 cfs = .028 m^3/s

TABLE 3

HEC-1 MODELING PARAMETERS

Brays Bayou Watershed

Subwatershed	PRESENT CONDITIONS t_p (hrs)	C_p	% Imp.	Area (mi²)
Upper Keegan's	9	.40	.08	5.5
Lower Keegan's	4.5	.55	.22	8.9
Upper Brays	5.5	.55	.15	35.6
Middle Brays	4.5	.65	.25	10.6
Willow Waterhole	2.5	.75	.44	18.4
Lower Brays	2.5	.75	.46	8.4

TABLE 4

HEC-1 RESULTS

STORM	t_p (hrs)	Q_p (c.f.s) OBSERVED	PREDICTED PRESENT	ULTIMATE
1 hr unit hydrograph	3.5	—	7,740	12,210
2 hr unit hydrograph	4.0	—	7,120	11,580
June 9, 1975	10.0	18,700	17,920	25,200
June 15, 1976	9.0	28,700	28,850	42,320
6 hr - 25 yr	5.5	—	34,070	56,260
6 hr - 100 yr	5.5	—	43,700	72,000

The results of the HEC-1 modeling demonstrate the expected hydrologic response to continuing development in Brays Bayou. Peak discharges will increase in the future, and indeed even a 25-year frequency event may exceed the capacity of the channel. Stormwater management alternatives were not directly considered in our study, but the anticipated increase in hydrologic response could be attenuated by some type of stormwater detention in the still largely undeveloped upper end of the watershed. A preliminary investigation of possible stormwater controls is presented below.

STORMWATER MANAGEMENT ALTERNATIVES FOR KEEGAN'S BAYOU

Keegan's Bayou is a small (12 square miles) watershed in the upper part of Brays Bayou. The Keegan's Bayou watershed is just now undergoing urbanization; therefore one can consider a range of management alternatives. Choices are limited in a watershed where most of the land is already devoted to urban activities. Since Houston is spreading onto watersheds adjacent to the immediate metropolitan area, a study of management options for Keegan's Bayou could become a prototype of solutions for other developing watersheds.

The hydrologic segment of the Corps of Engineers' STORM model was chosen to simulate the wet-weather response of Keegan's Bayou. Although STORM is primarily used to design solutions for urbanized areas, it contains a Soil Conservation Service curve number technique for calculation of runoff values. This feature allows direct consideration of a wide variety of land uses and soil types. The main disadvantage of the STORM model is that there is presently no routing of stormwater runoff in a sewer or channel network. Therefore, for use in this project, a program was added to route the runoff to the watershed outlet by means of a Muskingum flood routing procedure (Chow, 1964).

The hydrographs generated by STORM were combined with the load-runoff capacity of HLOAD to predict storm concentrations of suspended solids. The model HLOAD was best calibrated using a maximum concentration of 850 mg/l TSS and a minimum concentration of 150 mg/l TSS. A decay coefficient of -5.5 was found to be superior to the value of -4.6 assumed in the SWMM model. The curve fits are quite reasonable for water-quality simulation.

The real significance of stormwater modeling is its use in planning. Armed with calibrated water quantity and quality models, the investigator may simulate any number of management or development possibilities and estimate the impact of each on water quality.

One of the most promising techniques for managing stormwater is temporary storage in detention basins. Detention storage not only reduces but also retards peak outflows. The reduction in velocity of stormwater in a detention basin allows much of the transported sediment to fall out of suspension. Studies at The Woodlands showed that up to 90% of the suspended solids carried by stormwater through a series of holding basins was removed by sedimentation. Of course, strictly soluble pollutants are not affected by this type of physical action, but much of the total nitrogen and phosphorus load is associated with the solids.

To test the practicality and effectiveness of detention storage, some preliminary modeling at the subdivision level (200 acres) was conducted and then expanded to the entire Keegan's Bayou watershed. STORM provided the runoff hydrograph to be expected from the watershed and HLOAD provided the expected solids load. We hoped to study the anticipated peak flow reduction and the storage volume requirements. Water quality calculations were also made. The results indicate a considerable beneficial effect on both peak flows and water quality.

A computer program (STOREME) was developed to determine the storage volume necessary to reduce an input hydrograph until the peak flow does not exceed a given maximum outflow. The "maximum outflow" could be the maximum outflow from the drainage basin in its undeveloped state. This is a control criterion that is actually used in some parts of the country (Poertner, 1974).

The design of the detention basin is crucial in determining the resulting flow, water quality, and cost. The most critical design feature of a detention basin is its storage volume. Houston's flat topography and the cost of pumping severely limit the potential depth of a detention basin, so the storage volume is controlled by the amount of land available for the basin. For the purposes of this study, a three-foot deep basin, gravity-drained, was chosen. The downstream end of the basin was a broad-crested weir with a 100-foot spillway and an outflow pipe at the base. The storage-indication curve was derived from the hydraulic equations that govern pipe flow, orifice flow, and weir flow (Brater and King, 1976).

The water-quality calculations are made by a subroutine, QUALS, which utilizes a sedimentation model based on Stokes's law and described by Curtis and McCuen (1977). Three basic assumptions are made: 1) the stormwater moves through the basin in plug flow, i.e., no forward- or back-mixing occurs; 2) the distribution of different-sized solid particles in a "plug" of water is uniform when the water enters the basin; and 3) when a particle contacts the bottom of the basin, it is effectively removed—no re-suspension occurs. For any given distribution of particle sizes, QUALS calculates the percentage of removal by comparing the individual settling velocities with the velocity of the stormwater through the basin. Removal is therefore a direct function of detention time and basin depth. These simplifications introduce obvious flaws into the model, but even so it reduces a very complex system into one capable of yielding representative answers.

STOREME was used to design a detention basin to control runoff from a 200-acre residential catchment typical of southwest Houston. For storms ranging in magnitude from one to eight inches of rainfall and intensities of one to three inches per hour, STOREME calculated the volume of storage required to reduce the peak outflow to the maximum outflow from the same drainage area in its undeveloped state (table 5). Figure 5 represents the resulting hydrographs with and without detention storage from one and two inches of rainfall. It is apparent that even a small amount of stormwater detention can have a pronounced effect on stormwater quality. The attenuation of peak flows is likewise significant.

The promising results of the subdivision-level water quality and quantity calculations demonstrate the potential of detention storage. Our analysis will be extended to the entire Keegan's watershed to evaluate the cost-effectiveness of reducing flood peaks and stormwater pollution.

Preliminary results based on a one-inch rainfall and two land-use conditions (1975 and some ultimate fully-developed condition) and three possible control procedures are presented in figure 6. The three possibilities are 1) no detention storage, 2) 50% of the development utilizing storage to control runoff, and 3) 100% of the development utilizing storage. In 1975 the land was 13.7% urbanized, and the ultimate land use is assumed to be 95% urbanized. We chose 12 acre-feet per 200 acres of development as a reasonable amount of storage. For a 3-foot basin, this represents 2% of the total land area devoted to detention storage.

The continuing work will evaluate the efficiency of detention storage and other control methods for various storms. So far, detention storage appears to reduce both flooding potential and stormwater pollution in an acceptable manner.

TABLE 5

STORMWATER DETENTION RESULTS

RAINFALL	RUNOFF VOL. (ac-ft)	STORAGE VOL. (ac-ft)	STORAGE VOL. / RUNOFF VOL.	REDUCTION OF SOLIDS (%)
1''/hr	5.33	7.0	1.31	100
2''/hr	18.17	10.7	0.59	96
4''/2 hr	98.67	31.0	0.64	96
6''/2 hr	80.85	43.0	0.53	95
8''/3 hr	113.52	64.0	0.56	94

NOTE. 1'' = 2.54 cm
1 ac-ft = 0.124 ha-m

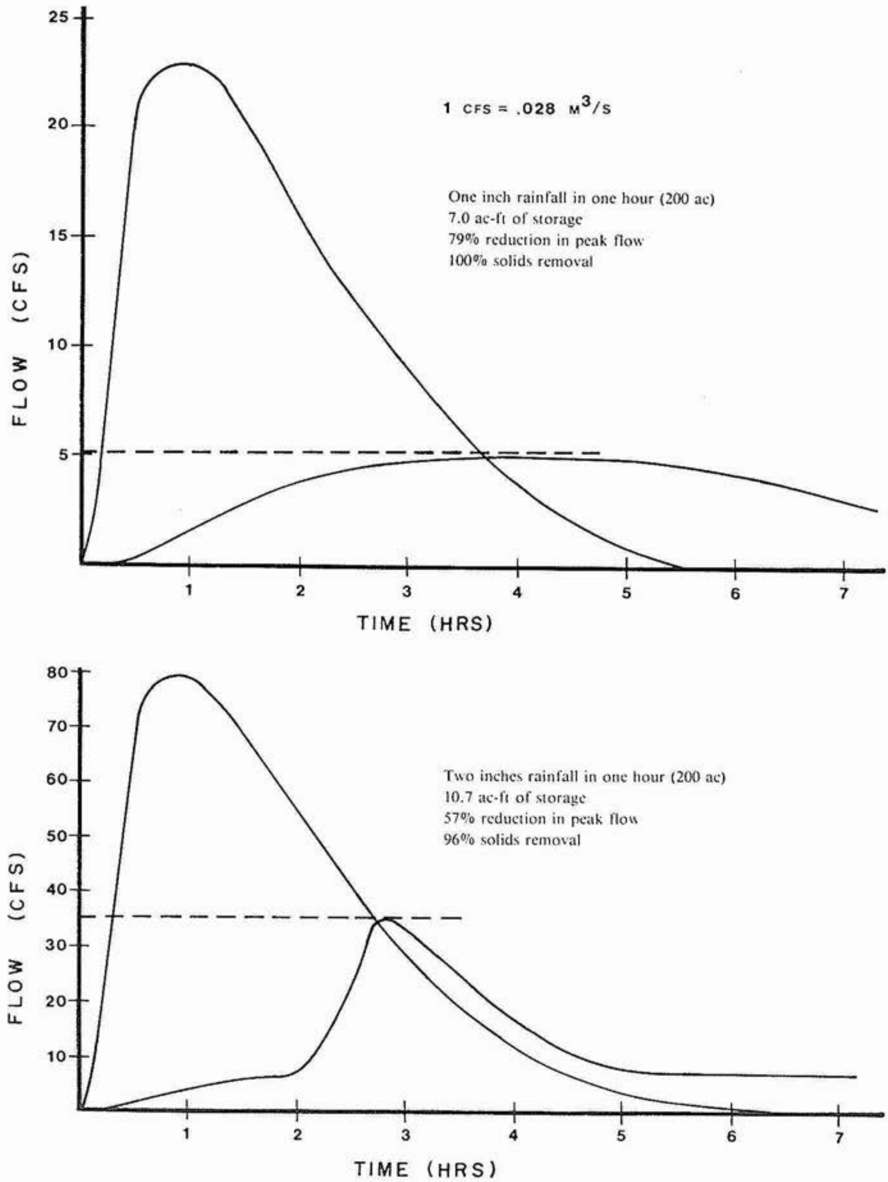

FIG. 5. EFFECTS OF STORMWATER DETENTION ON HYDROGRAPHS FROM 200-ACRE SUBDIVISION

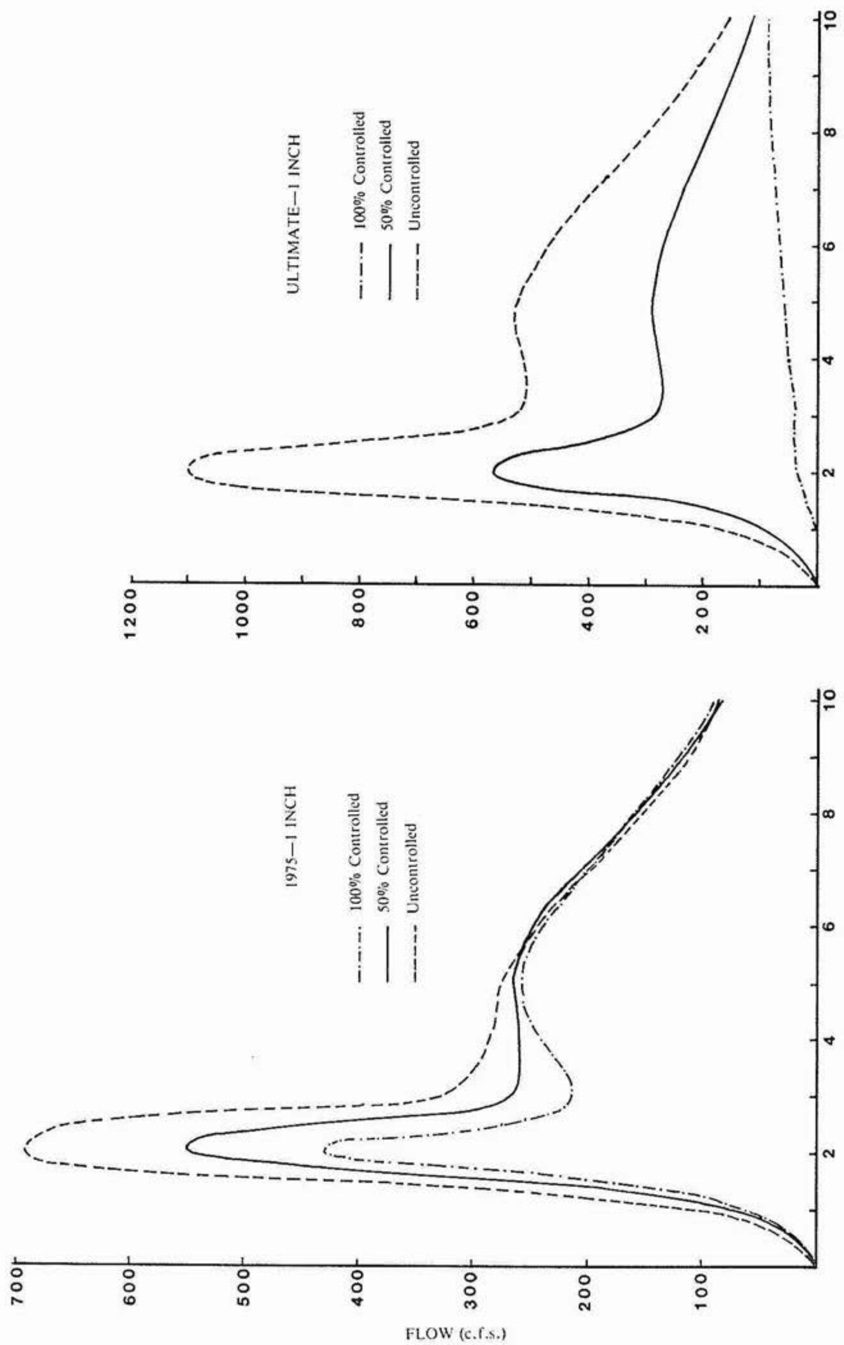

FIG. 6. EFFECTS OF STORMWATER DETENTION ON KEEGAN'S BAYOU HYDROGRAPH

CONCLUSION

The urban stormwater program at Rice University has collected data to characterize hydrologic and water quality response to urban development. Development of simple and dependable models for simulation in the Brays Bayou watershed has been invaluable for evaluation of the effects of development and various methods of stormwater control. Load-runoff relations have been used to predict response from sequential events as well as to calculate total annual loads. Stormwater TSS loads generally account for about 90% of the total load. Simulation results for Brays at Main indicate peak flood flows will increase dramatically in the future unless controls are instituted. A preliminary investigation of on-site detention in upper Keegan's Bayou shows a beneficial effect on both peak flows and water quality, with over 90% removal of TSS. Further research will evaluate the technical and economic efficiency of on-site control methods.

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