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14237 STORMWATER ANALYSIS AND PREDICTION

KEY WORDS: Rainfall; Runoff; Simulation models; **Storm water; Texas; Urbanization; Water pollution sources; Water quality**

ABSTRACT: Analyses of available stormwater hydrologic and water quality data for several Houston area watersheds yielded direct linear relationships between pollutant mass loading rates and cumulative storm runoff volume. These relationships were then used to rank the watersheds on a pollutant load per unit runoff basis, and to calculate total annual pollutant loads for each area. Further, a plot of dimensionless cumulative flow versus the dimensionless cumulative flux provides a quantifiable means to evaluate the first flush, allowing comparison of this effect between watersheds. Finally, the developed load-runoff relationships provide the basis for a simple, yet effective method of predicting pollutant mass flows for individual or sequential storm events.

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STORMWATER ANALYSIS AND PREDICTION IN HOUSTON

By Philip B. Bedient,[1] Douglas A. Harned,[2] and William G. Characklis[3]

INTRODUCTION

Water quality planning programs have often been hampered by the lack of a satisfactory means to predict changes in hydrologic and water quality response due to urban or agricultural development. This is in part due to a lack of emphasis in traditional studies on the linkage mechanisms which relate land use and drainage conditions to water quality responses. In addition, water quality prediction is a relatively new field of interest, and data constraints have often forced inconclusive results.

Stormwater runoff in urban areas has been intensively investigated over the past several years. Prediction techniques for both water quantity and quality have been advanced by several groups (11,12). However, the water quality portions of both SWMM and STORM models are very similar and require an extensive calibration procedure for each new application. Results from The Woodlands Project in Houston, Tex., where the Environmental Protection Agency (EPA) Storm Water Management Model was used, indicated some accuracy problems with the original water quality prediction method (4), especially in areas dominated by construction activity. Further research is needed to produce a successful prediction method, which is more dependent on actual water quality data.

An extensive data bank on stormwater collected at The Woodlands has been developed by the Department of Environmental Science and Engineering at Rive University. The EPA sponsored project resulted in a total of 17 storm events monitored on four watersheds of differing land use (2). Further analysis of this data has yielded significant new relationships between pollutant mass

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loads and runoff volumes as a function of land use. These load-runoff curves have been incorporated into a stormwater quality prediction model which has been tested on several Houston watersheds.

Stormwater Quality Relationships.—Recently, emphasis has been placed on the importance of monitoring both low and high flows in urban streams in recognition of the relative role that runoff plays in water quality (2,3,10,15). However, lack of extensive water quality data for storm events remains an obstacle in development of causal relationships between watershed characteristics and runoff water quality.

A number of significant parameters have been identified in the relative rates of accumulation of pollutants on land surfaces prior to washoff by rainfall. An EPA (14) study reviewed the available relevant literature to produce a list of significant parameters, including: (1) Climate; (2) season; (3) land use; (4) population density; (5) impervious area, as a percentage; (6) daily traffic; (7) type and condition of street surface; (8) road surface length; (9) time from last rain; and (10) street sweeping frequency. The potential pollutant load represented by the total pollutant accumulation present at the start of a rainstorm, is in turn subject to the rate and nature of washoff during storm events, the hydraulic character of the drainage system, and the hydrologic character of the watershed, before the load appears as time varying concentrations in the stream.

More recent studies have furthered the attempt to pin down watershed-water quality relationships. Haith (8), using statistical correlation and regression analysis examined land use and water quality, finding particular impact of forest, cropland, and transportation land used on nitrogen concentrations, and a correlation between densely populated urban residential areas and high suspended solids concentrations. Bedient, et al. (1) and Huber, et al. (7) found direct correlations between land use, drainage densities, and nutrient loading rates in agricultural watersheds.

Marsalek (11), using regression and correlation analysis, found the antecedent dry period to be the most important variable relative to the total pollutant loadings of chemical oxygen demand, nitrogen, phosphorous, and suspended solids. Further, Marsalek concluded that relationships between total loadings, rainfall intensity, and antecedent storm rainfall were not statistically significant in the 19 storms monitored from his Canadian test watershed.

Finally, although many factors are involved in the variation of pollutant concentrations and total loads produced during separate storm events, the shape of the pollutant mass curves are consistently related to the shape of the streamflow hydrograph (2).

Prediction of Stormwater Quality.—State-of-the-art attempts to predict the quality of runoff have been generally unsatisfactory (8). A common approach has been to develop regression equations relating pollutant total loads or concentrations to the watershed or hydrologic conditions (3,9,14). Other researchers have combined unit hydrograph techniques with regression equations modified by weighting factors (16). Unfortunately, the relationships developed are highly site specific, and must be reevaluated before application to other locales.

A different, deterministic approach is employed by the SWMM and STORM models. Both models use similar relationships to build up pollutant concentrations over the watershed during dry periods. When a storm occurs, these pollutant concentrations are washed off exponentially with time into the stream. The pollutant concentration appearing in the stream at any time is therefore considered a function of the concentration of pollutant on the watershed, the amount of runoff during any time interval and the exponential rate of washoff. This approach is covered in detail in a later section.

The SWMM has been adapted for natural drainage conditions at The Woodlands, Tex., in an effort to simulate stormwater quality response (5). The model operates from a relation between runoff rate and pollutant load, but the prediction of hydrographs has been more successful than pollutant simulation. The water quality portion of the model is not designed to simulate the response from natural drainage, and has been updated specifically based on The Woodlands storm runoff data. Relationships between cumulative load and cumulative runoff volume have been incorporated into SWMM for parameters such as suspended solids (SS), chemical oxygen demand (COD), total phosphorus (TP), and nitrates (NO_3). In this way, concentrations can be predicted as a direct function of runoff (4).

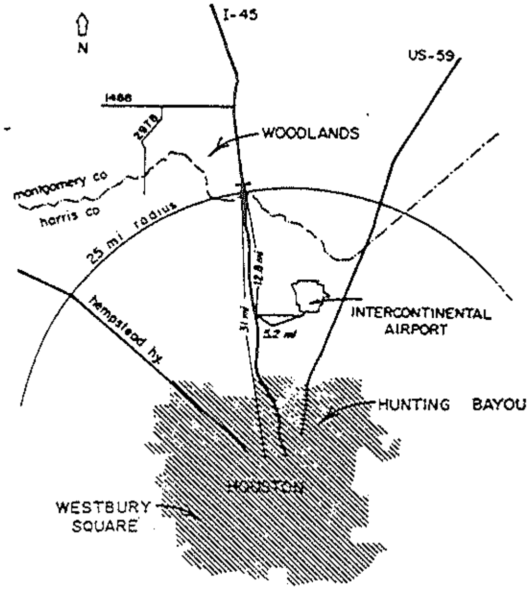

FIG. 1.—Location of Study Sites (1 mile = 0.62 km)

Analysis of Stormwater Quality Data

Woodlands Project Data Base.—The Department of Environmental Science and Engineering at Rice University has conducted a 3-yr comprehensive water quality sampling and monitoring program to characterize the initial development stages of The Woodlands, a new urban community. The main objective was to evaluate the effectiveness of the natural drainage system used in the development as it relates to water quality and hydrologic response. The project results have yielded a comprehensive data bank on stormwater runoff quantity and quality in the metropolitan Houston area (2).

In addition to the data collected at The Woodlands, two conventional urban watersheds were sampled during several storms. Hunting Bayou and Westbury were sampled to provide comparison to the forested watershed (P10) and the developing watershed (P30) at The Woodlands. The relative locations of these four watersheds are shown in Fig. 1. Woodlands sites are shown in Fig. 2.

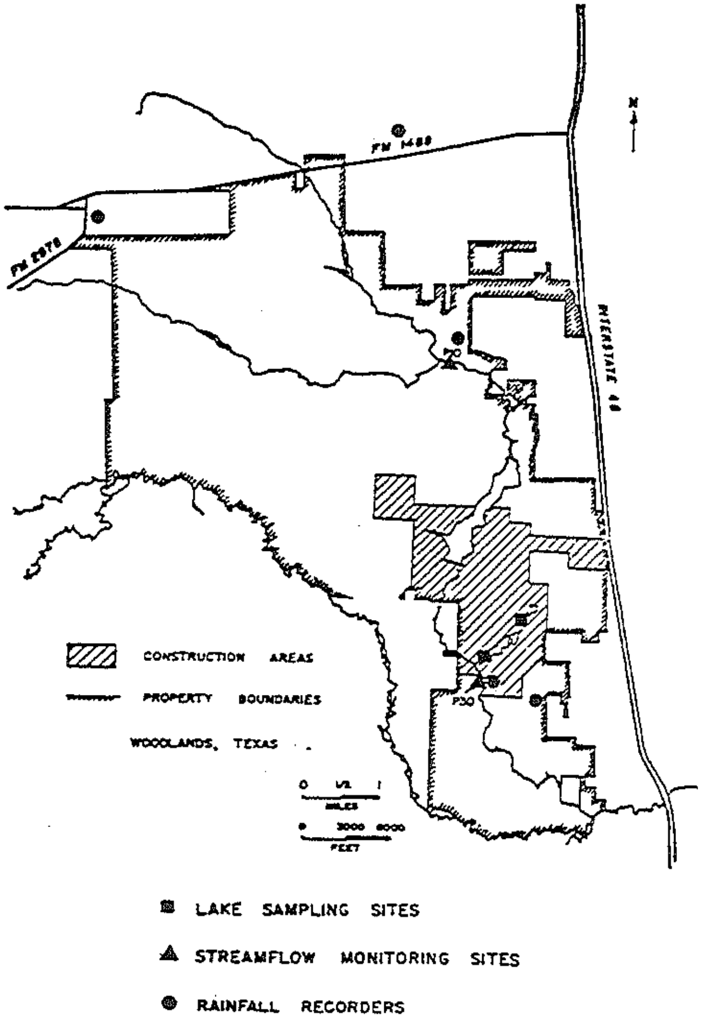

FIG. 2.—Location of Woodlands Sites (1 mile = 0.62 km)

The 1,976 acre (800 ha) Hunting Bayou Watershed is 94% developed, with 48% of the area land use in single and multiple family residences, 32% in commercial use, and 14% in industrial land use. Slopes are low (generally 0.1%) and clayey soil types predominate. The overall impervious cover of the watershed is 21%. The watershed is poorly drained, with few storm sewers, and the main stream channel is moderately to heavily vegetated.

Westbury Square is a totally urbanized (100% residential land use) watershed of 210 acres (85 ha). The area is well drained by conventional storm sewers and ditches. Impervious cover is approx 35.4%.

The Woodlands P30 watershed is 21,606 acres (8,744 ha) in size with only 10% developed area. During much of the sampling period there was considerable construction in the watershed. The drainage system planned for the community utilizes unimproved existing drainage where possible, with a concerted effort to maintain natural drainage conditions where improvements are necessary. The P10 watershed is a subset of P30, consisting of 16,050 acres (6,495 ha) above the development in a heavily forested area. The slopes are low (approx 0.1%) and soils are predominately clay for both watersheds (Fig. 2).

Approx 15 parameters were monitored for each watershed during each storm event. A total of 17 storms were sampled over the duration of the 3-yr project. An abbreviated summary of the measured storm events, with pound per acre

TABLE 1.—Summary Storm Data

Storm number (1)	Date (2)	Site (3)	Stream-flow, in acre-feet (4)	Run-off, in inches (5)	TP × 10^3, in pounds per acre (6)	$NO_3 \times 10^3$, in pounds per acre (7)	SS, in pounds per acre (8)	TCOD, in pounds per acre (9)
1	1/18/74	P30	2334	1.29	—	8.38	69.05	—
2	3/20/74	Hunting	2.51	0.013	—	1.49	0.24	0.26
3	3/26/74	Hunting	42.1	0.26	23.4	29.40	11.39	5.77
4	4/11/74	Hunting	12.4	0.075	10.3	5.77	2.08	1.74
5	4/22/74	P30	5.8	0.0032	0.348	0.17	0.69	0.068
6	11/28/74	P30	937	0.52	11.8	4.36	35.87	—
7	12/5/74	P30	1,267	0.70	15.2	3.70	13.70	9.08
		P10	833	0.62	10.7	1.72	3.77	8.72
8	3/4/75	P30	3.3	0.0018	0.053	0.0044	0.020	0.014
9	3/13/75	P30	119	0.066	2.42	1.66	1.33	0.89
		P10	79.1	0.059	1.23	1.38	0.89	0.85
10	4/8/75	P30	2,829	1.57	31.2	54.70	60.72	18.69
		P10	1,614	1.20	16.4	17.70	10.47	16.03
11	5/8/75	Hunting	28.9	0.18	42.6	20.20	8.20	7.09
12	6/30/75	Hunting	116	0.70	204	59.20	25.81	12.75
13	9/5/75	P30	9.8	0.0054	0.219	0.38	0.12	—
		P10	0.9	0.0007	0.0052	0.0005	0.0009	—
14	10/25/75	P30	117	0.065	2.16	0.38	2.49	0.63
		P10	57.1	0.042	0.456	0.29	0.076	0.44
15	3/7/76	P30	14.9	0.0082	—	—	0.44	—
		P10	11.3	0.0084	—	—	0.43	—
16	3/8/76	P30	99.3	0.0055	—	2.22	3.61	—
		P10	58.3	0.0044	—	0.23	1.28	—
17	4/4/76	P30	45.9	0.025	0.867	2.45	—	0.29
		P10	2.8	0.021	0.029	0.0065	—	0.018

Note: 1 lb/acre = 1.12 kg/ha; 1 in. = 2.54 cm.

loads for several parameters appears in Table 1. The largest storm events include storms numbered 1, 7, and 10, which generated the greatest pollutant loads.

Pollutant Load-Runoff Relationships.—Total loads of various pollutants were plotted against total runoff of each storm event for each of the four study watersheds. Regression lines and associated correlation coefficients are shown in Fig. 3(*a*) for total suspended solids (TSS) and total chemical oxygen demand (TCOD); Fig. 3(*b*) for soluble organic carbon (SOC), and soluble COD (SCOD); and Fig. 3(*c*) for total Kjeldahl nitrogen (TKN) and total phosphorus (TP).

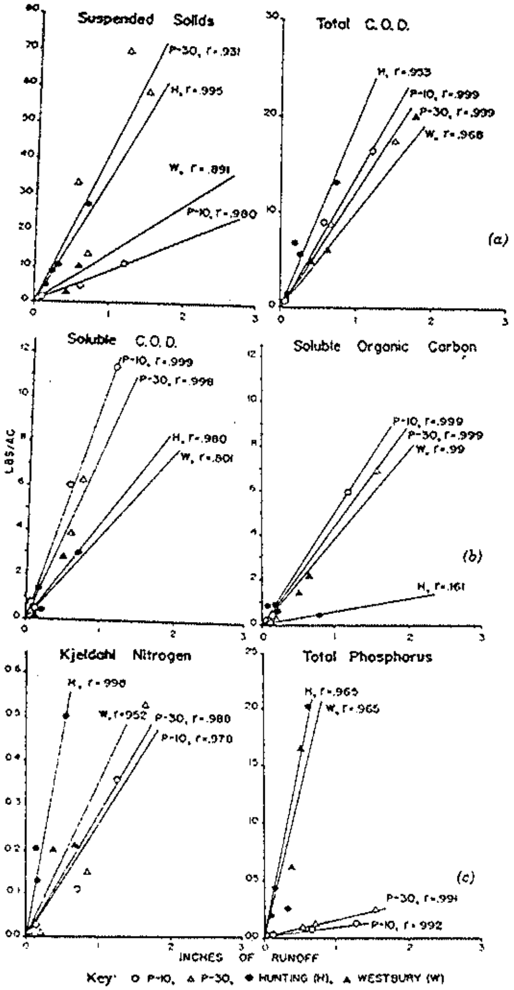

FIG. 3.—Load-Runoff Relationships: (*a*) TSS and COD; (*b*) SCOD and SOC; (*c*) TKN and TP (1 lb/acre = 1.12 kg/ha; 1 in. = 2.54 cm)

The nutrient relationships [TP and TKN shown in Fig. 3(*c*)] indicate that the two urban watersheds, Hunting and Westbury, have the heaviest loads of

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TABLE 2.—Pollutant Load Ranking of Four Study Area Watersheds

Runoff quality parameter (1)	Sites Ranked as to Pollutant Loads, in pounds per acre per 1 in. Runoff; 95% Confidence Level for Mean Regression Values			
	(2)	(3)	(4)	(5)
Suspended solids	P30[a] 43.5 ± 18.1[b]	HB[a] 37.7 ± 4.6[b]	WB[a] 13.7 ± 74.4	P10[a] 8.2 ± 2.0[b]
Total chemical oxygen demand	HB 18.9 ± 6.7	P10 13.5 ± 0.6	P30 12.1 ± 0.6	WB 9.5 ± 23.7
Soluble chemical oxygen demand	P10 9.9 ± 0.2	P30 8.8 ± 0.5	HB 4.4 ± 0.2	WB 4.1 ± 27.5
Soluble organic carbon	P10 5.0 ± 0.1	P30 4.54 ± 0.24	WB 3.75 ± 1.09	HB 0.7 ± 2.0
Nitrate	WB 0.09 ± 0.03	HB 0.09 ± 0.01	P30 0.02 ± 0.02	P10 0.012 ± 0.007
Ammonia	HB 0.5 ± 0.1	WB 0.07 ± 1.2	P30 0.03 ± 0.01	P10 0.02 ± 0.002
Total Kjeldahl nitrogen	HB 1.0 ± 0.1	WB 0.4 ± 1.1	P30 0.3 ± 0.1	P10 0.3 ± 0.1
Total phosphorus	HB 0.28 ± 0.12	WB 0.24 ± 0.67	P30 0.021 ± 0.007	P10 0.014 ± 0.003

[a] Study Sites: P30 = Woodlands P30 Watershed Sampling Site; P10 = Woodlands P10 Watershed Sampling Site; HB = Hunting Bayou Watershed Sampling Site; and WB = Westbury Watershed Sampling Site.

[b] Mean ± 95% confidence level.

Note: 1 in. = 2.54 cm; 1 lb/acre = 1.12 kg/ha.

TABLE 3.—Annual Mass Loads from P-10 and P-30 Watersheds (October, 1974–September, 1975)

	P-10 Watershed				P-10 and P-30 Watersheds Combined				
Month (1)	Suspended solids, in pounds $\times 10^{-5}$ (2)	Total phosphorous, in pounds $\times 10^{-2}$ (3)	NO_3, in pounds $\times 10^{-2}$ (4)	COD, in pounds $\times 10^{-4}$ (5)	Suspended solids, in pounds $\times 10^{-5}$ (6)	Total phosphorous, in pounds $\times 10^{-2}$ (7)	NO_3, in pounds $\times 10^{-2}$ (8)	COD, in pounds $\times 10^{-4}$ (9)	Number of storms (10)
October, 1974	0.483	0.80	0.96	8.85	6.18	2.32	1.92	18.8	1
November, 1974	6.27	6.84	7.71	88.89	43.56	15.66	15.92	123.5	4
December, 1974	3.71	4.16	4.42	54.46	26.84	12.02	8.79	81.1	4
January, 1975	1.12	1.32	2.14	47.38	5.26	5.04	2.40	21.1	4
February, 1975	2.18	2.61	5.21	30.71	17.22	6.50	5.70	55.0	1
March, 1975	1.05	2.65	1.68	13.20	6.84	3.92	2.45	18.8	2
April, 1975	4.42	7.54	7.78	65.67	37.40	14.16	12.10	117.8	3
May, 1975	1.42	1.66	2.46	29.18	8.00	4.12	4.81	27.8	4
June, 1975	0.59	2.59	8.21	5.68	1.06	1.40	0.62	6.1	2
July, 1975	0.17	0.14	0.23	3.25	0.46	1.30	0.37	3.9	0
August, 1975	0.08	0.065	0.068	1.50	0.26	0.77	0.21	2.2	0
September, 1975	0.01	0.005	0.006	0.13	0.027	0.80	0.022	0.2	0
Total load	21.50	30.35	40.87	348.91	154.10	67.35	55.37	476.3	25
	P-10 Watershed				P-30 Less P-10 Watershed				
Total load, in pounds per acre	134	0.189	0.255	217	2387	0.665	0.261	229	

Note: 1 kg = 2.21 lbs; 1 acre = 4047 m^2

nitrogen and phosphorous. Hunting clearly produces the greatest loads, with Westbury close behind. The nutrient loads from the P10 and P30 sites are much less, in several cases producing relationships with slopes an order of magnitude lower.

Pollutant Load Ranking of Watersheds.—A ranking of the four watersheds on a pound per acre per inch of runoff basis for each pollutant gives a normalized measure of the relative magnitude of the stormwater pollutant loads produced by each site (Table 2). This ranking further substantiates the pattern of total nitrogen and phosphorous response for the urban watershed (Hunting) compared to The Woodlands. These high nutrient levels are primarily due to nonpoint source runoff from urbanized areas. Differences in TCOD between urban and forested sites are not significant. Finally, suspended solids loads from the urban and developing sites are much higher than the loads from the forested P10 watershed. In particular the forested P10 watershed is shown to produce large TCOD and SCOD loads but very small TSS loads. This suggests possibly that the forested watershed provides erosion control of suspended solids, but that organic loads create a considerable chemical oxygen demand in the stream.

Total Annual Load Calculation.—The input of any pollutant into a system can be represented as a total mass introduced over a set time period. One such measure, the total annual load, can be calculated using the developed load-runoff relationships. The common method of calculating total annual loads in streams has been to continuously monitor discharge and take grab samples for water quality analyses. Continuous monitoring of water quality is generally infeasible, so random sampling is usually employed.

The annual load calculation first requires that the available streamflow data for the period of interest be divided into individual storm events and low flow periods, where low flow is defined as the streamflow maintained by ground water and wastewater treatment plant discharges, and storm events are flows produced from direct runoff. If data for pollutant concentrations are available for each between storm period, low flow loads (mass/time) should be estimated by multiplying the average concentration by the streamflow volume for each respective period, and summing.

Loads (mass/time) for storm events are approximated from the load-runoff relationships for the watershed under study. The runoff for each storm event is calculated and the corresponding loads are determined from the load-runoff curves. The storm event loads are in turn added to the low flow loads to produce a total pollutant load.

The procedure was applied to calculate total annual loads for The Woodlands watersheds. The water year of October, 1974 to September, 1975 was examined for both P10 and P30. The results of these calculations for TSS, TP, NO_3, and TCOD appear in Table 3. The urbanizing watershed appears to contribute greater loads of TSS on an annual basis compared to the forested site, with 85% of the TSS load at P30 produced during storm events.

It is evident that if the load-runoff relationship for a watershed can be approximated, this method will have considerable utility for calculating annual pollutant loads. This method better accounts for the pollutant load contribution of storm events in relation to low flows because point source loads versus nonpoint source loads can be compared from a more realistic standpoint.

Dimensionless Cumulative Analysis.—Marsalek (8) outlines another approach to studying the cumulative relationship between runoff and pollutant mass flow. When dimensionless cumulative pollutant mass flow is plotted against the dimensionless cumulative runoff for one or more storm events, the resultant curve presents a useful picture of storm response. If there is a constant pollutant concentration throughout the event, which can occur for certain soluble components, the plot is a straight line with a slope of 1, which passes through the origin.

When the TSS results for several storm events are plotted for the P10, P30 and Hunting Bayou watersheds, in all cases a clear deviation from the 45° line is seen. The majority of the measurements fall above the line. The P30 results show a particularly outstanding upward deviation [Fig. 4(*a*)].

The TSS mass flows show a marked tendency to be greater at the earlier stages of the runoff event, diminishing with time. This approach therefore gives a clear representation of the first flush effect, as shown for P30. The effect is not as pronounced for the P10 and Hunting Bayou watersheds, in part due to the smaller magnitude of the storm events plotted. However, a comparison of the Storm 7 results between P10 and P30 does show a greater first flush for the P30 watershed.

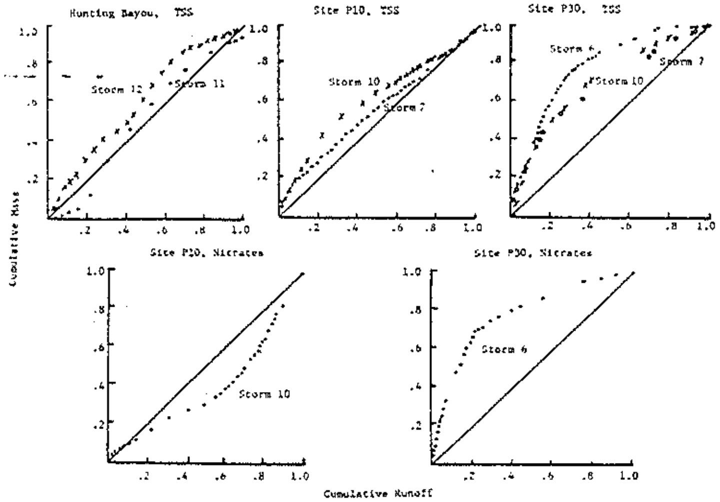

FIG. 4.—Dimensionless Cumulative Plots: (*a*) TSS; (*b*) NO_3

Soluble constituents would not be expected to show a first flush response in stormwater runoff. Indeed, a dimensionless plot for Storm 10 nitrates at the P10 watershed shows a clear lag of constituent mass flow with respect to runoff [Fig. 4(*b*)]. This result may be compared to the Storm 10 P10 plot for suspended solids, which shows a clear first flush. On the other hand, a plot of P30 Storm 6 nitrates shows an outstanding first flush [Fig. 4(*b*)]. This result is possibly accounted for by the heavy nitrate fertilization of the golf course just above the P30 monitoring site.

There is a considerable variation of the magnitude of the resultant plots produced by different storms, so the use of a fitted exponential equation to quantify the overall watershed first flush effect requires a considerable amount of data. However, this approach does provide a useful means of demonstrating the timing of cumulative runoff volume relative to the cumulative pollutant mass flow. From a control standpoint, the dimensionless cumulative relation for a particular site allows one to design detention storage capacity necessary to capture a given percent of suspended solids. For example, collection of 30% of initial runoff volume on site P30 would result in a 60%–70% capture of suspended solids load. Of course, more data is required to properly define the percentages for a given area.

Simulation of Pollutant Loads

The load-runoff relationships provide the foundation for a simplified method pollutant load simulation of multiple or individual storm events. Given time incremented values for runoff, the model uses the time varying load-runoff relationships to calculate mass flows during storm events (6).

Variation in the average pollutant concentration over time is approximated by variation of the load-runoff line slopes. These slopes represent the ratio of mass/time and volume/time, or mass/volume which is an average pollutant quality concentration for each watershed. Initially three slope parameters are defined for each load-runoff relationship: the average slope, the initial slope, and a factor that sets the range within which the slope can vary. The average slope can be roughly determined from the cumulative relationship produced from field data. The initial slope value depends primarily on antecedent conditions, and the range variable is determined by the spread in observed pollutant concentrations from the storm sampling program.

During dry periods the slopes are incrementally increased up to a predefined maximum. This corresponds to the buildup of available pollutants on a watershed between storm events. An increment chosen to increase the slopes is required as input, and is obtained primarily by calibration. During a storm event the values of the slopes are decayed exponentially, by means of the same theoretical approach employed in the Stormwater Management Model (12):

Mass pollutant washed off in any time interval

$$\propto \text{Mass remaining on the ground} \quad \text{(1a)}$$

$$\text{or} \quad -\frac{dP}{dt} = kP \quad \text{(1b)}$$

which when integrated takes the form:

$$P_o - P = P_o(1 - e^{-kt}) \quad (2)$$

in which $P_o - P$ = pounds washed away in time, t: and k is assumed to vary in direct proportion to the rate of runoff, r:

$$k = br \quad (3)$$

The coefficient b can be evaluated given the assumption used in the SWMM that 1/2 in. of runoff uniformly delivered in 1 hr washes away 90% of the pollutants. As a result the equation can be written:

$$P_o - P = P_o(1 - e^{-4.6rt}) \quad (4)$$

The equation used to decay the load-runoff line slopes is:

$$C(t) = C_o e^{-brt} \quad (5)$$

in which $C(t)$ is the load-runoff curve slope (pollutant concentration) at some point in time during the storm event and C_o is the initial value.

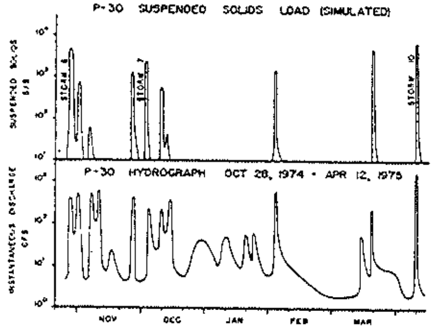

FIG. 5.—Hydrograph and Simulated TSS—P30 Site (1 cfs = 0.028 m³/sec; 1 lb = 454 g)

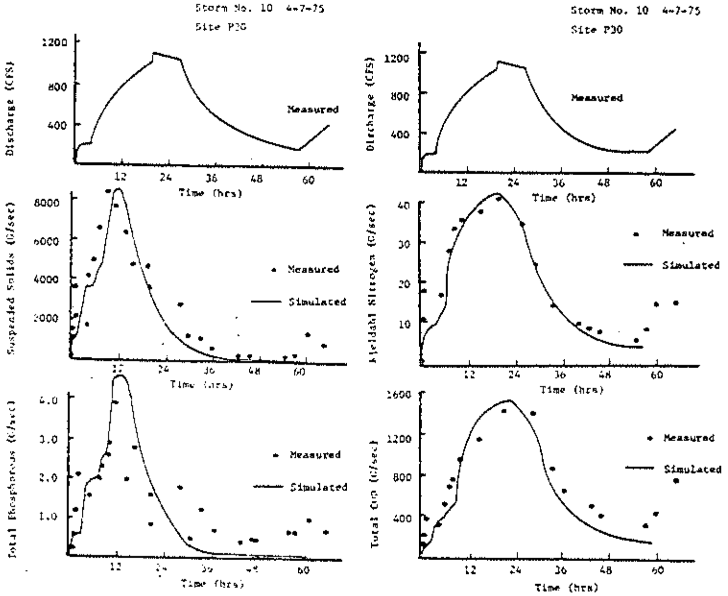

FIG. 6.—Measured and Simulated Response—P30 Storm 10 (1 cfs = 0.028 m³/s; 1 lb = 454 g)

A six-month period of streamflow at site P30 was chosen for sequential simulation. This period dating from October 28, 1974 to April 8, 1975 includes storm events 6, 7, and 10 monitored during the study. Storm events 8 and 9 were considered too small for use in the simulation. Predicted solids loads and the observed streamflow hydrographs are presented in Fig. 5. Slope parameters used were derived from the load-runoff relationship, with the upper limit values based on actual storm data.

TABLE 4.—Comparison of Simulated and Observed Results

Storm number (1)	Constituent (2)	Total mass, simulated/observed (3)	Peak heights, simulated/observed (4)
		(a) P10	
7	SS	0.96	0.96, —
9	SS	1.53	1.00
10	SS	1.05	1.08
9	TP	0.86	0.55
10	TP	1.13	1.10
7	TKN	1.00	0.93
9	TKN	1.12	0.74
10	TKN	1.11	1.06
7	COD	0.93	1.01
9	COD	0.80	0.68
10	COD	0.84	1.00
		(b) P30	
6	TSS	1.21	1.04, 0.96, 0.93
7	TSS	1.39	1.13
10	TSS	0.87	1.00
6	TP	1.10	1.09, 1.08, 1.46
10	TP	0.89	0.96
7	TKN	0.93	1.03, 0.95
10	TKN	1.10	1.02
7	TCOD	0.89	1.25, 1.04
10	TCOD	0.91	1.19
		(c) Hunting	
11	TSS	1.20	0.71
12	TSS	0.91	1.00, 0.27
11	TP	0.98	0.96
12	TP	1.31	0.88, 1.33
11	TKN	0.95	1.00
12	TKN	1.11	0.82, 0.93
11	TCOD	1.16	0.31
12	TCOD	1.00	0.86, 0.49

Simulation results can be evaluated by comparing observed and simulated mass flows for individual storm events. Predictions of TSS, TP, TKN and TCOD concentrations and loads for storm event 10 are shown in Fig. 6. The simulated curves compare satisfactorily to the observed mass flow and concentration curves. Table 4 gives comparisons of simulated and observed values for storms on P10, P30, and Hunting sites. Total mass of TSS, TP, TKN, and TCOD are compared as a ratio of simulated to observed. The average ratio for TSS for all three sites is 1.14. Peak height comparisons are also listed in Table 4 according to the ratio of simulated to observed. Storm 6 on P30 and Storm 12 on Hunting Bayou were multiplepeaked. The average ratio for TSS peak heights for all three sites is 0.99.

Based on the preceding simulation results, the load-runoff prediction method appears to give an accurate picture of nonpoint source loading in developing watersheds.

Conclusions

Analysis of available stormwater data for several Houston area watersheds yielded direct linear relationships between pollutant mass loading rates and total storm runoff volume. A ranking of the watersheds on a pollutant load per unit runoff basis indicated the highest nutrient loads for the more urbanized areas. Differences in chemical oxygen demand between urban and forested sites were not significant, due to organic forest runoff. Suspended solids was much higher from the urban and developing sites, while the forested site provided erosion control.

Total annual loads were calculated using the load-runoff relationships for storm events and low flow data during low flow periods. This method of accounting has considerable utility for calculating annual loads because it distinguishes point source versus nonpoint source loads. For the developing watershed, 85% of the TSS load was produced during storm events.

In analyzing the relationship between cumulative runoff and pollutant mass flow, the dimensionless cumulative plot of flow versus pollutant flux presents a useful picture of storm response. This approach also provides a quantifiable means to evaluate the first flush effect, determined from the deviation from a 45° line relating the two parameters.

Finally, the developed load-runoff relationships provide the basis for a simple and effective method of predicting pollutant mass flows for individual or sequential storm events. Simulations using measured streamflows for various water quality parameters (TSS, TP, TKN, TCOD) compare favorably to observed mass flow and concentration curves. Once a total load-runoff relation has been developed for a watershed, prediction of pollutant mass flows for other storm events can be simulated by using an associated hydrologic model to predict streamflow.

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Appendix I.—References

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APPENDIX II.—NOTATION

The following symbols are used in this paper:

b = coefficient (L^{-1});
$C(t)$ = slope of load-runoff curve (M/L^3);
C_o = initial load-runoff curve slope (M/L^3);
k = decay coefficient for stormwater mass (T^{-1});
P = mass of stormwater pollutant remaining (M);
P_o = initial mass of stormwater pollutant (M); and
r = rate of runoff (L/T).