An Evaluation of the Efficiency of Stormwater Sumps in an Urban Watershed to Reduce Nonpoint Source Pollution

Final Report to Texas Water Development Board
Board Contract Number 93-483-380

Southern Methodist University
Environmental Engineering Program
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Contents

1 INTRODUCTION

1.1 Overview and Objectives

Texas Cities and Flood Control Districts have made substantial investments in flood control projects. Projects typically involve recovery and protection of land from a riverine floodplain by the construction of a system of levees and sumps. Stormwater flowing towards the river is thereby intercepted and temporary storage provided by the sumps before eventual release to the river by: (1) a gravity sluice; (2) pumping over the levees; or, (3) gravity flow through the sump system until it reaches the river. Although flow of stormwater through a sump system is regulated solely by flood-control requirements and not detention factors as in an actual stormwater detention basin, these sumps nevertheless may function as sedimentation basins that potentially provide purification of stormwater. The literature confirms that stormwater detention basins can provide a significant level of removal of solids and associated pollutants from stormwater for appropriate design and operating conditions. The treatment capabilities of flood-control sumps, however, have not been systematically investigated to date. Moreover, due to the complex array of outfalls and variability of sump design, little is known concerning their hydraulic performance. If these sumps can be utilized in such a way as to contribute significantly to stormwater treatment, then they can be included as a best management practice (BMP) for nonpoint source pollution control, and the owner will receive credit for the treatment provided.

Therefore, the **primary objectives** of this study were to:

1) develop an assessment procedure that is adaptable to flood-control systems of variable character by developing a hydraulic performance model for sumps;

2) assess the treatment efficiency of flood-control sumps in an urban watershed; and,

3) based on the results of (1) and (2), propose minor structual and/or operational modifications that would improve the treatment efficiency of existing sumps.

A secondary objective of the study was to sample sump-bottom sediments to attempt to verify pollutant capture and identify problems associated with potential contamination of sediments.

1.2 Context and Study Area

The Texas Natural Resource Conservation Commission (TNRCC) has a database containing the Reclamation Engineer Information Master Report starting in April 1910 and ending in January 1994. A paper copy and computer disks of the report were obtained which contains complaint, inquiry, and reclamation records filed with their office. The Master Report was reduced to include only eight cities in Texas qualifying as 'large' (*i.e.*, population of 250,000 or more); namely Arlington, Austin, Corpus Christi, Dallas, El Paso, Fort Worth, Houston, and San Antonio. The levee projects for each of these cities were identified from the database, with the number of such projects as follows.

Arlington	6
Austin	7
Corpus Christi	2
Dallas	59
El Paso	1
Fort Worth	11
Houston	5
San Antonio	7
Total	98

These results are not necessarily complete nor entirely relevant to the current project because:

- The TNRCC records may not include all levee projects.
- The TNRCC records may include levee projects that are abandoned.
- Not every levee project may have a sump for water storage.

For instance, San Antonio has no sumps as does Dallas, but instead there is a large detention basin, two large drainage tunnels, and several Soil Conservation Corps dams utilized for storm water management.

The current study is a survey of Dallas sumps along the Trinity River. The Trinity River is channelized and levied through most of the city. The original levees were constructed in the early 1920s in accordance with a Corps of Engineers design, and since that time there have been numerous improvements. The City of Dallas is the current owner with the operation and maintenance of the system under the auspices of the Streets and Sanitation Division.

The system (City of Dallas, 1993) contains sumps for every drainage basin that was cut off by the levees. The constructed sumps represent a wide variety of storage capacities, drainage area, and land use. There are 10 sump areas in the Dallas System with 6 of these having pumping stations as noted in Table 1. Each sump area is actually a set of interconnected basins, the number of which is also given in Table 1. The entire system is computer mapped and monitored by a SCADA network located at Sump/Pumping Station B at 2255 Irving Blvd. The pumping stations consist of both high and low rate pumps that start automatically when sump water levels reach preprogrammed values. In some instances, the sumps are drained in part by gravity sluices. Several of the sumps are indeed dry throughout during dry periods, while a few, e.g., Sump Area D, have sizeable areas in which a low water level is maintained even during dry periods. Pressure sewers discharging directly to the river are given in Table 2.

Sumps C and D were selected for detailed analysis and stormwater / sediment sampling. As will be demonstrated, these sumps offer the opportunity to study the effects of highly variable hydraulic characteristics on stormwater pollutant removal efficiency. Sump areas C and D are shown in locator Map 1.

Table 1: City of Dallas Sump System

Sump	Basins	Storage Capacity (acre-feet)	Sump Area (acres)	Drainage Area (acres)	Pumping Station
East Side					
A	10	873	87	1813	Yes
B	7	1392	123	3418	Yes
Hampton	11	1750	160	1750	Yes
Noble's Branch	5	744	81	1722	No
West Side					
C	4	192	26	779	Yes
Pavaho	3	386	34	1843	Yes
D[a]	4	1318	104	1704	Yes
Trinity Portland	5	1012	83	3034	No
Eagle Ford	4	1124	124	2050	No

[a]Includes Francis Street Sump which is directly connected. For high flow events, Sump D may also receive floodwaters from Trinity Portland, and Eagle Ford Sumps and, occasionally, excess runoff from Pavaho Sump

Table 2: Trinity River Pressure Sewers

East Side	West Side
Turtle Creek	Lake Cliff
Woodall Rogers	Coombs Creek
Dallas Branch	Coombs Creek Bypass
Bellvue	Eagle Ford (a gravity sluiceway)

2 APPROACH AND METHODS

2.1 Sump Characteristics and Hydraulics

Information on the general physical characteristics and operation of the sumps was obtained by numerous site visits and interviews with personnel of the City of Dallas Streets and Sanitation Division (DSS) who are responsible for maintaining and monitoring sump operations. Photographs and visual investigations were made of various stormwater discharge points to sumps, pumping stations and associated discharge conduits to the river, gravity sluices, and potential sampling locations. Additional information on sump operating procedures was obtained by observations made in the main control room which employs a SCADA monitoring network. DSS also provided detailed engineering sketches of the sump system and associated drainage works (URS / Forest and Cotton, 1979). All of the above information was used to select three sumps, namely B, C, and D, for preliminary study. These were chosen with the expectation that they represented a broad range of drainage areas, land-use areas, and stormwater detention during events.

Next, detailed contour maps prepared by the Corps of Engineers in 1993 were obtained. These were digitized and the relevant sections enlarged for analysis. Autocad planimetry was conducted at every-two-feet contours to calculate the relationship between sump water elevation and the corresponding surface area and volume for Sumps B, C, and D. Polynomial fits were obtained for sump volumes and areas as a function of elevation for Sumps B, C, and D as a whole as well as for individual basins within the sumps. Plots of measured values from digitized maps and model fitting curves for entire Sumps B, C, and D are presented in Figures 1-3. This information enables time-variable calculations of sump volume and area during an event since sump levels are monitored continuously by DSS. These values are important inputs to both hydraulic and pollutant transport model calculations for storm events.

Figure 4 illustrates time-variable rainfall and sump elevations for Sumps A, C, and D provided by DSS for a June 1993 storm. Time-variable pumping and river stage data are also included, from which the total volume of water leaving the sump, V_p, can be estimated. When divided by the duration of the discharge event, this gives an estimate of the average flow rate out of the sump, Q_s, which will roughly represent the total inflow for the assumption of the sump level returning to its pre-discharge value. By calculating a time-averaged volume of water in the sump for the event, V_s, using the elevation-volume curves developed above, a rough estimate of the hydraulic detention time in the sump, τ, is simply V_s/Q_s. This provides a starting point for comparisons between sumps of variable morphology and loading characteristics. The hydraulic detention time can also be used to correlate pollutant removals and storms of variable character for individual sumps. Calculations of τ were performed for four storms during 1992-93 using survey data provided by DSS and the results summarized in Table 3. These results confirmed the hypothesis of the variable hydraulic characteristics of the three sumps chosen for analysis. Sump D exhibits lengthy detention while Sump C very short, with Sump B typically in between. The results also contributed to the selection of Sumps C and D for detailed storm analysis.

A more advanced, time-variable sump hydraulic model was developed in the form of a flow balance that, once calibrated, was used to help calculate estimates of pollutant removals in sumps during storm events. A time variable flow balance is, in general form:

$$\frac{dV(t)}{dt} = \sum Q_{in}(t) + R(t) - \sum Q_{out}(t) \tag{1}$$

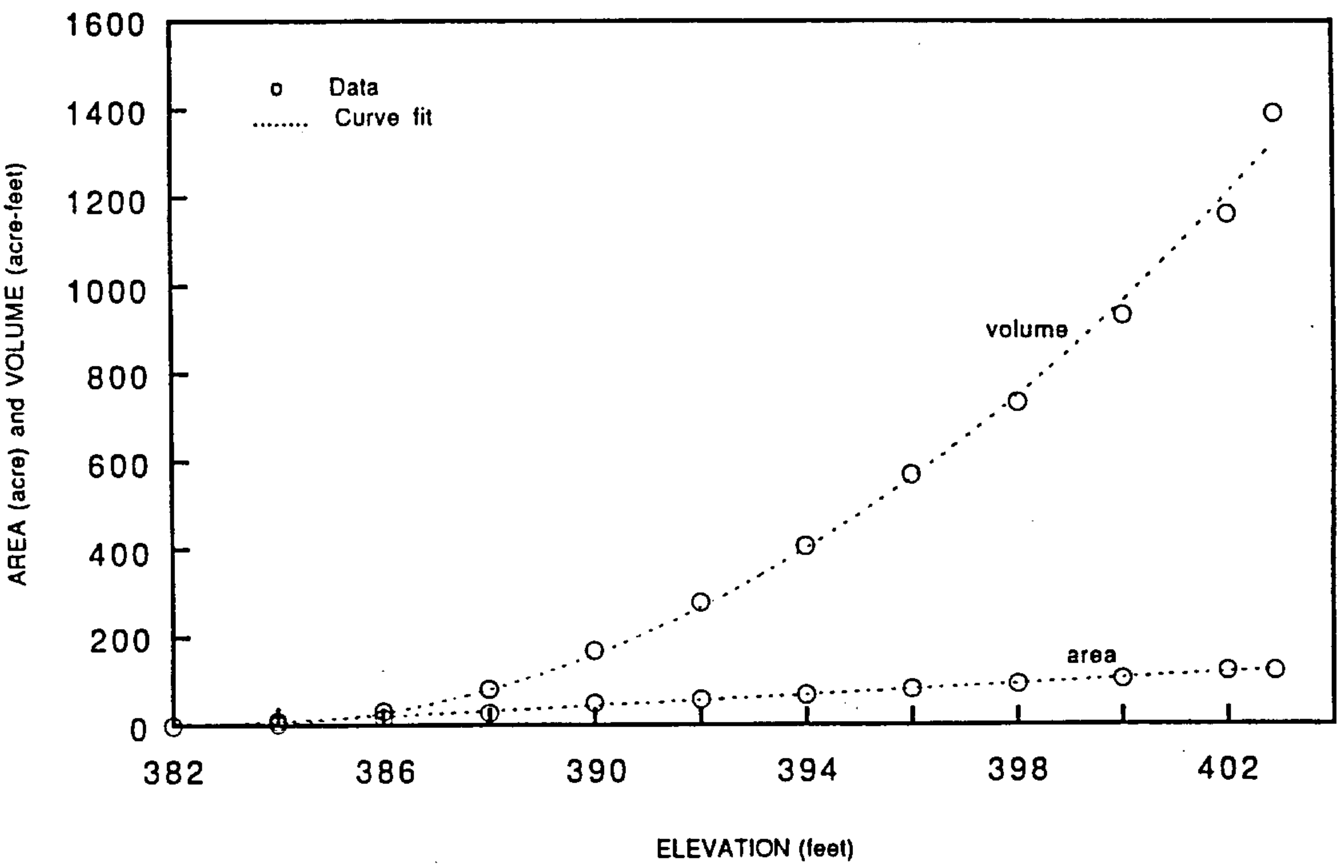


Figure 1: Sump B – Area and Volume Versus Elevation

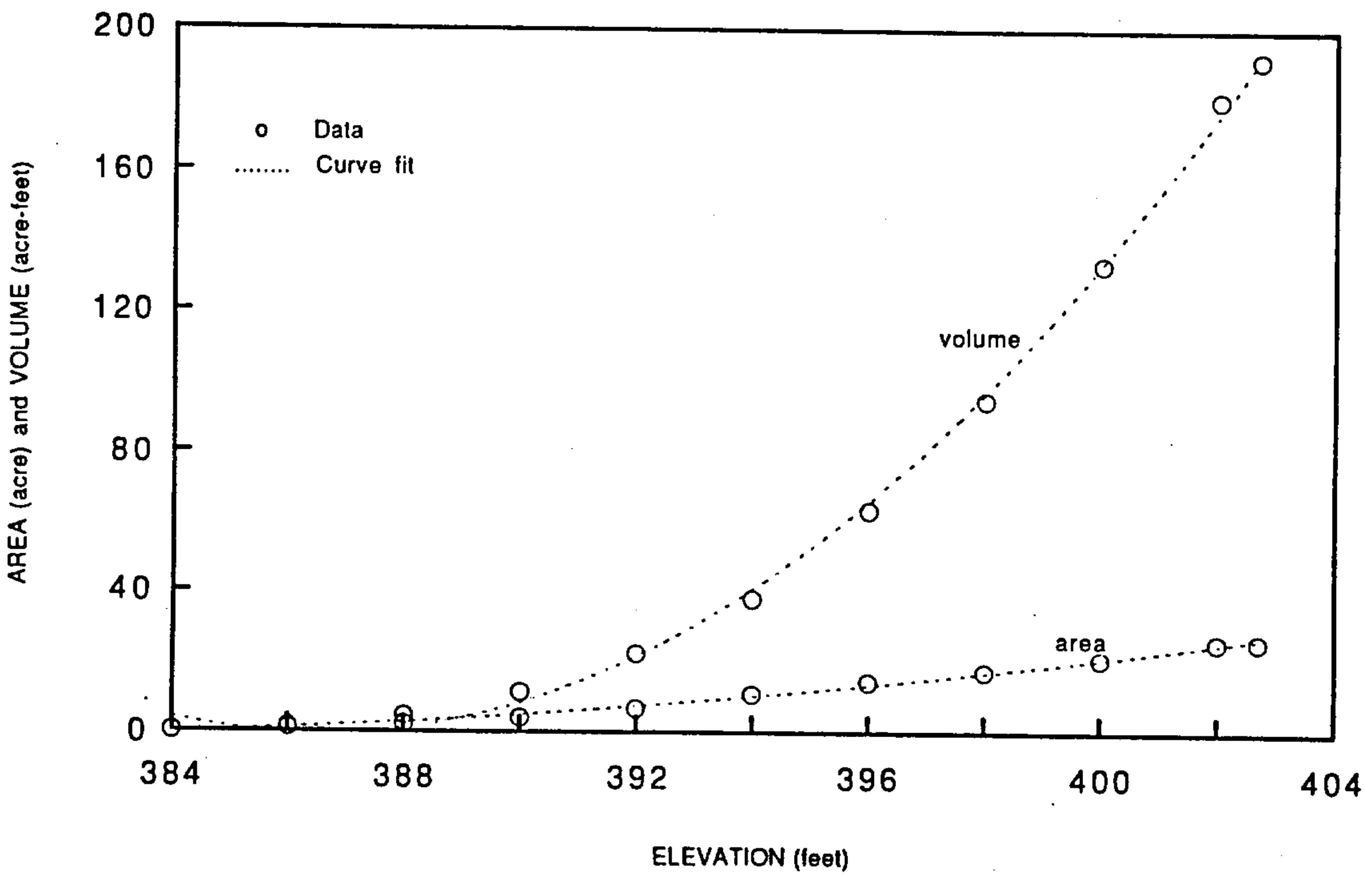


Figure 2: Sump C – Area and Volume Versus Elevation

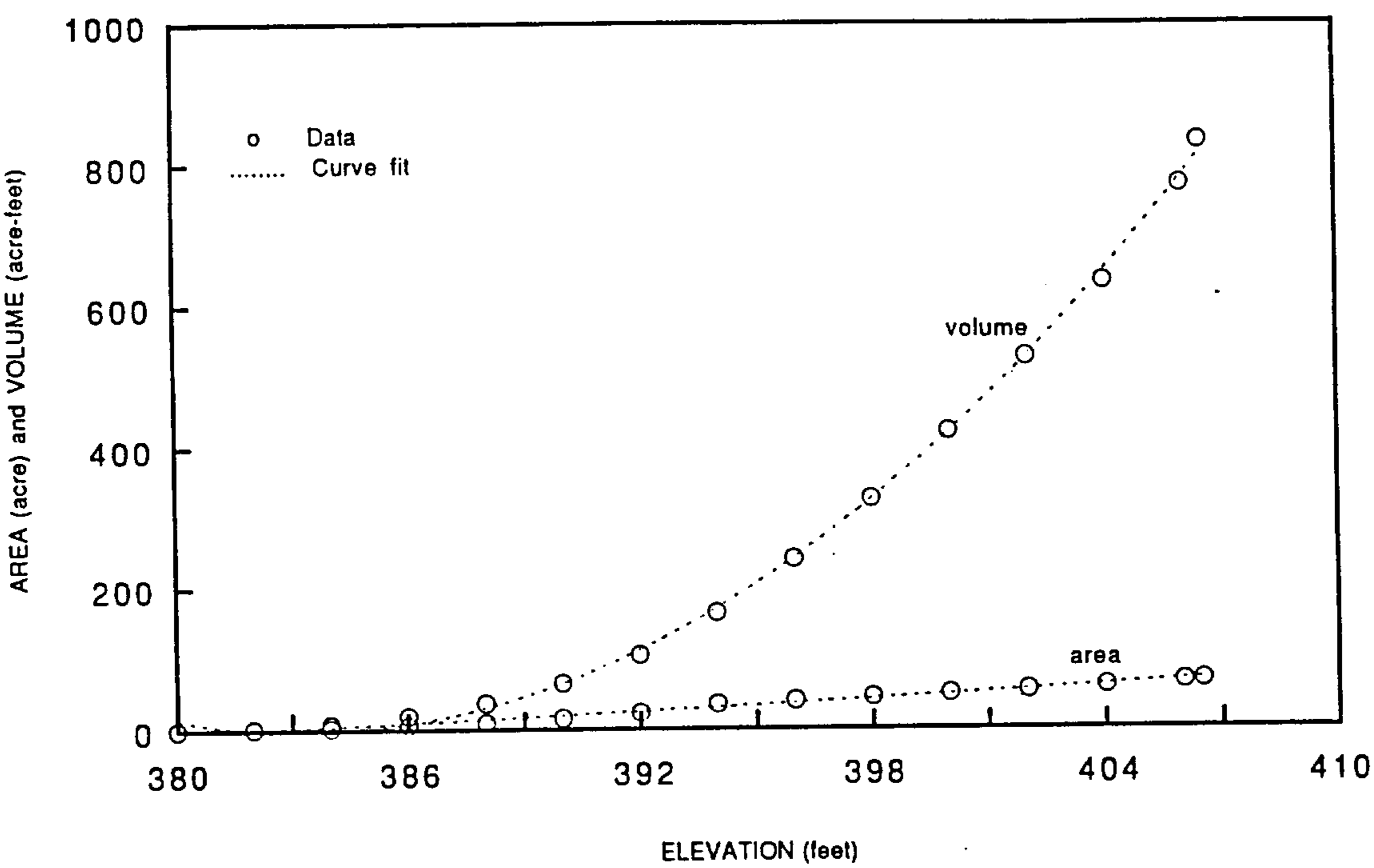


Figure 3: Sump D – Area and Volume Versus Elevation

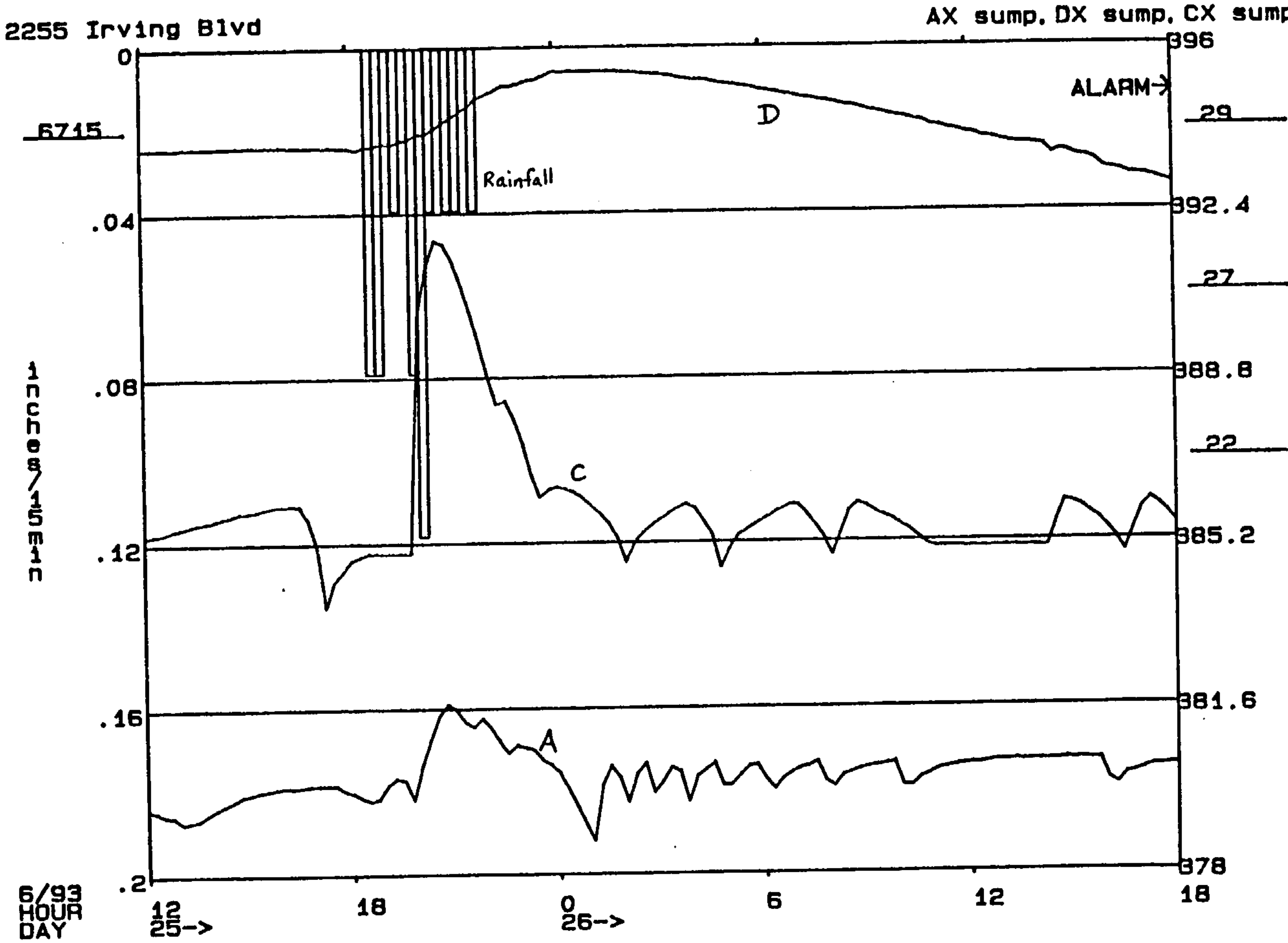


Figure 4: Example of Time Variable Rainfall and Sump Elevation Data Provided by DSS for Storm Events

Table 3: Estimate of Hydraulic Detention Time, τ, in Sumps B, C, and D for Four Storms During 1992–1993

Dates of Event	Total Rainfall (in)	Rainfall Duration (hrs)	τ (hrs) Sump B	τ (hrs) Sump C	τ (hrs) Sump D
2/24-2/27/92	0.96/0.24	7.7/5.0	3.75	0.82	37.2
3/17-3/19/92	0.80/0.32	1.2/1.1	3.99	1.49	122.0
10/15-10/16/92	1.16	2.0	8.03	0.92	NP[a]
4/29/93	1.66	2.8	3.32	2.02	242.6

[a]No pumping during this event

where V(t) represents the volume of water in the sump at time, t, $Q_{in}(t)$ the time-variable stormwater inputs to the sump, R(t) the runoff (including rainfall) directly onto the sump area at time, t, and Q_{out} the releases of water from the sump by pumping or gravity drainage. Each of these quantities is estimable from individual event data and the morphological rating curves shown. The most difficult term to estimate is Q_{in}. The strategy utilized in this work was to obtain the drainage locator maps for individual sump areas from the Department of Public Works and the Oak Cliff Municipal Center Water Department together with information from previous site visits to identify the drainage outfalls into a sump. The drainage areas were delineated by hand for each outlet using both sets of maps concurrently, followed by digitizing individual areas for the target sumps into microstation files for drainage area calculations (see Maps 2 and 3 and Tables 4 and 5 for mapping of drainage outfalls and corresponding areas). Note that Sump C has 14 outfalls, including a drainage area directly connected to the sump itself, and Sump D contains 33 (Sump B has nearly 60 and was thereby eliminated from this study). Since continuous flow monitoring of the many outfalls of each sump is practically impossible, a flow estimator was selected to determine the flow hydrograph for each outfall as part of the flow balance for the sump. HEC-1 software developed by the U.S. Corps of Engineers was chosen for this purpose, mainly because: (1) a major objective of the project is to develop a transferable protocol for evaluating sump hydraulics / pollutant removal characteristics, and HEC-1 is one of the more widely applied and available hydrologic models of this type; and (2) the drainage characteristics for each outfall to a sump required for implementation of HEC-1 are obtainable either by direct, independent measurement or calibration of available data, including drainage area, time of concentration, land use, and volume of water in the sump versus elevation.

2.2 Sampling Stations

Since available resources were not sufficient for sampling and analysis of each individual outfall in the target sumps, a critical task was to decide which outfalls will be the most strategic for sampling. Six automatic sampling units were available for use. One unit was placed at each of the pumping stations of target Sumps C and D, respectively, to determine the quality of waters leaving the sump and in the sump as a whole. The selection of 2 stormwater inputs for each sump from among the drainage areas listed in Tables 4 and 5 was based upon: (a) size of drainage area; (b) distribution of sampled areas throughout the total sump area; (c) land use; and, (d) amenability of the field

Table 4: **Drainage Areas of Individual Sewer Outfalls for Sump C**

Outfall	Area (Ac)	Outfall	Area (Ac)	Outfall	Area (Ac)
C1	75.8	C6	69.7	C11	25.1
C2	28.5	C7	26.3	C12	159.6
C3	18.5	C8	16.9	C13	6.5
C4	76.0	C9	86.8	C14	170.8
C5	15.7	C10	14.4		

Table 5: **Drainage Areas of Individual Sewer Outfalls for Sump D**

Outfall	Area (Ac)	Outfall	Area (Ac)	Outfall	Area (Ac)
D1	174.5	D12	6.8	D23	19.8
D2	6.3	D13	6.8	D24	35.0
D3	3.1	D14	7.1	D25	7.8
D4	8.3	D15	5.9	D26	697.8
D5	20.1	D16	3.4	D27	12.7
D6	13.6	D17	33.8	D28	12.4
D7	15.4	D18	13.3	D29	31.4
D8	10.7	D19	13.7	D30	87.8
D9	11.9	D20	67.1	D31	19.3
D10	16.7	D21	6.3	D32	3.8
D11	5.9	D22	16.6	D33	412.9

site to construction of an autosampling station. Two additional sites in Sump D were included in some of the sampling for Events 3 and 4. Stormwater samples at these sites were collected manually (i.e., no autosampling device) using collection and preservation procedure described in section 2.3.1. A description of the sampling stations is presented in Table 6 below, and the locations noted on individual maps of the target sumps, Maps 2 and 3, along with the designated drainage areas contributing to each sampled outfall (sampling stations used for Events 3 and 4 for Sump D are shown on Maps 4 and 5, respectively). The storm water quality data gathered at these chosen stations is assumed to represent that of the immediately surrounding zones. Furthermore, resources limited the collection of just two samples per event at each outfall, a first-flush sample plus a second sample typically collected within 10 to 12 hours of the first flush. Sediment samples were collected before and after each storm event at each sump in the vicinity of the pumping station.

Table 6: Stormwater Sampling Locations

Location	Actual[a] Drainage Zone(s)	Drainage Area (Acres)	% of Total Drainage Area
Sump C			
Pumping Station	C14	170.8	21.6
Drain Box at Beckley at IOSCO	C1/C2/C3	122.8	15.5
98-in CIP at Concrete Channel	C12/C13	166.1	21.0
Sump D			
Pumping Station	D1	174.5	9.7
Headwall–Channel at Fishtrap Lake	D33	412.9	22.8
Residential Outlet Along Sump	D12	6.8	0.4
Francis Street at Westmoreland Bridge	D26/D31	717.1	39.7
Residential Outlet into Creek	D29	31.4	1.7

[a]From Tables 5/6 and Maps 2/3/4/5

2.3 Sampling Procedures and Analysis

2.3.1 Sampling

Tables 7 and 8 list, respectively, stormwater and sediment quality parameters measured for at least one event of the study. Also included are the sample volume and container type used for sampling, and the division of labor for analysis between the Pretreatment and Laboratory Services' Analytical Laboratory of Dallas Water Utilities and the Environmental Engineering Laboratory at SMU. The stormwater sampling procedure is summarized as follows.

1) Based on weather forecasts, pre-event stormwater and sediment samples were collected at the sump pumping stations. These were typically within one or two days of the start of the storm event. The depth sensors on the autosamplers at the basin (i.e., outfall) stations were also set and the program initiated for collection of the first-flush sample.

2) An SMU representative received notification of the onset of a stormwater event from the DSS monitoring center *via* an automatic dialing system that activated at the detection of 0.04 inches of rainfall in a gauge located within the drainage area of Sump C.

3) Two sampling teams of two persons each (one team each for Sumps C and D, respectively) assembled to collect the designated vehicles and sampling kit and confirm a communication / sample delivery scheme. Each sampling kits consisted of two ice chests, 4-L wide-mouth glass bottles to resupply the autosampler, 100-mL plastic bottles for biologicals, 1-L plastic bottles for metals, vial of 1:1 nitric acid with dropper for immediate preservation of metals samples, field meter and probe for pH measurement, field meter and probe for TDS measurement, hand-held thermometer for temperature measurement, field notebook and pencil for notes, walkie-talkie for communication with alternate team, rain coats and boots, flashlight, and keys/combinations for sump station and other security gates. In addition, the Sump C team required a safety harness and jackline for sampling at the Beckley Station.

4) Each team was responsible for sampling all of the respective sites in succession, beginning with the basin (outfall) stations and proceeding to the pumping station. By the time the teams arrived at the outfall sites, the first-flush sample had been collected by the autosamplers. Depending upon the nature of the event, the desired sampling scheme for the basin stations was as follows:

   a) 1 'first flush' sample within one hour of the start of an event (i.e., initiation of detectable flow in outfall).

   b) a second sample, normally collected 8–15 hours after the start of the event. This was a composite (3-way split between the three, 1-L bottles in the autosampler) sample collected over a 6–8 hour period.

   The "nature of the event" refers to the observable and speculated storm conditions at the time of collection of the first-flush sample. For instance, in Event 1, it was evident that the rain was very light and forecasted over several days. Therefore, the second set of outfall samples was not collected until 50 hours into the event, in an attempt to obtain samples that would be representative over the duration of the event. The other three events were much more intense storms with rainfall concentrated near the beginning of the event. therefore, the second set of outfall samples was collected while runoff was still expected to be substantial.

5) The event samples at the pumping stations were collected "manually" using the autosampler, since the nature of sump operations made depth-sensing autostarting unfeasible. Depending upon the nature of the event (*i.e.*, anticipated subsequent conditions as noted above), the sampling scheme for the pump stations for a single event was as follows:

   a) 1 pre-event sample (establishes the conditions for time zero of the event)

   b) 1 sample at 2–4 hrs after start of event

   c) 1 sample at 8–15 hrs after start of event

   d) 1 sample at 24–48 hrs after start of event

   e) 1 sample at 56–72 hrs after start of event

   f) 1 sample at 96–120 hrs after start of event if available

   The timing of the sampling scheme reflects: (1) the resource limitations in this type of work (*e.g.*, the ideal would be to sample more frequently in the early hours of the event), and (2) the goal of tracking the dynamic nature of pollutant concentrations in the sumps well after the runoff period of the event, but during which time pollutant removals may continue to occur due to retention.

6) The field sampling procedure at each station was as follows:

   a) Ensure that sampler is programmed and performing correctly. A 'sample' is comprised of filling the 3 loaded 4-L glass containers.

   b) Containers 1 and 2 were capped with teflon closures and labelled for delivery as 'inorganics' and 'pesticides', respectively for Dallas Water Utilities Central Laboratory (DWU).

   c) Container 3 was poured among the following:

      (i) 100-mL plastic container for 'biological' analysis – (Samples to DWU)

      (ii) 1-L plastic container for 'metals analysis' (add 10 drops of 1:1 nitric acid) – (Samples to SMU)

      (iii) Small amount of sample into glass container for field measurement of pH, temperature, and TDS using field instruments. Measurements were recorded in field notebook for each sample measured in this fashion.

      (iv) Remainder of 4-L glass container No. 3 to SMU for COD and solids analyses.

   d) All samples (except for metals sample) were carefully placed in ice chests.

   e) All samples were then labelled according to (i) sample station; (ii) date and time; (iii) type of analysis.

   f) Clean set of 3 No. 4-L glass containers were placed into autosampler and any programming adjustments made.

After samples were collected from all stations, the teams met at Sump C pumping station to record any pertinent observations or problems encountered and complete chain of custody forms, followed by delivery of samples to DWU Central Wastewater Research Laboratory (with chain of custody form) and SMU laboratory as appropriate.

Sediment samples were collected before and after an event at a consistent location near the point where stormwater samples were taken at the respective pumping stations. The samples were bottom sediment samples and collected manually using the bottom half of a polypropylene bottle mounted to a pole. For an individual sample, three to five grabs were composited/mixed in a pan and the water drained so that only the sediment slurry remains. From this mixed sample, three 1-qt glass jars (with teflon caps) and one 100-mL polypropylene container were filled and sealed. The four containers (per sample) were labeled, place in an ice chest, and distributed as follows:

1) Container 1 (1-qt): DWU for inorganic analysis

2) Container 2 (1-qt): DWU for pesticide analysis

3) Container 3 (100-mL): DWU for biological analysis

4) Container 4 (1-qt): SMU for solids and metals analyses

2.3.2 Pollutant Analysis

As noted previously, a portion of pollutant analysis were performed by DWU Pretreatment and Laboratory Services Division. The methods used by DWU are given in Table 9.

Some Notes on Metal Analysis

The detection limits for the test metals were Lead (15 μg/L), Copper (2 μg/L), Zinc (1.5 μg/L), Arsenic (15 μg/L), Cadmium (1.5 μg/L), and Calcium (1.5 μg/L). Precisiòn was established by replicate (total of 3) analyses of each sample. A replicate is defined here as independent analyses of an already prepared sample. ICP calibration standards were prepared as needed and run for each analysis. Standard concentrations bracketed the anticipated concentration range of test samples and included a calibration blank (i.e., metal concentration equal to 0). The standards were prepared as serial dilutions and digested by the same procedure used for stormwater samples according to Standard Method 3030 (E) to minimize background matrix effects. Accuracy was confirmed by validation of the standard calibration curve by a check standard from an independent source. A midpoint instrument check standard was prepared from standard 1000 μg/ml cadmium and lead solutions (*SPEX* brand plasma-grade standards distributed by Fisher, Scientific — these standards have a guaranteed concentration of $\pm 5\%$ of the label value for one year).

Table 7: Parameters for Stormwater Analysis

Parameter	Volume and Type[a] of Container	Preservation[b]	Maximum Holding[c] Time
DWU			
BOD	4-L (G)	Cold[d]	24 hr
TOC	(Same)	Cold[d]	24 hr
Total Phosphorus	(Same)	Cold[d]	48 hr
Dissolved Phosphorus	(Same)	Cold[d]	48 hr
Total Kjeldahl Nitrogen	(Same)	Cold[d]	48 hr
Total $NO_2 + NO_3$	(Same)	Cold[d]	48 hr
Chlordane, Total	4-L (G)	Cold[d]	72 hr[e]
Fecal Coliforms	100-mL (PP)	Cold[d]	6 hr
Fecal Streptococcus	(Same)	Cold[d]	6 hr
SMU			
pH	On-Site Analysis		
Temp	On-Site Analysis		
TDS	On-Site Analysis		
COD	1-L (G)	Cold[d]	24 hr
TSS	(Same)	Cold[d]	7 days
VSS	(Same)	Cold[d]	7 days
Settleable Solids	(Same)	Cold[d]	7 days
Lead	1-L (P)	HNO_3 to pH$\leq$2	3 months
Copper	(Same)	HNO_3 to pH$\leq$2	3 months
Zinc	(Same)	HNO_3 to pH$\leq$2	3 months
Arsenic	(Same)	HNO_3 to pH$\leq$2	3 months
Cadmium	(Same)	HNO_3 to pH$\leq$2	3 months
Calcium	(Same)	HNO_3 to pH$\leq$2	3 months

[a]Polyethylene (P), polypropylene (PP), or glass (G). All glass containers equipped with teflon-lined caps.
[b]Steps performed immediately upon sample collection.
[c]Samples analyzed as soon as possible after collection. Data obtained beyond maximum times are flagged.
[d]Ice transport and laboratory refrigeration @ 4 °C.
[e]Prior to extraction.

Table 8: Parameters for Sediment Analysis

Parameter	Volume and Type[a] of Container	Preservation[b]	Maximum Holding[c] Time
DWU			
BOD	1-Qt Wide Mouth (G)	Cold[d]	24 hr
Total Phosphorus	(Same)	Cold[d]	48 hr
Dissolved Phosphorus	(Same)	Cold[d]	48 hr
Total Kjeldahl Nitrogen	(Same)	Cold[d]	48 hr
Total $NO_2 + NO_3$	(Same)	Cold[d]	48 hr
Chlordane, Total	1-Qt Wide Mouth (G)	Cold[d]	72 hr[e]
Fecal Coliforms	100-mL (PP)	Cold[d]	6 hr
Fecal Streptococcus	(Same)	Cold[d]	6 hr
SMU			
COD	1-Qt Wide Mouth (G)	Cold[d]	24 hr
% Solids	(Same)	Cold[d]	7 days
Volatile Solids	(Same)	Cold[d]	7 days
Lead	(Same)	HNO_3 to pH$\leq$2	3 months
Copper	(Same)	HNO_3 to pH$\leq$2	3 months
Zinc	(Same)	HNO_3 to pH$\leq$2	3 months
Arsenic	(Same)	HNO_3 to pH$\leq$2	3 months
Cadmium	(Same)	HNO_3 to pH$\leq$2	3 months
Calcium	(Same)	HNO_3 to pH$\leq$2	3 months

[a]Polyethylene (P), polypropylene (PP), or glass (G). All glass containers equipped with teflon-lined caps.
[b]Steps performed immediately upon sample collection.
[c]Samples analyzed as soon as possible after collection. Data obtained beyond maximum times are flagged.
[d]Ice transport and laboratory refrigeration @ 4 °C.
[e]Prior to extraction.

Table 9: Methods for Pollutant Analysis

Parameter	Analytical Method	Modifications/Notes
DWU		
BOD	SM[a] #9230-C	
TOC	SM #5310 (B)	
Total Phosphorus	SM #4500-P (B+E)	
Dissolved Phosphorus	SM #4500-P (B+E)	
Total Kjeldahl Nitrogen	SM #4500-NH_3 (F)	
Total NO_2 + NO_3	EPA Method 300.A	(1) 300-μL sample loop (2) 40 mM Boric Acid / 20 mM NaOH Eluent
Chlordane	EPA Method 608	Used beakers + stir plates vs. separatory funnel technique
Fecal Coliforms	SM #9222 (B)	
Fecal Streptococcus	SM #9230 (C)	
SMU		
pH	SM #4500-H^+ (B) (on site)	
Temperature	Field Thermometer (on site)	
COD	Digestion[b]	
% Solids	SM #2540 (D + G)	
Volatile Solids	SM #2540 (E + G)	
Settleable Solids	SM #2540 (F)	
Total Dissolved Solids	Field Probe (on site)	
Metals		
Lead	EPA Method 6010A (ICP)[c]	Digestion by SM #3030 (E) for Stormwater
Copper	EPA Method 6010A (ICP)	
Zinc	EPA Method 6010A (ICP)	
Arsenic	EPA Method 6010A (ICP)	EPA Method 3050-A for Sediments
Cadmium	EPA Method 6010A (ICP)	
Calcium	EPA Method 6010A (ICP)	

[a]Standard Methods, 18th Edition
[b]Hach Reactor Digestion Method for 0-150 mg/L COD range
[c]Metal analysis by inductively coupled plasma spectroscopy from SW-846

3 RESULTS AND DISCUSSION

3.1 Sump Operation and Hydraulic Modeling

As noted in Section 3.1, HEC-1 was used for estimating the flows of the numerous outfalls to each sump. A major task, therefore, was to design a method to verify the ability of HEC-1 to estimate runoff quantities and thereby estimate pollutant loads to a sump for a given event.

HEC-1 was used to estimate the runoff hydrograph for each individual outfall using drainage characteristics derived from drainage locator maps and land use information compiled from data supplied by the North Central Texas Council of Governments. The times of concentration and drainage areas in mi^2 required as input to HEC-1 are listed for each drainage area in Tables 10 and 11.[1] Land use data is supplied in Table 12 along with Map 6. The rainfall pattern for each event was obtained from DSS which operates a rain gauge in both Sump C and D drainage areas. Rainfall data for the four events for which stormwater and sediment sampling was performed are presented in Figures 5–8 and 9–12 for Sumps C and D, respectively. Once the individual outfall hydrographs were developed, a composite stormwater inflow hydrograph for the sump was obtained by superposition. Figure 13 is a composite runoff hydrograph for a portion of Event 2 for Sump C showing sensitivity of HEC-1 calculations to curve number. The symbols labelled as "Real Data" refer to runoff estimates by a water balance that will be explained below. The starting time for an event was estimated from reconciliation of both the first record of rainfall and the recorded time of auto-collection of the first-flush sample at the outfall sampling stations. The total runoff for the event is then calculated by integrating the composite hydrograph. A summary of the total runoff for each event is presented in Table 13. As noted in this table, the four events span several seasons, with Events 1 and 2 occuring during winter-spring, Event 3 in spring, and Event 4 in summer. They also represent a very light rainfall over several days (Event 1), medium-sized events (3 and 4), and a heavy rain (3-4 inches, Event 2), the latter three being fairly concentrated events. Event 2 and, to some extent, Event 3 had considerable antecedent moisture, while Event 4 occured after a lengthy dry period. An attempt was made to account for these conditions by selection of appropriate loss terms / curve numbers in HEC-1 modeling. These adjustments are reflected in HEC-1 total runoff values in Table 13 versus the total rain runoff (right-hand column of Table 13) which is simply the total rainfall times the total drainage area of the sump. For instance, HEC-1 runoff for Event 2 is a relatively high percentage of total possible runoff owing to the antecedent moisture condition. This is not as evident in Event 3 since for lower rainfalls (e.g., less than 1 inch) there are inherent losses in the HEC-1 modeling scheme.

To attempt to validate HEC-1 results, a water balance after Eq. 1 was used to estimate the total runoff hydrograph using sump operational data. The water balance is:

$$V_{R,t} = V_{P,t} \pm \Delta V_t - V_{G,t} + V_{L,t} \qquad (2)$$

where $V_{R,t}$ is the storm runoff to the sump during a prescribed time interval, t; $V_{P,t}$ is the volume of water pumped from the sump (to the river) in the time interval; ΔV_t is the change in volume of water in the sump during the time interval; and $V_{G,t}$ and $V_{L,t}$ are other quantifiable gains and losses, respectively, during the time interval. DSS continuously monitors the status of high- and low-flow pumps during an event, enabling calculation of $V_{P,t}$. A time interval of 15 minutes was

[1] Because of the large numbers of Tables and Figures in this portion of the report, they are all collected at the end of the section rather than dispersed in the text.

used throughout the study. Data on sump elevations as a function of time was also obtained from DSS and used to calculate ΔV_t using the volume-elevation relationships presented in Figures 2 and 3 for Sumps C and D, respectively. Estimation of $V_{G,t}$ and $V_{L,t}$ is by no means a trivial matter for the rather complex combination of natural and engineered structures comprising the sump drainage systems. Certainly there are many factors and variables in nonpoint source systems such as these that are difficult to account for and which could have a significant impact on the model prediction of $V_{R,t}$. Some specific examples and the strategy followed in the present study for incorporating their effects are the following.

- There may be an uneven rainfall pattern across a sump drainage region. This is more likely in Sump D due to its much larger drainage area. This was not addressed in the study as the single gauges in each basin were considered to represent their respective areas.

- Substantial seepage losses in a sump and/or inconsistent infiltration losses in drainage areas, depending on the nature of the rainfall event and antecedant conditions (e.g., a storm in summer after an extended dry period, such as Event 4, may have considerable seepage and/or infiltration losses versus an event in March or April during the more rainy spring season). Adjustments in the implementation of HEC-1 calculations have been mentioned previously. For the mass balance check, these losses should be largely accounted for within other terms of Eq. 2 (for instance, ΔV_t).

- Gravity flow through the sluices from a sump to the river may be a significant loss term with respect to the sump water balance. However, according to observations of sump operations, perusal of detailed data from 1992-93 storms, and discussions with sump operation personnel, the gravity sluices have had little or no use in draining Sumps B, C, and D in recent years, but instead virtually all of the sump drainage has been by pumping. The primary reason for this strategy has been the buildup of silt in the main river channel, at least in the area that includes the sluice outfalls, creating a less than favorable hydraulic grade for gravity drainage. Thus it was not necessary to include this term for the test events. While this makes hydraulic modeling of the sumps easier by virtue of reducing the number of outflow terms, the sluiceways should nonetheless be rated for inclusion into the longer term sump management strategy.

- As noted previously, what is designated as a "sump" is actually a collection of interconnected smaller basins. We have noted that, on rare but unpredictable occassions, the flow gate from an 'upstream' basin may be temporarily closed preventing flow to the main basin at the pumping station. Since sump elevation is continuously monitored only in the vicinity of the pumping station, this can occassionally result in reporting an elevation which is unrepresentative of the true storage of water in the sump at a given time. Because of the unpredictable nature of this phenomenon, incorporation of its effects into the modeling exercise is beyond the scope of the current project.

- A more predictable event is water gain from distinct interconnected sump systems. This has already been noted, e.g., in Table 1 with respect to Sump D. The neighboring Francis Street Sump was considered as part of Sump D since it is directly connected without any flow control structure separating them. Under high-flow events, however, Sump D may also receive flows from the Trinity-Portland Sump through a gate at the so-called Ledbetter Dike, just west of the Sump D proper – Francis Street system. Still further to the west and south is the Eagle Ford sump with has a sluiceway connection to the river. As with the Trinity-Portland Sump, however, under high-flow events (i.e., when river elevations exceed sump levels) stormwater will pass through a gate maintained in open position to Trinity-Portland which in turn makes its way to the Sump D pumping area. Associated with a high-flow condition, a high river stage for an extended time period may result in some backflow of water from the river to the sump. Such backflows and feed from neighboring sump systems are not monitored and therefore are difficult to account for.

In addition to sump elevations, river elevations in the vicinity of the sump pumping station outfalls to the river are also continuously monitored by DSS. Events 2 and 3 had extended periods during which the river stage was as much as 10-15 feet higher than the sump elevations in both Sumps C and D. Figure 14 illustrates comparative elevations for Event 2 for C and D. Under these conditions, a substantial quantity of water may enter the Sump D drainage area from neighboring sumps. Some water may also "backflow" to the sumps *via* the pumping station channel and unsealed sluicegates. An estimate of the miscellaneous water gain was obtained by first plotting the water balance hydrograph given by Eq. 2 without considering any adjacent sump drainage or backflow. The square symbols in Figure 15 depict the calculations for Event 2 in Sump D (the solid line is the HEC-1 simulation). With the exception of small amounts of runoff at about 38 and 72 hours, given by the recorded rainfall shown in Figure 10 and the HEC-1 spikes in Figure 15, we know that there was essentially no runoff to the sump after about 30 hours. The storm record indicates, however, that there was substantial (i.e., high-flow) pumping during this period. Yet as further revealed in Figure 15, the incremental decrease in volume in the sump for most time intervals after 30 hours did not offset the volume of water pumped, resulting in the appearance of substantial runoff according to Eq. 2. In some instances the incremental sump volume even increased despite pumping and the knowledge of no runoff. While it may be useful with more data from more events to attempt to develop a relationship between water gain to the sump, actual elevation, and difference in sump-river elevations, the methodology utilized here was to compute an average backflow rate to satisfy the zero runoff requirement over the time period of known zero runoff, and apply it to the water balance hydrograph whenever the difference in sump-river elevations was substantial. Note that it was not possible to distinguish between inflow from neighboring sumps and backflow from the river in Sump D. The result is Figure 16. The procedure was applied to Sumps C and D for Events 2 and 3 when river elevations exceeded sump elevations by more than 5 feet.

A more detailed example of water balance calculations in Sump D for a portion of Event 2 is presented on the following page. The columns lettered A through K in this example represent the following.

A - Event time in 15 minute intervals

B - Real time

C - HEC-1 estimated runoff in cfs

D - HEC-1 runoff converted to acre-ft/15-minutes (to compare with water balance calculations)

E - Elevation of water in the sump in feet

F - Volume of water in sump calculated from elevation-volume relationship (in acre-ft)

G - Calculation of volume of water pumped for the time interval (acre-ft). This is based on the status of the low and high flow pumps (Columns H-J), their respective rated flows, and an estimated pump efficiency of 75% of the rated values.

H - Status of low flow pump (6,000 gpm) during time interval (1 = on, 0 = off)

I,J - Status of high flow pumps (40,000 gpm - each of two) during time interval (1 = on, 0 = off)

K - Runoff calculation from Eq. 2 – ΔV_t is the difference between the current volume in column F and the previous time interval. Column G is loss by pumping. In instances where gains from neighboring sumps (Sump D) or the river Sumps C and D) were included, these were incorporated into the calculation for column G since pumping is always occuring during identified periods of water gain.

Example Water Balance Calculations of Runoff After Eq. 2 for Sump D, Event 2

A	B	C	D	E	F	G	H	I	J	K
4.25	2215	2	0.041322314	387.29	3.334228016	0.207149894	1	0	0	0.135890426
4.5	2230	0	0	387.26	3.281523017	0.207149894	1	0	0	0.154444895
4.75	2245	0	0	387.26	3.281523017	0.207149894	1	0	0	0.207149894
5	2300	0	0	387.2	3.177988678	0.207149894	1	0	0	0.103615555
5.25	2315	0	0	387.21	3.195072221	0.207149894	1	0	0	0.224233436
5.5	2330	0	0	387.22	3.212224337	0.207149894	1	0	0	0.22430201
5.75	2345	0	0	387.22	3.212224337	0.207149894	1	0	0	0.207149894
6	2400	0	0	387.26	3.281523017	0.207149894	1	0	0	0.276448574
6.25	15	73	1.508264463	387.94	4.641892875	0.207149894	1	0	0	1.567519751
6.5	30	402	8.305785124	388.53	6.13780471	1.380999291	0	1	0	2.876911127
6.75	45	229	4.731404959	388.24	5.362703782	1.588149185	1	1	0	0.813048256
7	100	144	2.975206612	388.1	5.016431471	1.588149185	1	1	0	1.241876874
7.25	115	202	4.173553719	390.07	11.76767616	1.588149185	1	1	0	8.339393877
7.5	130	623	12.87190083	390.39	13.30495723	1.380999291	0	1	0	2.918280359
7.75	145	473	9.772727273	392.37	26.28035776	2.969148476	1	1	1	15.94454901
8	200	940	19.4214876	392.6	28.22213787	2.969148476	1	1	1	4.910928582
8.25	215	346	7.148760331	393.01	31.93353057	2.969148476	1	1	1	6.680541176
8.5	230	84	1.73553719	392.76	29.63180104	2.969148476	1	1	1	0.667418952
8.75	245	430	8.884297521	392.44	26.86090342	2.969148476	1	1	1	0.198250853
9	300	246	5.082644628	392.17	24.67108179	2.969148476	1	1	1	0.779326841
9.25	315	154	3.181818182	391.83	22.0991842	2.969148476	1	1	1	0.397250888
9.5	330	50	1.033057851	391.47	19.59246255	2.969148476	1	1	1	0.462426824
9.75	345	94	1.94214876	391.19	17.79017113	2.969148476	1	1	1	1.166857059
10	400	117	2.417355372	390.99	16.57876702	2.969148476	1	1	1	1.757744364
10.25	415	205	4.23553719	390.77	15.31690937	2.969148476	1	1	1	1.707290825
10.5	430	74	1.52892562	390.36	13.1548726	2.969148476	1	1	1	0.80711171
10.75	445	18	0.371900826	389.97	11.31545928	2.969148476	1	1	1	1.129735159
11	500	169	3.491735537	389.7	10.15893953	2.969148476	1	1	1	1.812628718
11.25	515	230	4.752066116	389.56	9.59521136	2.969148476	1	1	1	2.405420309
11.5	530	80	1.652892562	389.38	8.905224685	2.969148476	1	1	1	2.279161801
11.75	545	102	2.107438017	389.18	8.183024547	2.969148476	1	1	1	2.246948338
12	600	37	0.76446281	388.96	7.440580886	2.969148476	1	1	1	2.106704815

The results are presented alongside HEC-1 calculations in Table 13, and in Figures 16–23 together with HEC-1 simulated hydrographs. The conclusion from this effort is that when reasonable approximations are made for water gain/loss terms that cannot be directly measured, HEC-1 calculations provide a satisfactory estimate of the total runoff and its time-distribution to the sump. HEC-1 calculations underestimated water balance runoff in three of four cases for Sump C, and slightly overestimated water balance calculations for all four test events. The relative percent difference between HEC-1 and water balance values of total runoff ranges from 9 to 33 percent with an average of 22 percent for Sump C, where relative percent difference, RPD, is defined as:

$$\mathbf{RPD} = \frac{(C_1 - C_2)}{(C_1 + C_2)/2} \times 100\% \qquad (3)$$

where RPD = relative percent difference
C_1 = larger of the two observed values, and
C_2 = smaller of the two observed values.

For Sump D, RPDs ranged from 0.1 to 37 percent with an average of 14 percent. That percent differences in Sump C are higher is not surprising given the appreciably lower flows and flash nature of stormwater passage through the sump versus Sump D. Furthermore, Event 1 with its very small quantity of flows contributes significantly to average percent differences for both sumps, especially D. The overall corroboration of results of the two modeling methodologies has several strategic implications.

1. HEC-1 is validated as a useful tool for estimating stormwater runoff to the sump as a component to a total sump operation management model and for estimating pollutant loads to a sump. It is important to note, however, that the HEC-1 runoff hydrographs developed for individual drainage zones within a sump drainage area have not been validated in this study. While good estimates of total runoff lend credibility to such an assumption, further studies including field measurements of runoff in outfalls are required to validate whether HEC-1 hydrographs are representative of the actual runoff pattern for individual outfalls.

2. The water balance model can be used to estimate the impacts of operational parameters such as pumping rates and timing on overall sump hydraulics which, in turn, may effect pollutant levels/removals in the sump. For instance, pumping might actually be reduced during higher-flow events to achieve a better balance between river and sump levels, since a large difference results in significant quantities of backflow to the sumps that must eventually be released anyway. The model can also be a useful tool for estimating pollutant loads from the sump to the river and, with sufficient pollutant data, may enable estimation of reaction rate constants for pollutant removal processes in the sumps.

Table 10: Times of Concentration and Drainage Areas for Sump C for Use in HEC-1 Calculations

Drainage Area	Total Tc(min)	Area (mi2)
C1	22.5500	0.1184
C2	15.5376	0.0445
C3	17.8196	0.0289
C4	24.6659	0.1188
C5	17.4887	0.0245
C6	11.7702	0.1089
C7	10.8555	0.0410
C8	10.3160	0.0263
C9	12.1880	0.1357
C10	10.6062	0.0225
C11	10.8481	0.0392
C12	14.1157	0.2494
C13	10.0000	0.0102
C14	10.0000	0.2668

Table 11: Times of Concentration and Drainage Areas for Sump D for Use in HEC-1 Calculations

Drainage Area	Total Tc(min)	Area (mi2)
D1	10.0000	0.2727
D2	13.1970	0.0098
D3	12.2775	0.0048
D4	13.3437	0.0131
D5	14.5933	0.0313
D6	13.3699	0.0213
D7	14.2041	0.0240
D8	14.1895	0.0167
D9	19.8761	0.0187
D10	12.1134	0.0261
D11	10.3239	0.0092
D12	10.2963	0.0106
D13	11.1721	0.0107
D14	10.6731	0.0111
D15	10.6731	0.0092
D16	11.0122	0.0053
D17	10.1190	0.0528
D18	14.7717	0.0207
D19	14.8283	0.0214
D20	10.3882	0.0105
D21	10.4487	0.0099
D22	11.4816	0.0260
D23	10.8852	0.0310
D24	16.1276	0.0547
D25	10.0000	0.0121
D26	102.9412	1.0903
D27	13.1207	0.0199
D28	10.6731	0.0194
D29	13.5687	0.0491
D30	21.4777	0.1372
D31	36.9048	0.0301
D32	10.0000	0.0059
D33	22.4318	0.6452

Table 12: Land Use Summary for Sumps C and D

SUMP C

	Landuse	Landuse Code	Acres	% of Total Acreage
1	Single Family	111	118.2	15.1
2	Multi Family	112	59.4	7.6
3	Mobile Home Parks	113	11.4	1.4
4	Group Quarters	114	1.1	.1
5	Office	121	16.7	2.4
6	Retail	122	55.3	7.0
7	Institutional	123	42.9	5.5
8	Industrial	131	178.1	22.9
9	Transportation	141	6.44	.8
10	Roadway	142	55.4	7.11
11	Utilities	143	.12	.0
12	Parks & Rec	171	10.9	1.4
13	Flood Control	181	169.1	21.7
14	Vacant	300	54.2	6.9

SUMP D

	Landuse	Landuse Code	Acres	% of Total Acreage
1	*	5	20.6	1.1
2	Single Family	111	305.5	16.7
3	Multi Family	112	311.2	17.1
4	Mobile Home Parks	113	24.7	1.4
5	Office	121	2.82	.2
6	Retail	122	50.97	2.8
7	Institutional	123	93.5	5.1
8	Industrial	131	570.5	31.2
9	Transportation	141	24.66	1.4
10	Flood Control	181	223.6	12.3
11	Vacant	300	196.4	10.8

* NCTCOG : Level 2 designations be maintained

Table 13: Calculated Runoff for Test Events in Sumps C and D

Event	Dates	Total Rain (inches)	Total Rain (ac-ft)	Runoff HEC-1 (ac-ft)	Runoff Eqn. 2 (ac-ft)
Sump C					
1	2/28/95–3/6/95	0.20	13.2	0.202	0.275
2	3/12/95–3/17/95	3.19	211.1	180.950	165.128
3	4/10/95–4/14/95	0.64	42.3	21.033	29.463
4	7/5/95–7/10/95	1.15	76.1	37.624	48.362
Sump D					
1	2/28/95–3/6/95	0.44	66.8	12.169	8.342
2	3/12/95–3/17/95	3.85	584.8	515.124	514.703
3	4/10/95–4/14/95	0.87	132.1	78.120	72.256
4	7/5/95–7/10/95	1.36	206.6	113.264	100.690

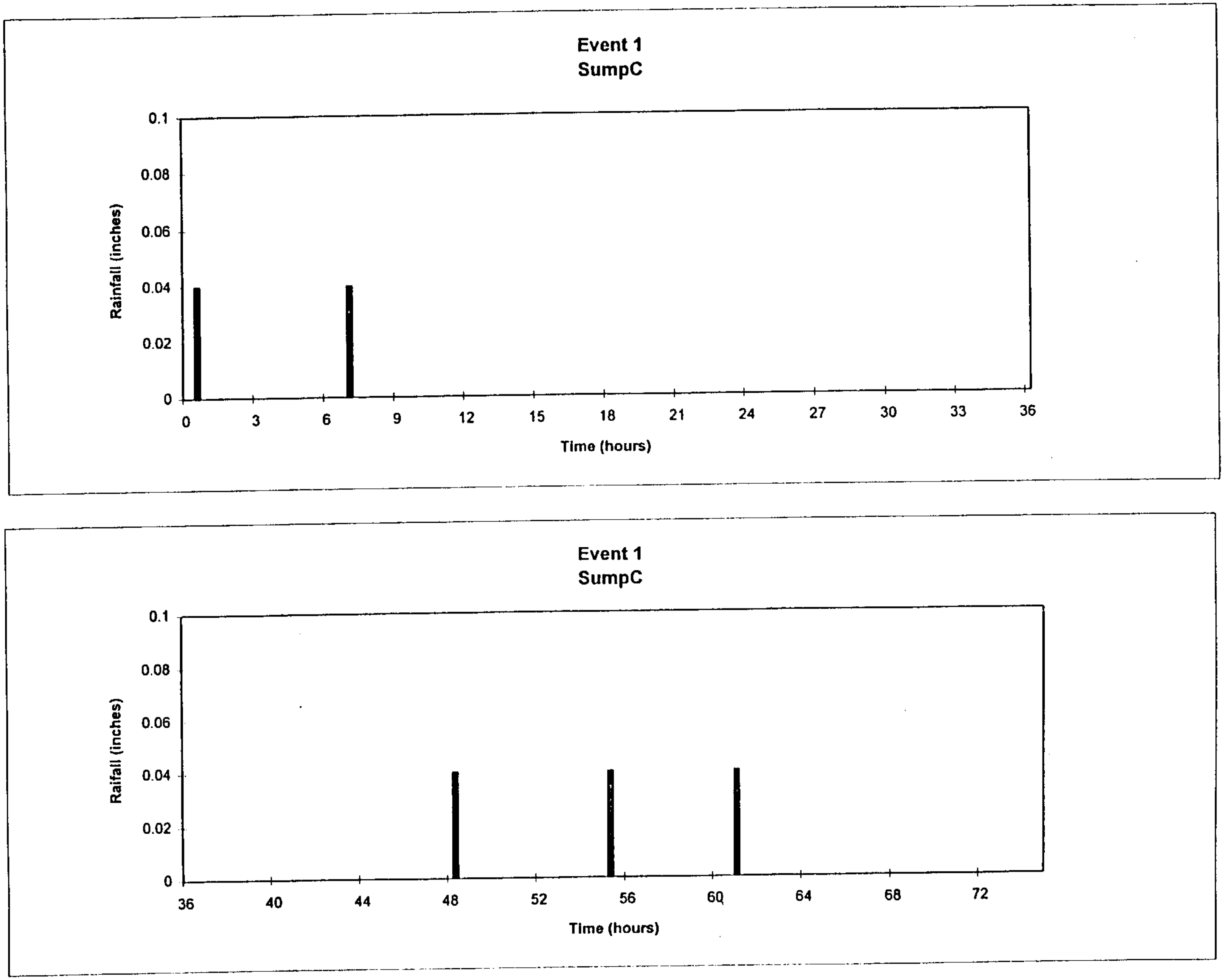


Figure 5: Rainfall Record for Sump C - Event 1 (2/28/95-3/6/95)

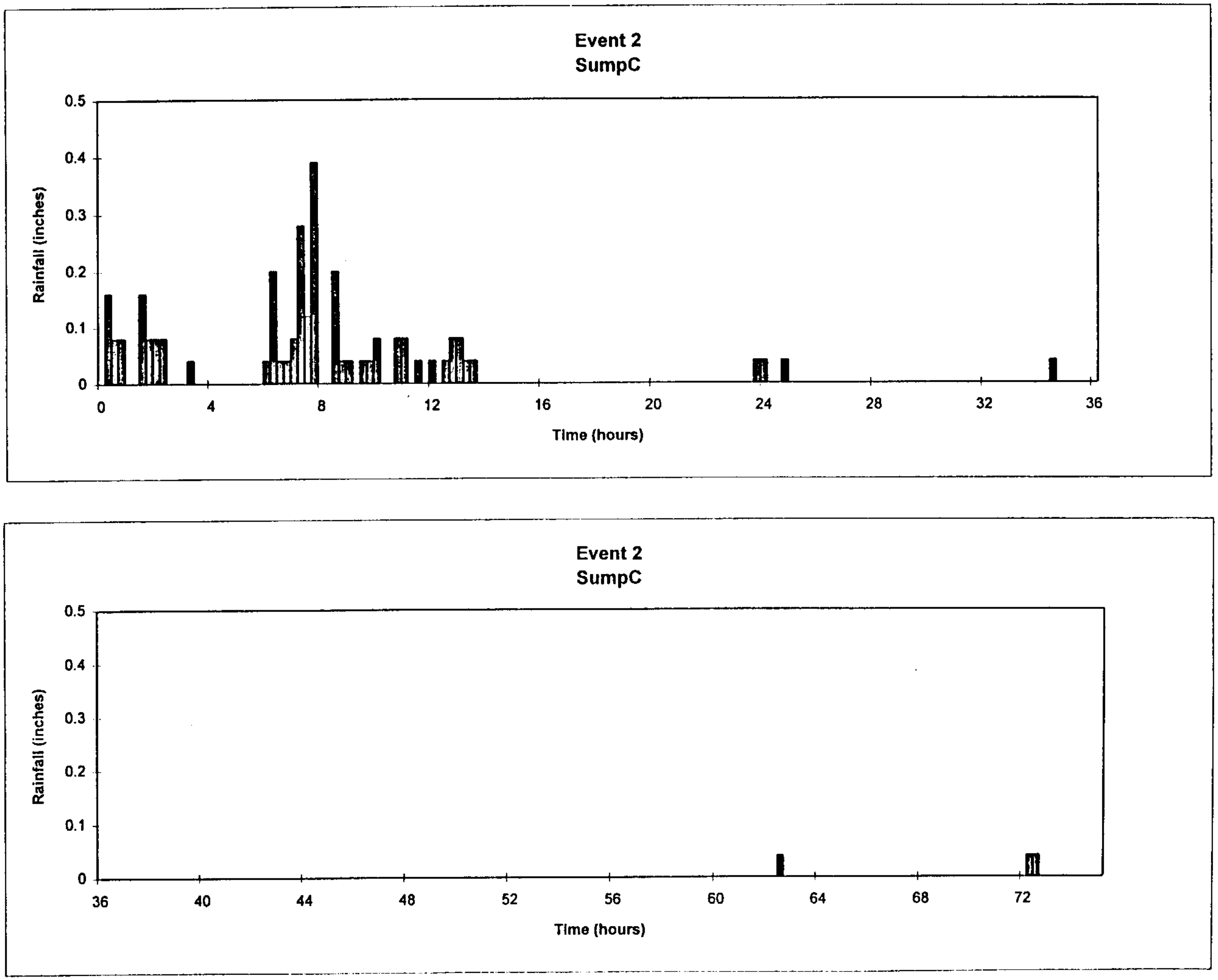


Figure 6: Rainfall Record for Sump C – Event 2 (3/12/95-3/17/95)

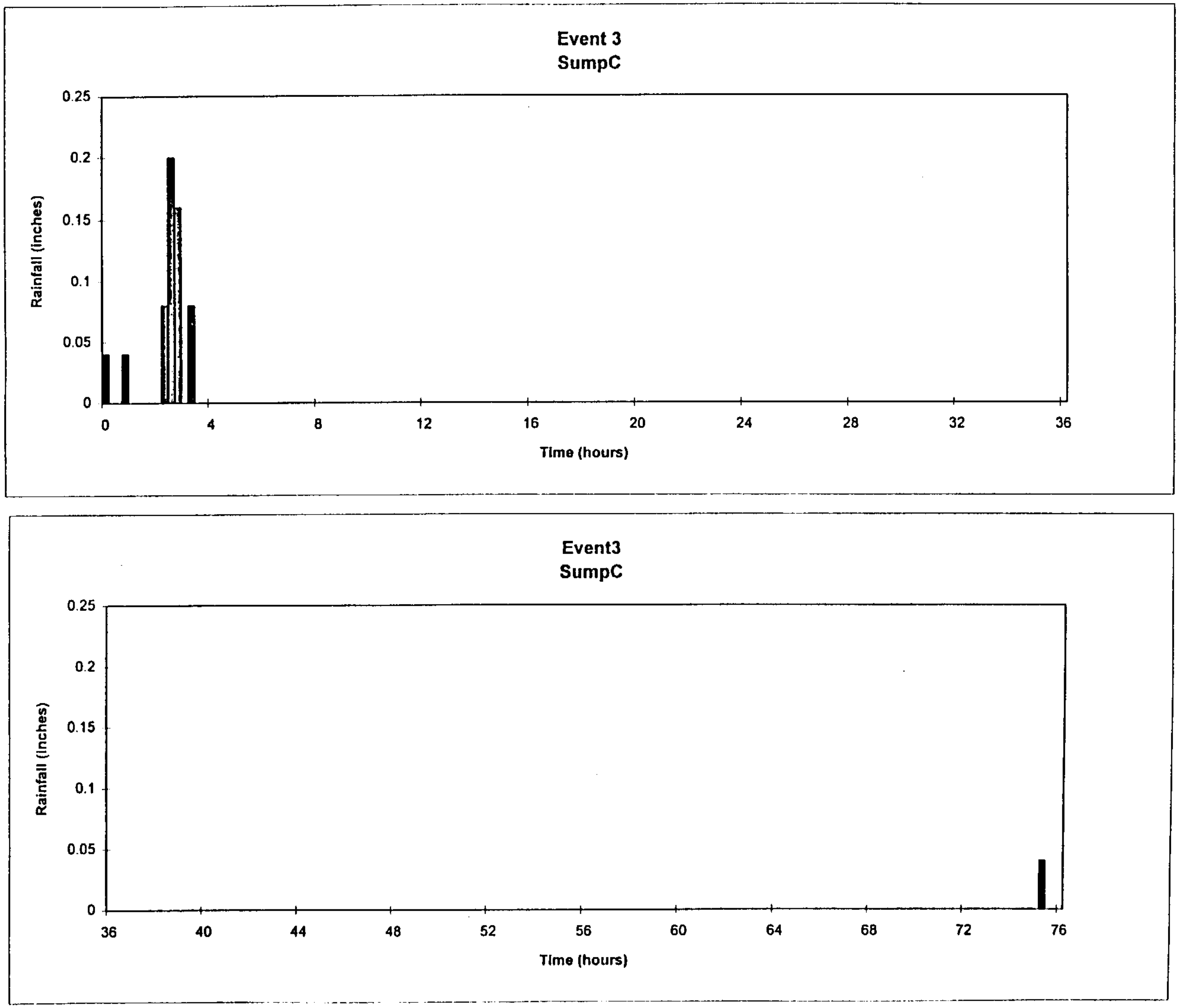


Figure 7: Rainfall Record for Sump C - Event 3 (4/10/95-4/14/95)

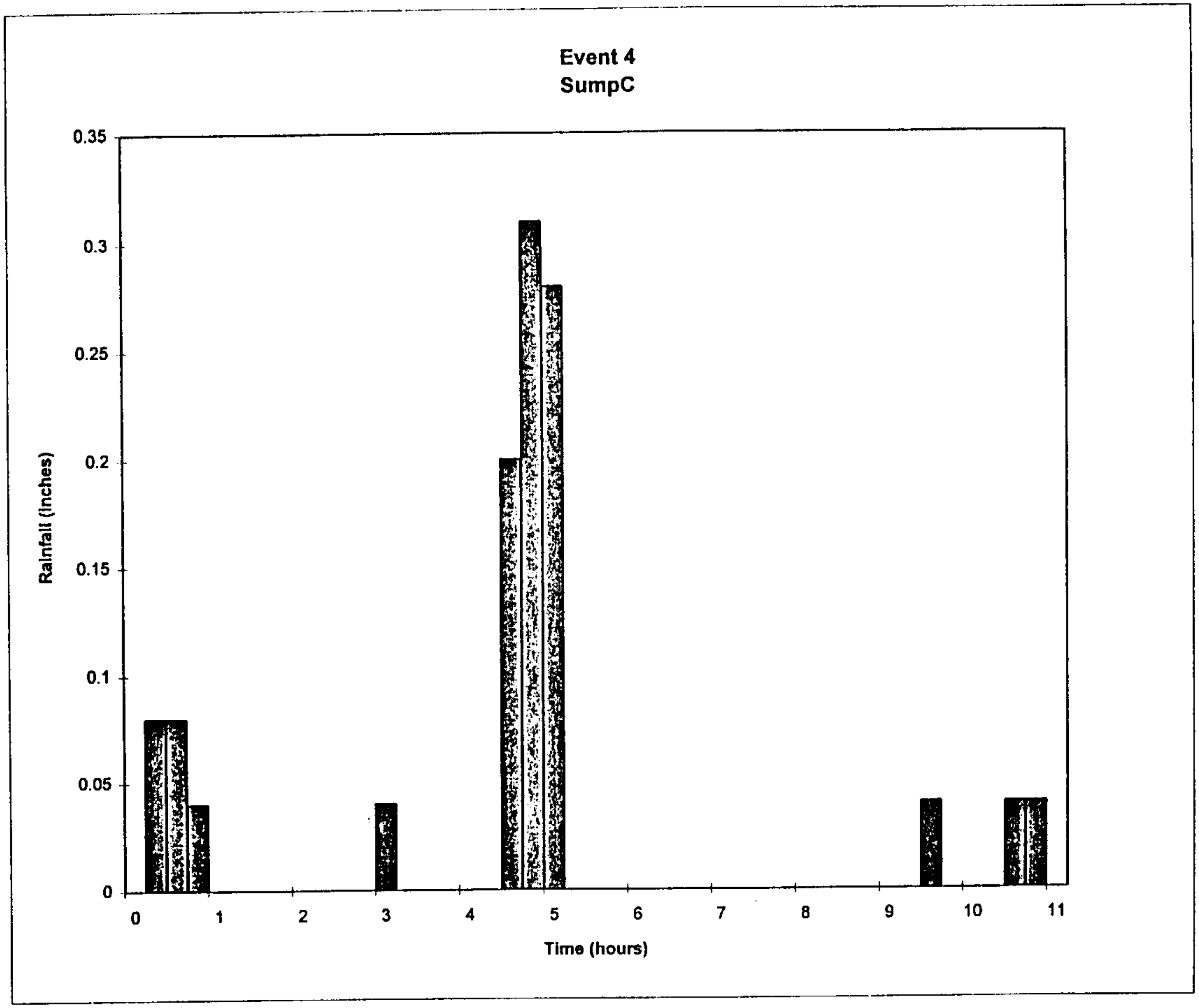


Figure 8: Rainfall Record for Sump C – Event 4 (7/5/95-7/10/95)

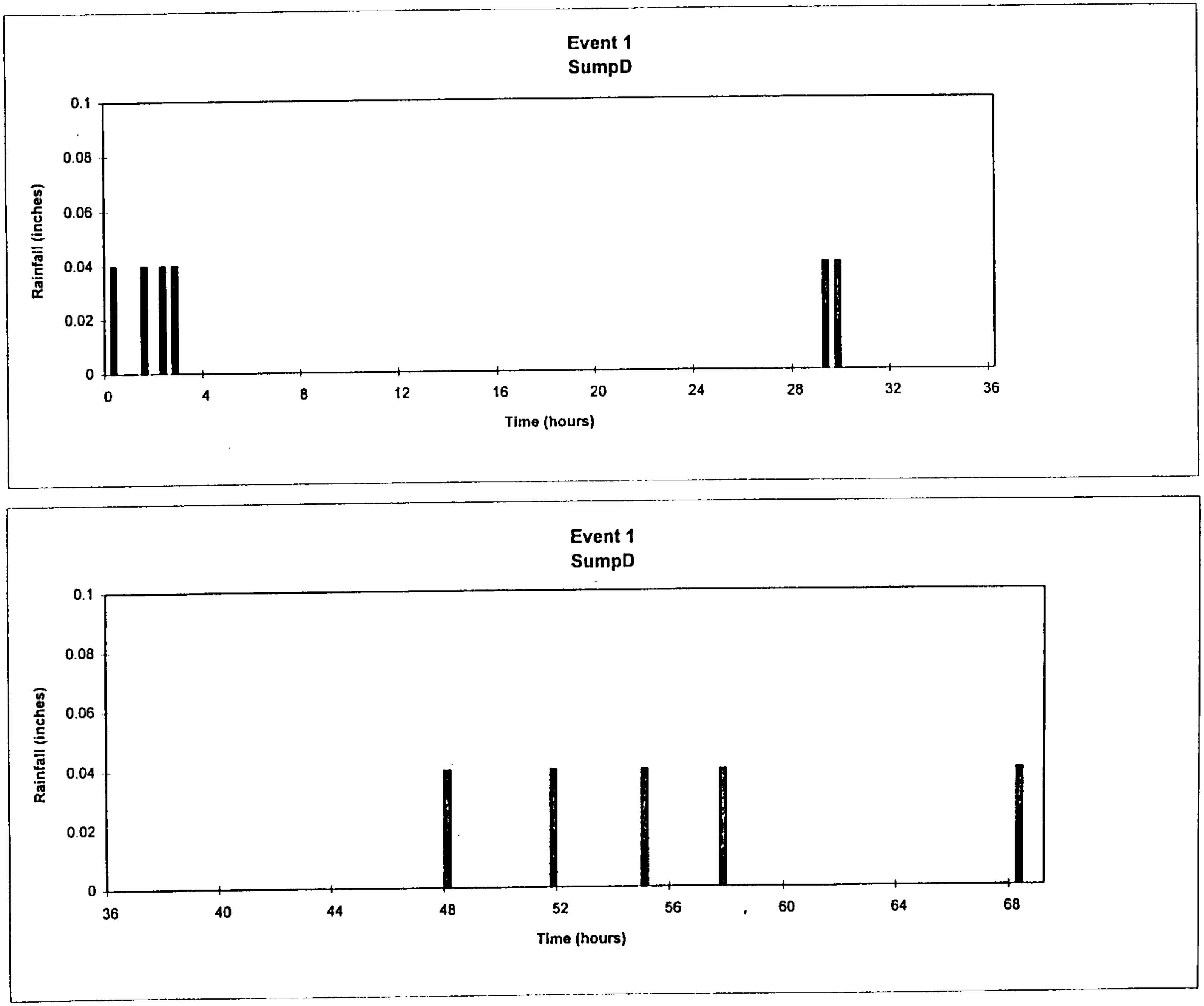


Figure 9: Rainfall Record for Sump D – Event 1 (2/28/95-3/6/95)

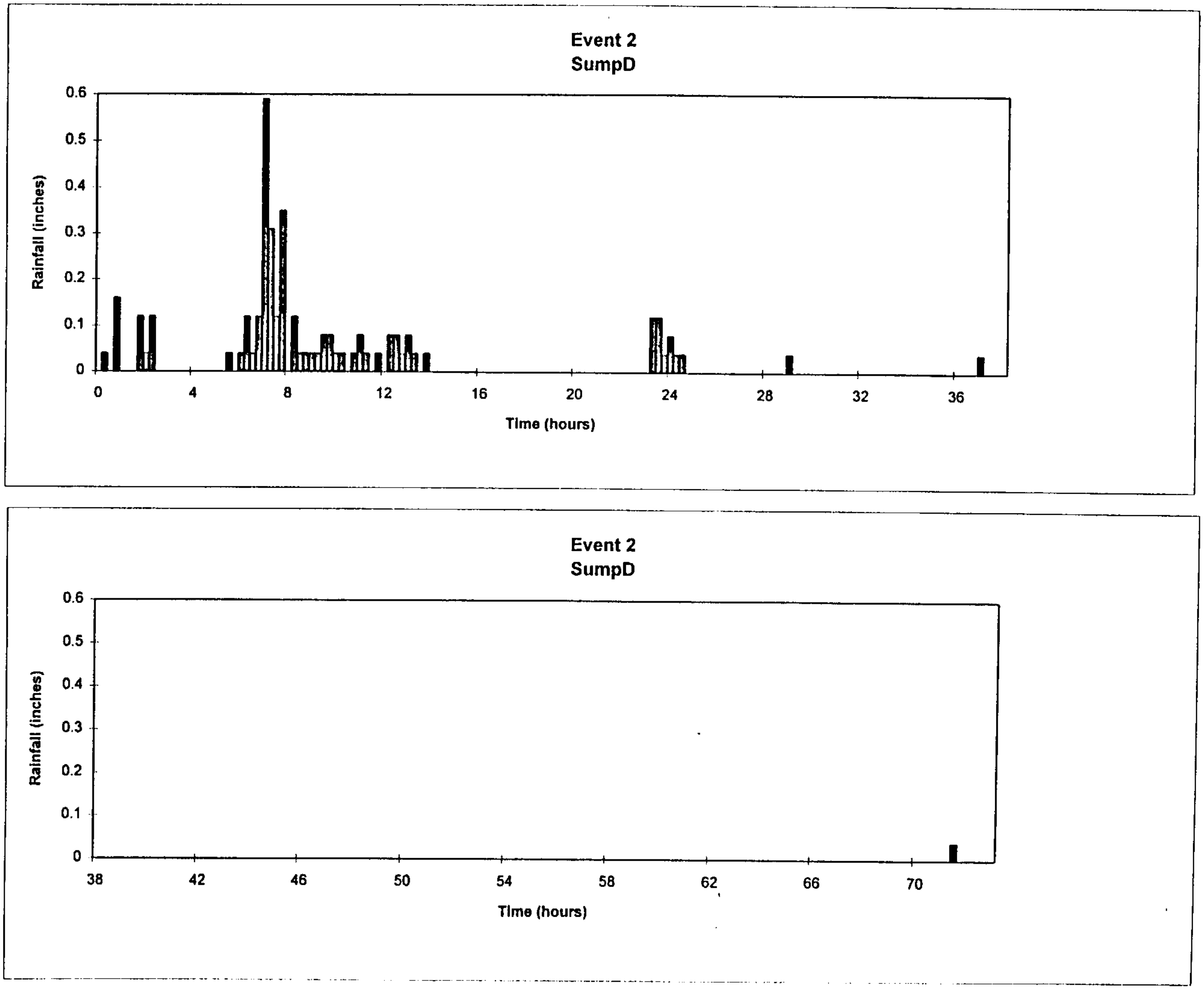


Figure 10: Rainfall Record for Sump D   Event 2 (3/12/95-3/17/95)

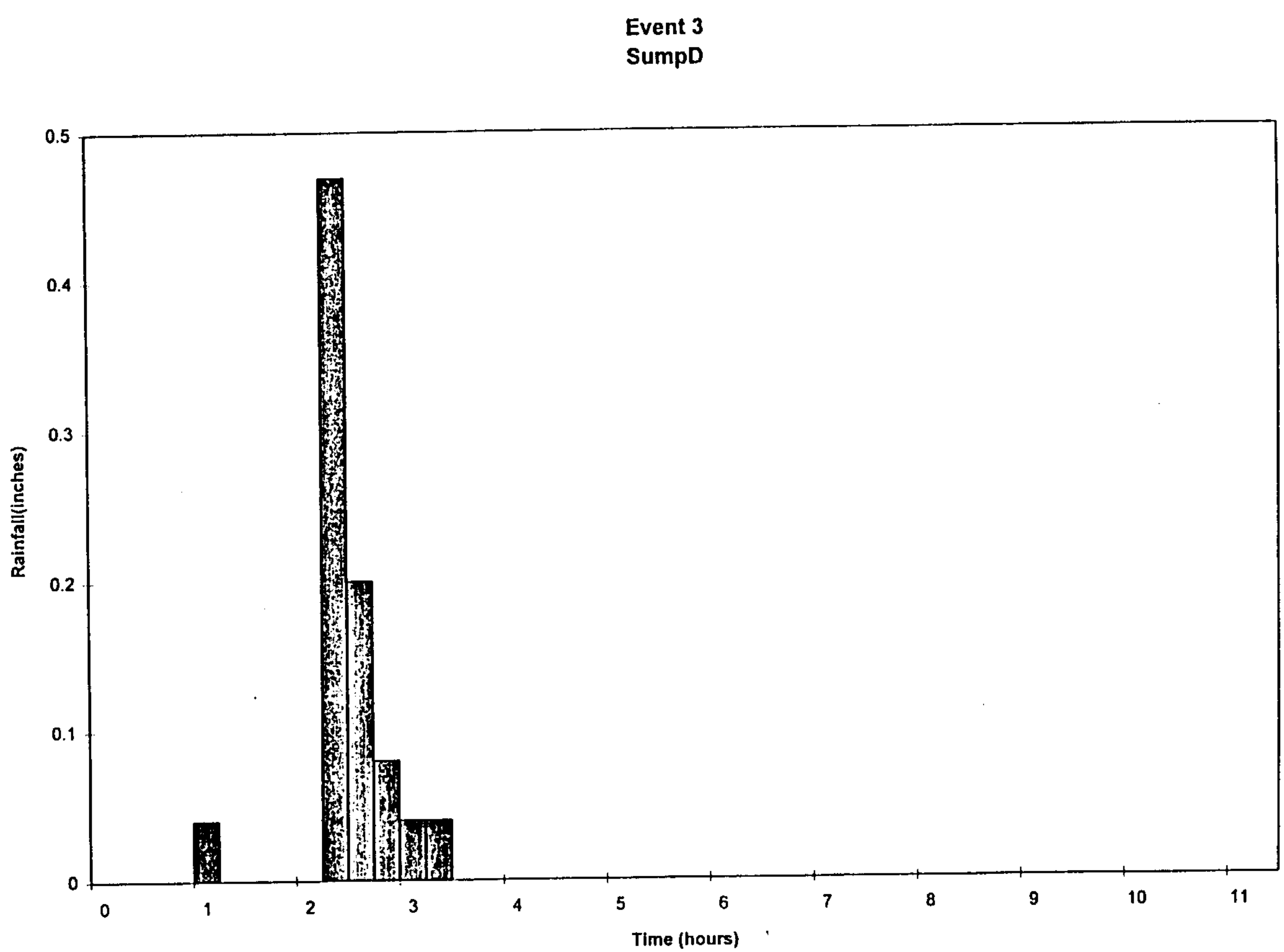


Figure 11: Rainfall Record for Sump D – Event 3 (4/10/95-4/17/95)

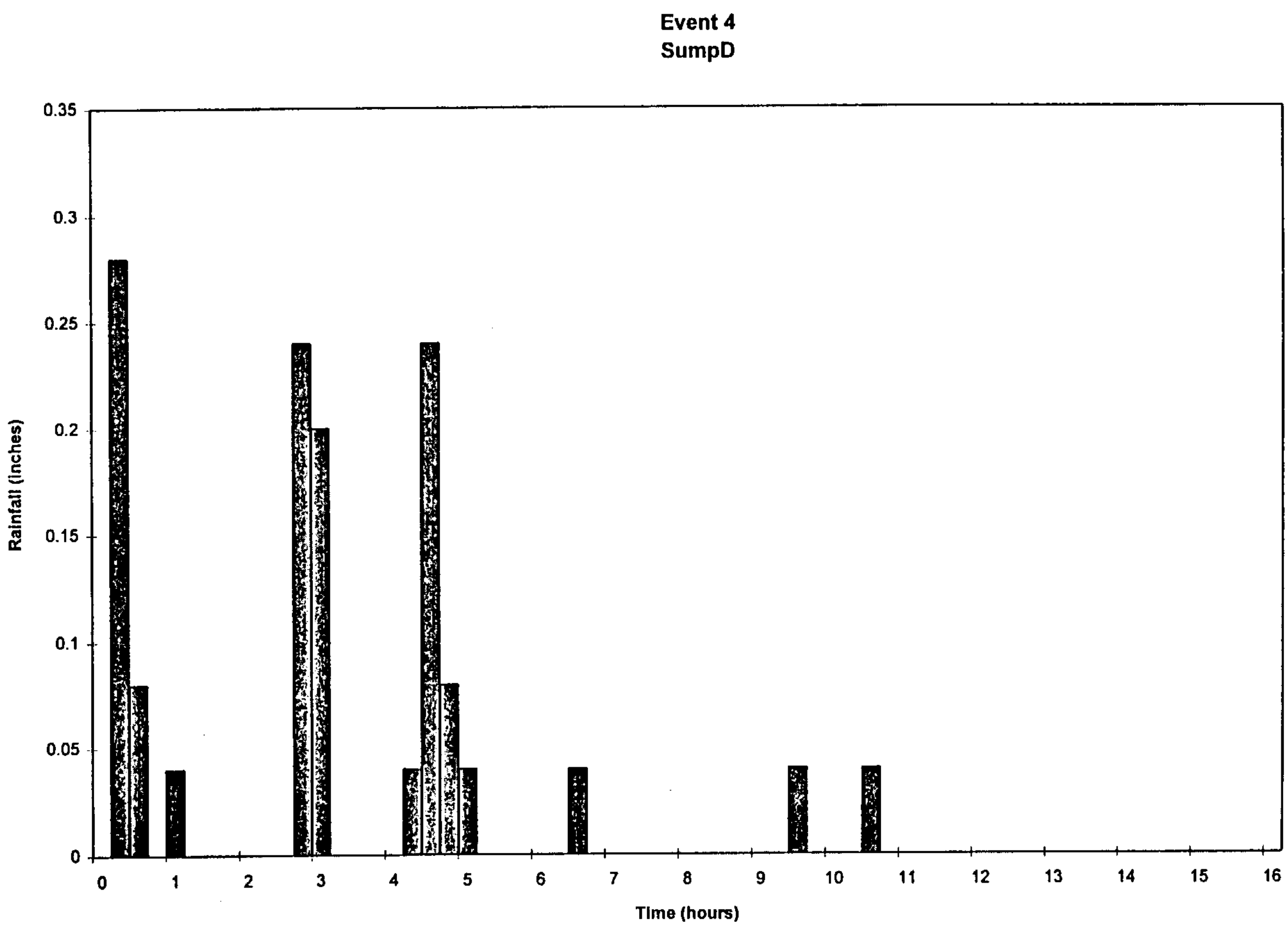


Figure 12: Rainfall Record for Sump D – Event 1 (7/5/95-7/10/95)

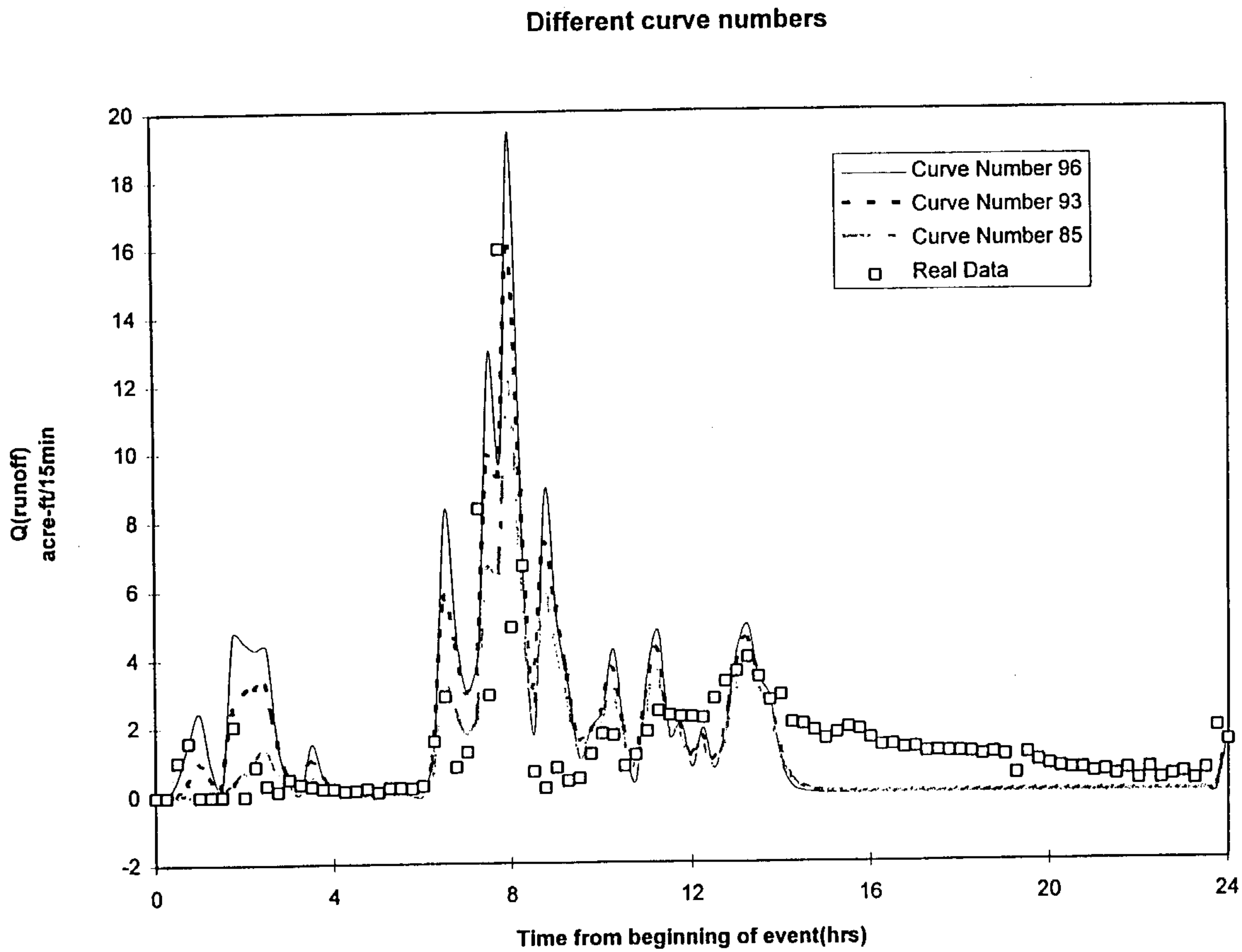
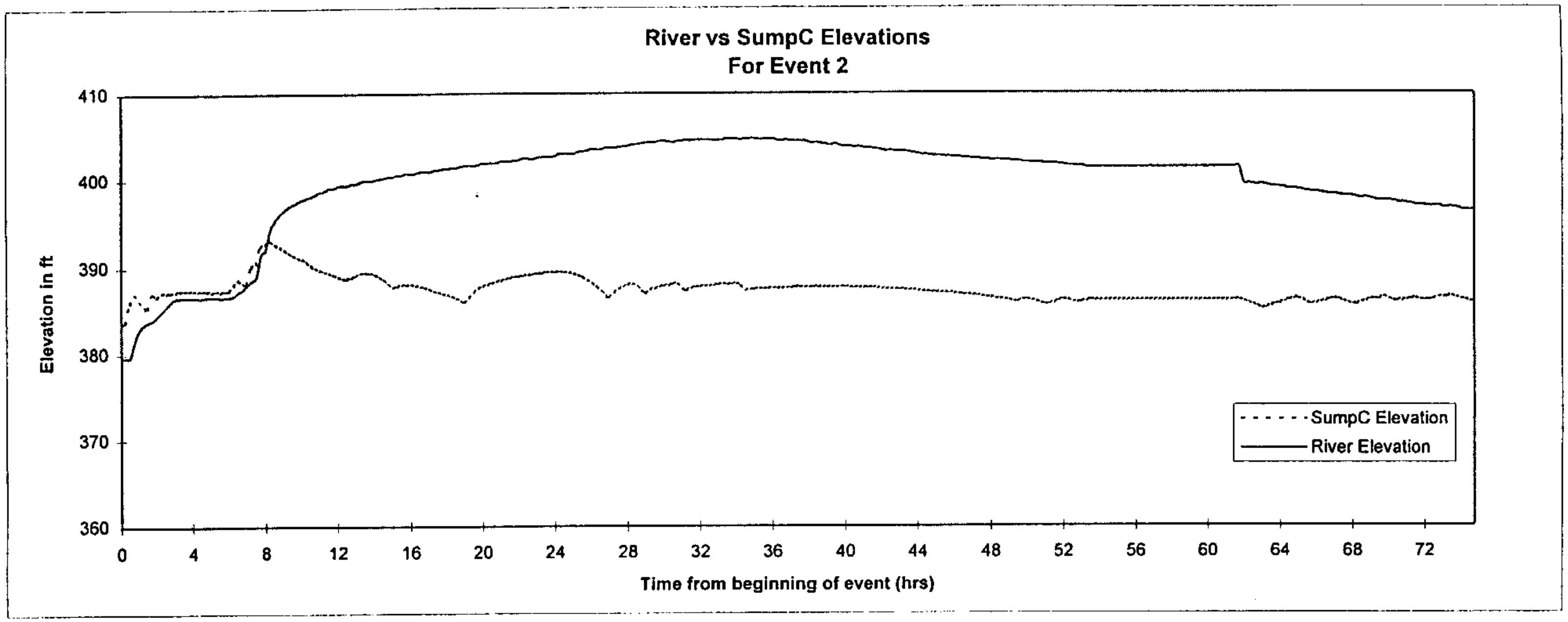


Figure 13: HEC-1 Total Runoff Hydrograph for Sump C and Event 2 Showing Sensitivity to Curve Number.



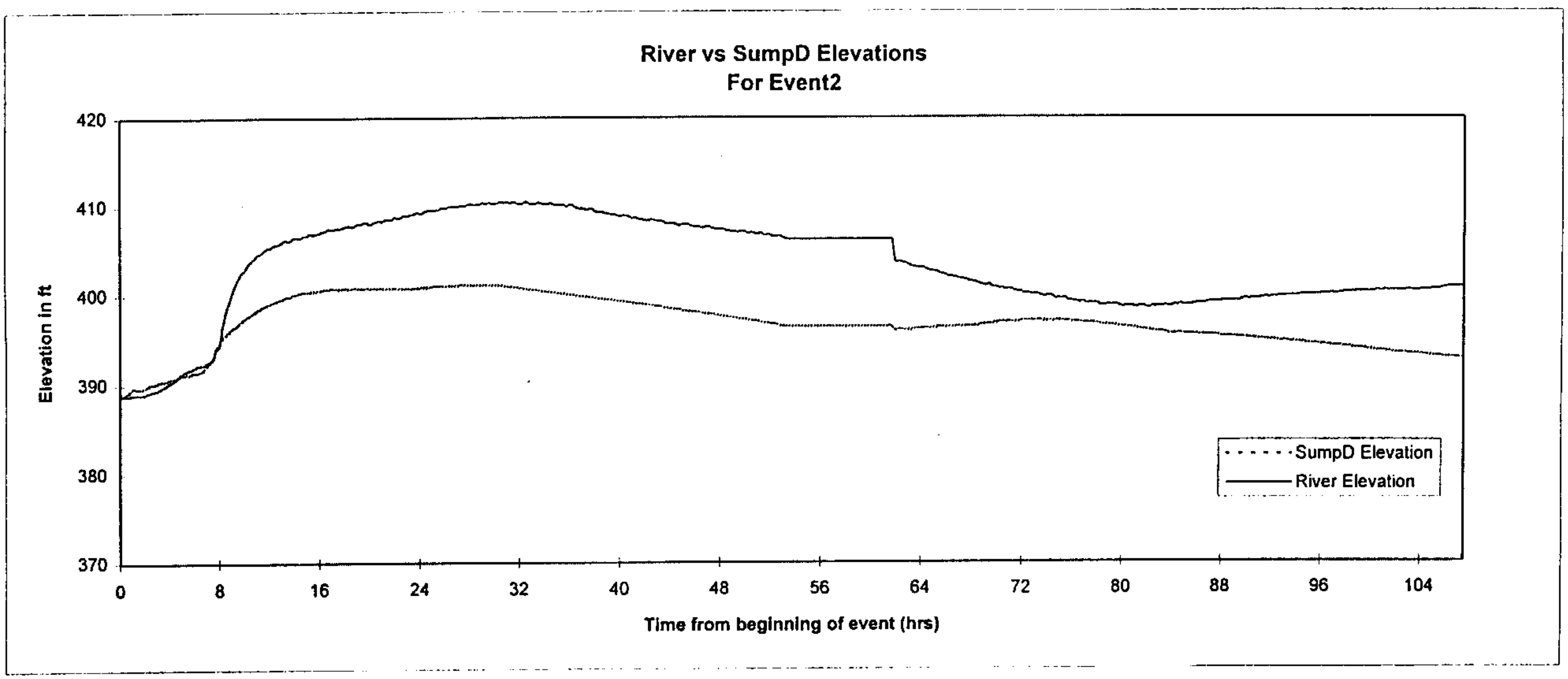


Figure 14: Sump Versus River Elevations for Event 2, Sumps C and D.

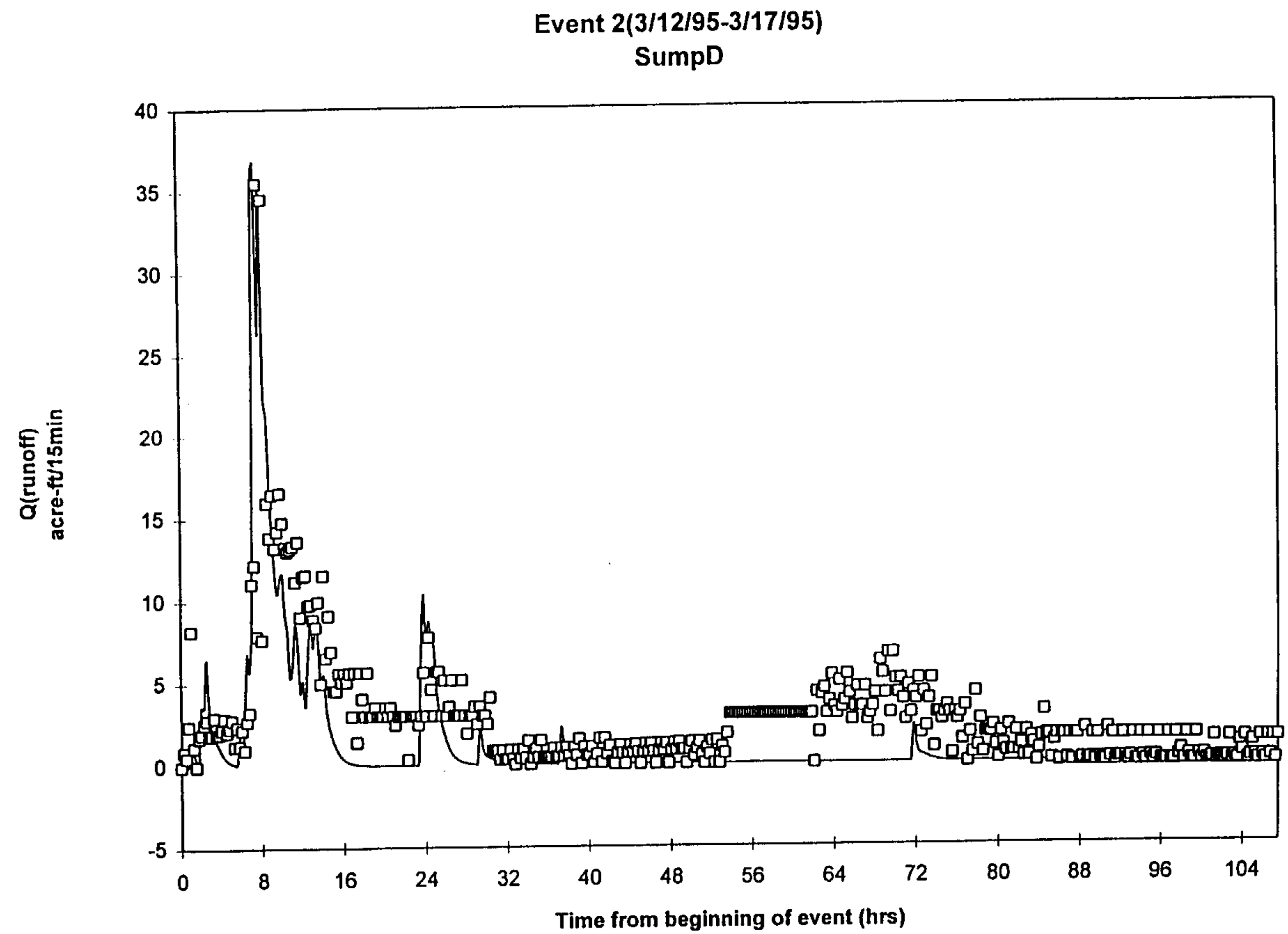


Figure 15: Total Runoff Hydrograph to Sump D for Event 2. Symbols Represent Water Balance Calculation *Without* Consideration of Miscellaneous Water Gains.

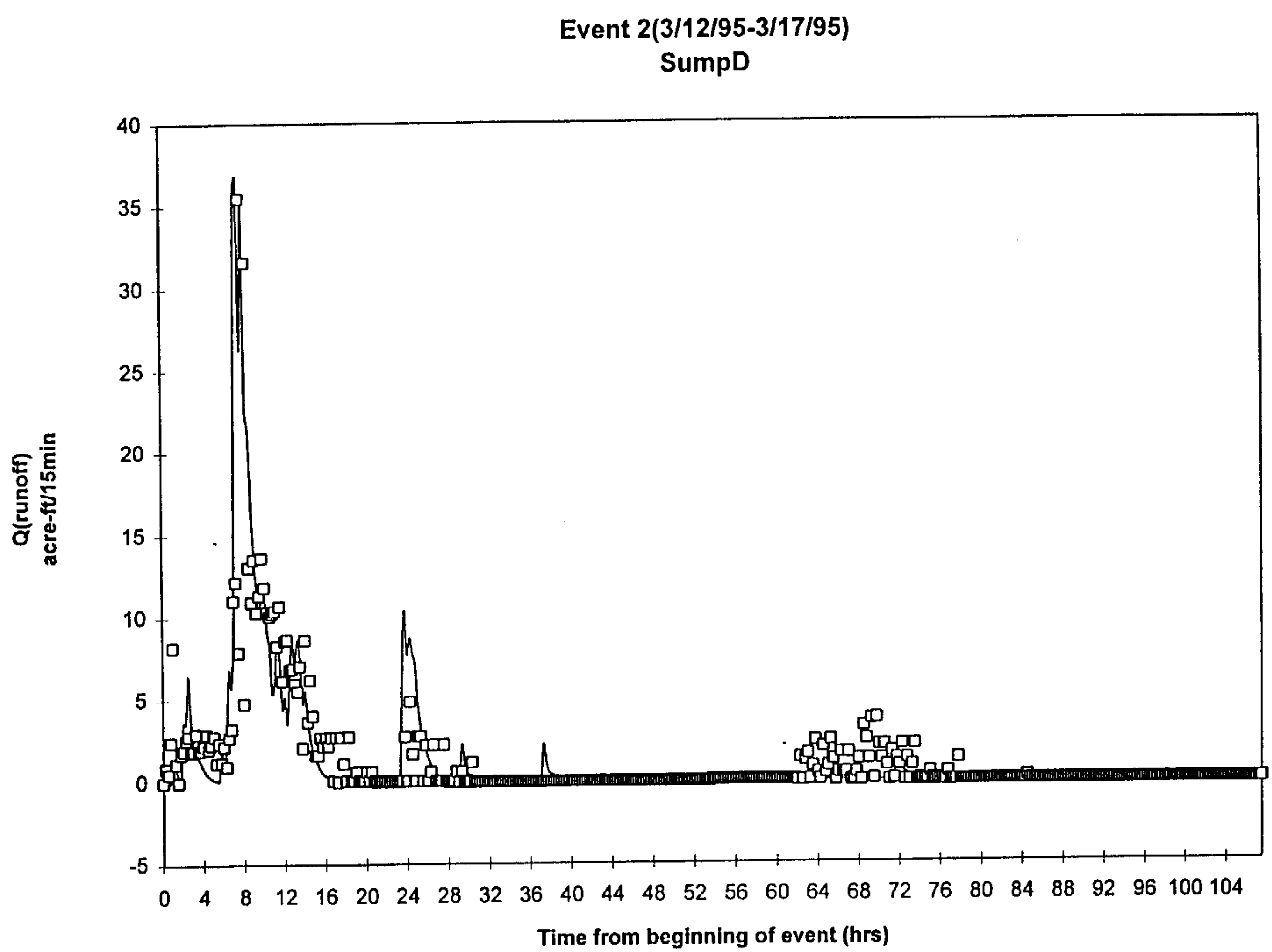


Figure 16: Total Runoff Hydrograph to Sump D for Event 2. Symbols Represent Water Balance Calculation *With* Consideration of Miscellaneous Water Gains. Solid Line is HEC-1 Simulation.

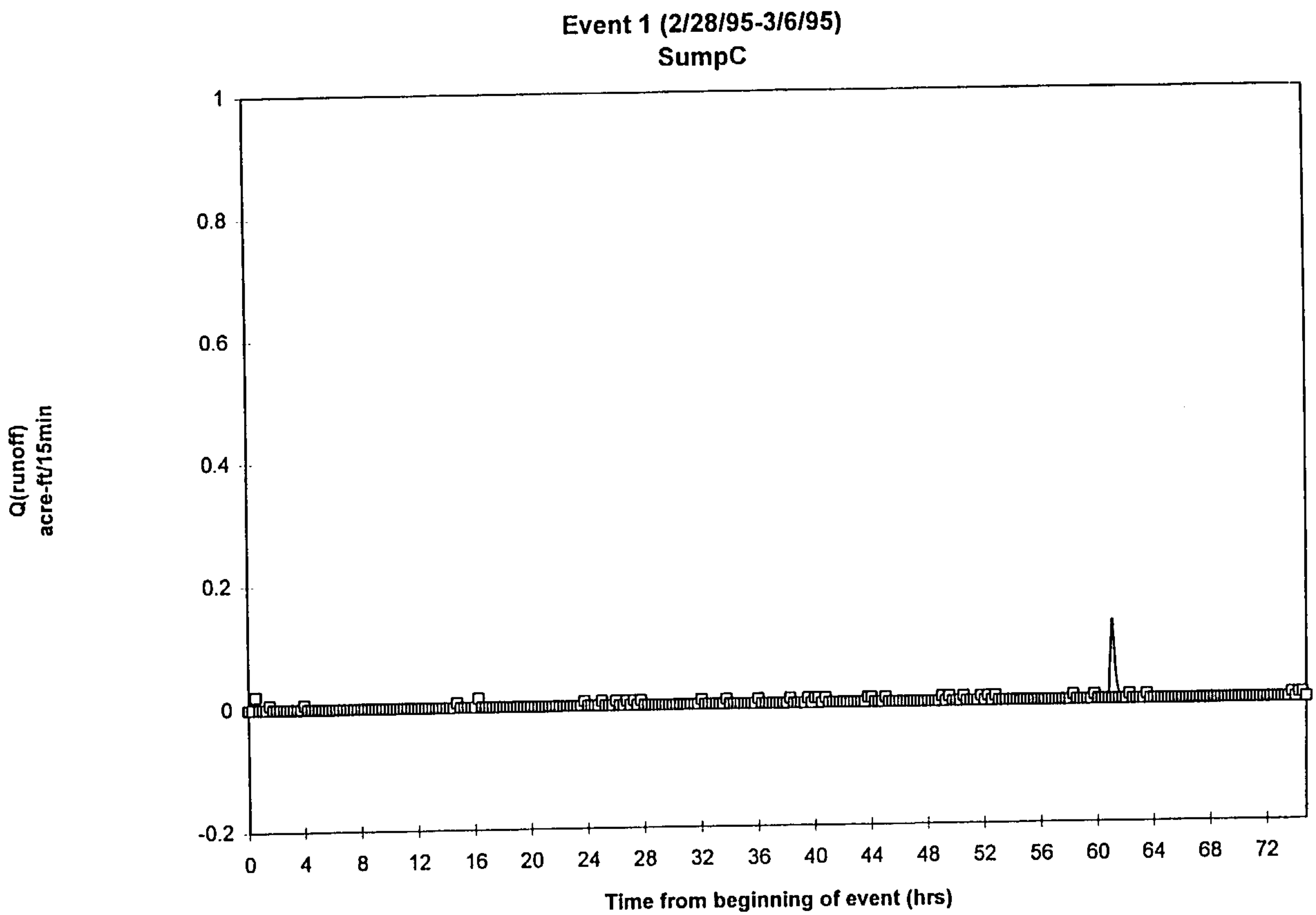


Figure 17: Total Runoff Hydrograph to Sump C for Event 1. Symbols Represent Water Balance Calculation. Solid Line is HEC-1 Simulation.

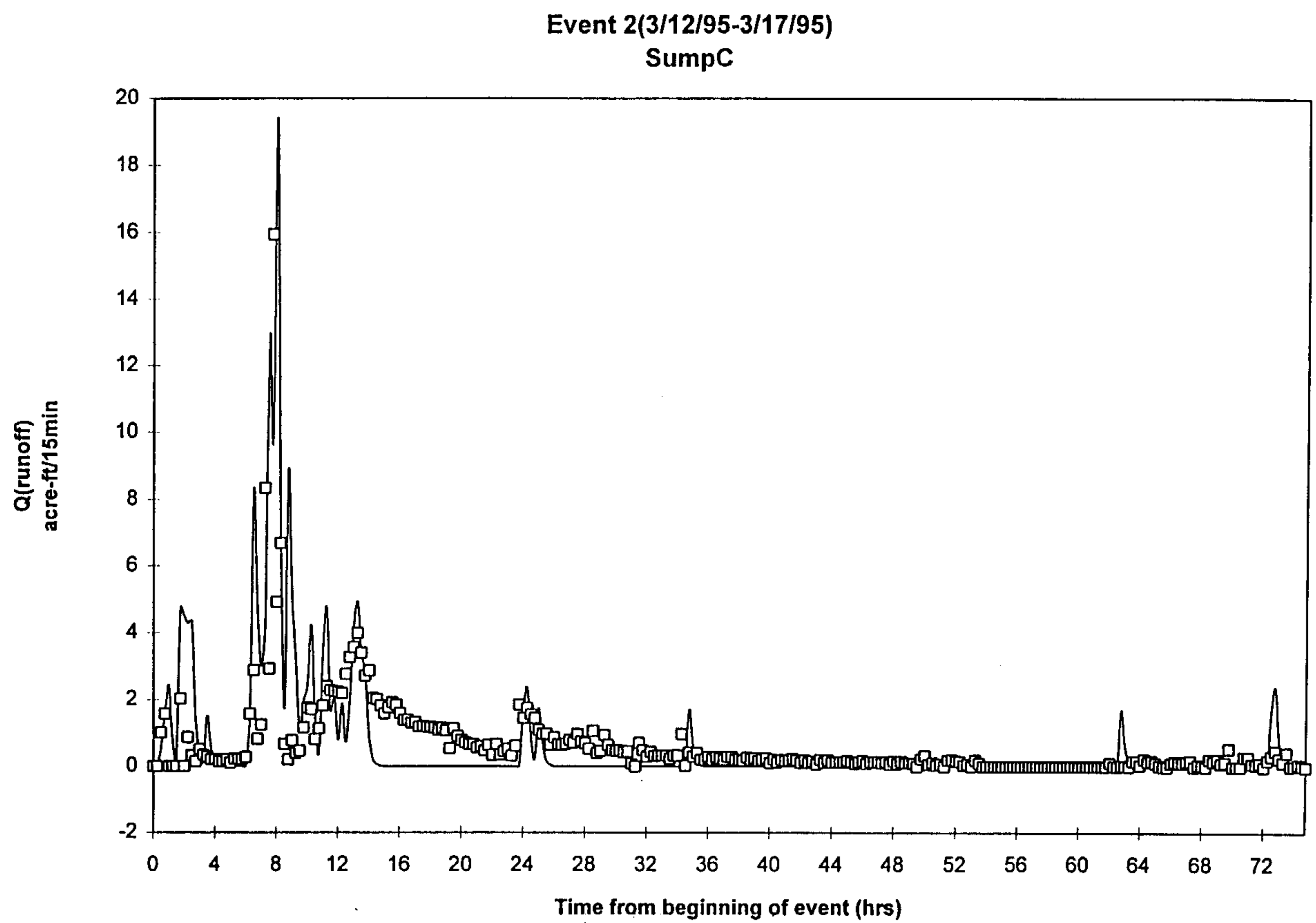


Figure 18: Total Runoff Hydrograph to Sump C for Event 2. Symbols Represent Water Balance Calculation. Solid Line is HEC-1 Simulation.

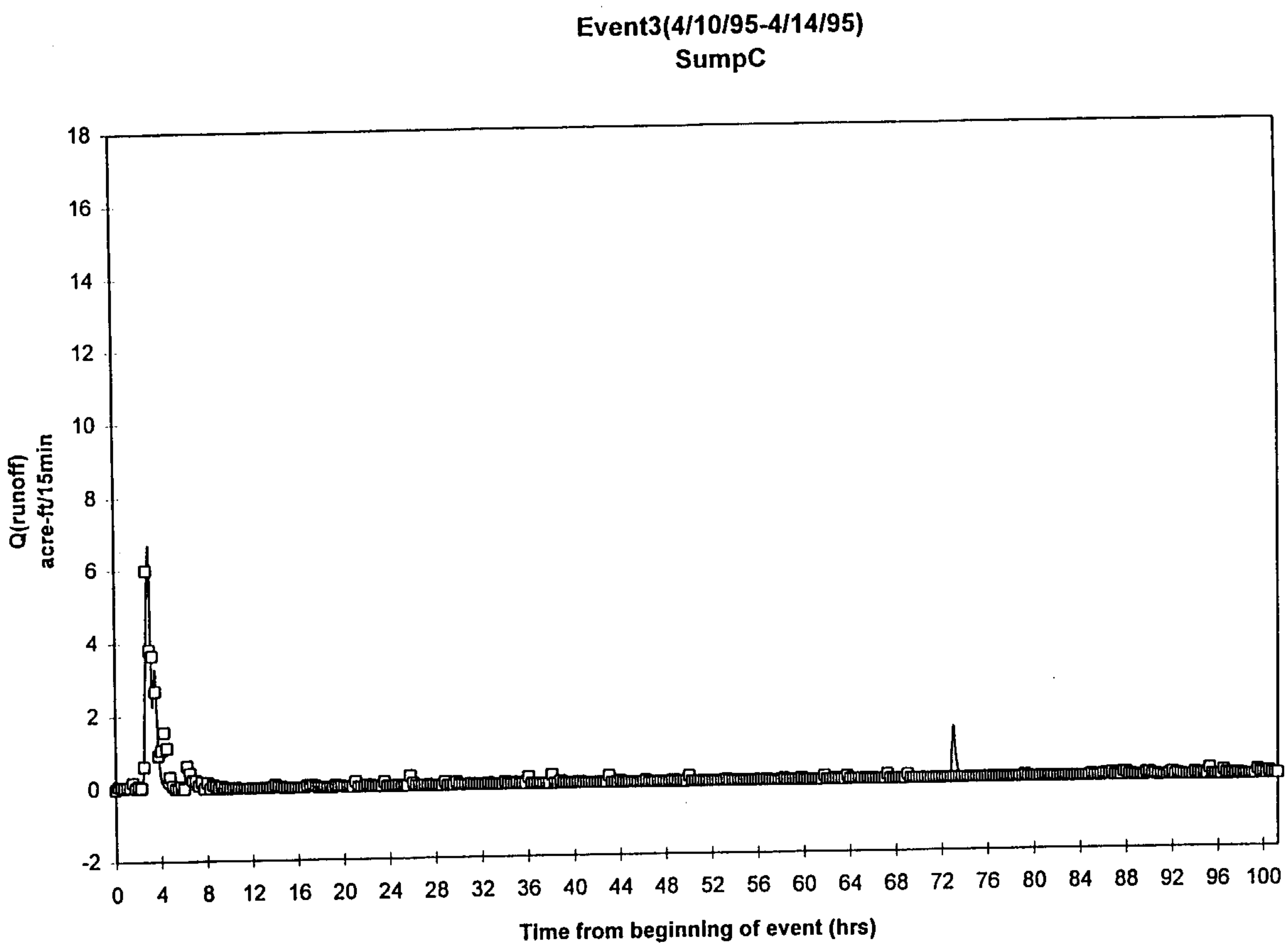


Figure 19: Total Runoff Hydrograph to Sump C for Event 3. Symbols Represent Water Balance Calculation. Solid Line is HEC-1 Simulation.

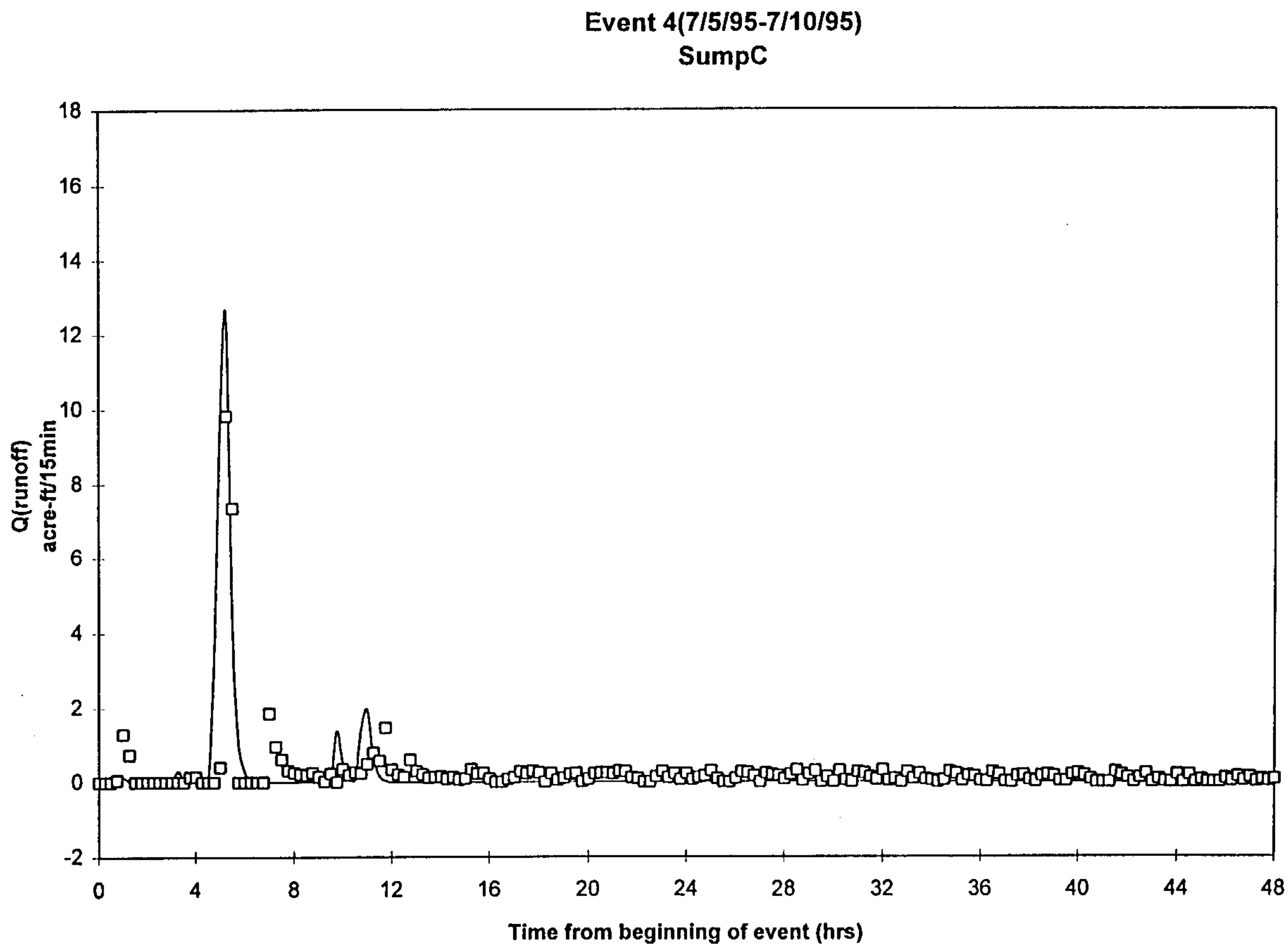


Figure 20: Total Runoff Hydrograph to Sump C for Event 4. Symbols Represent Water Balance Calculation. Solid Line is HEC-1 Simulation.

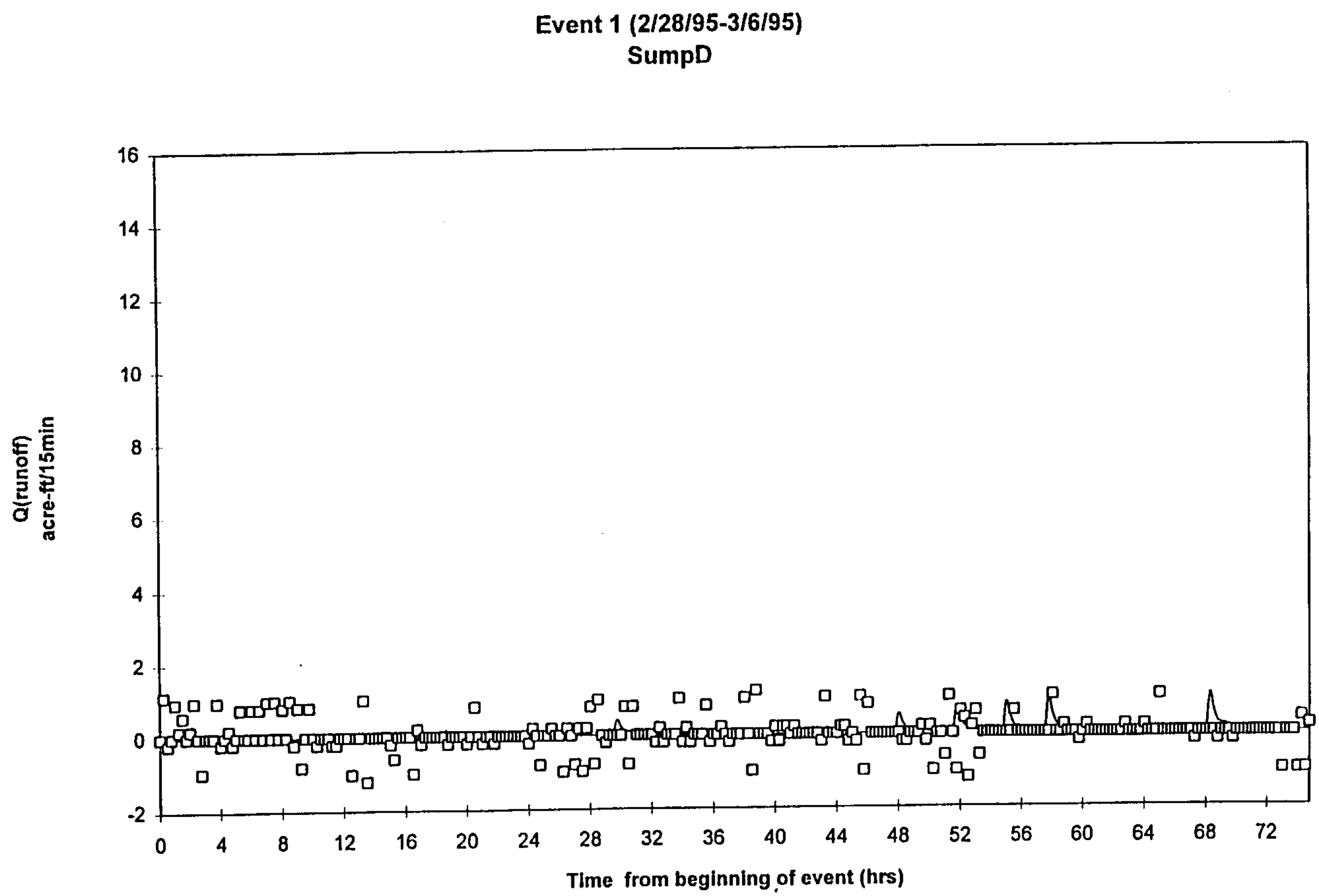


Figure 21: Total Runoff Hydrograph to Sump D for Event 1. Symbols Represent Water Balance Calculation. Solid Line is HEC-1 Simulation.

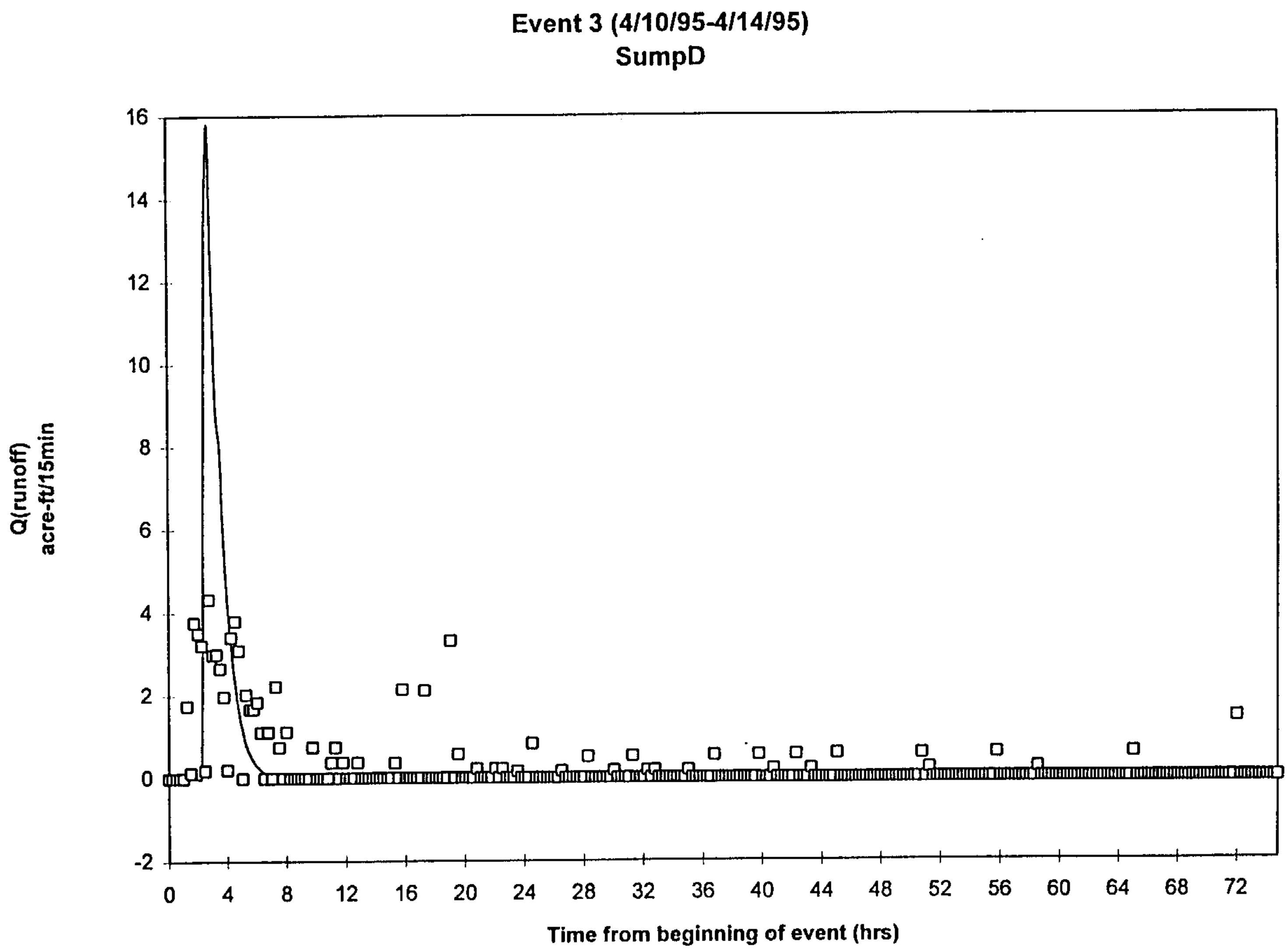


Figure 22: Total Runoff Hydrograph to Sump D for Event 3. Symbols Represent Water Balance Calculation. Solid Line is HEC-1 Simulation.

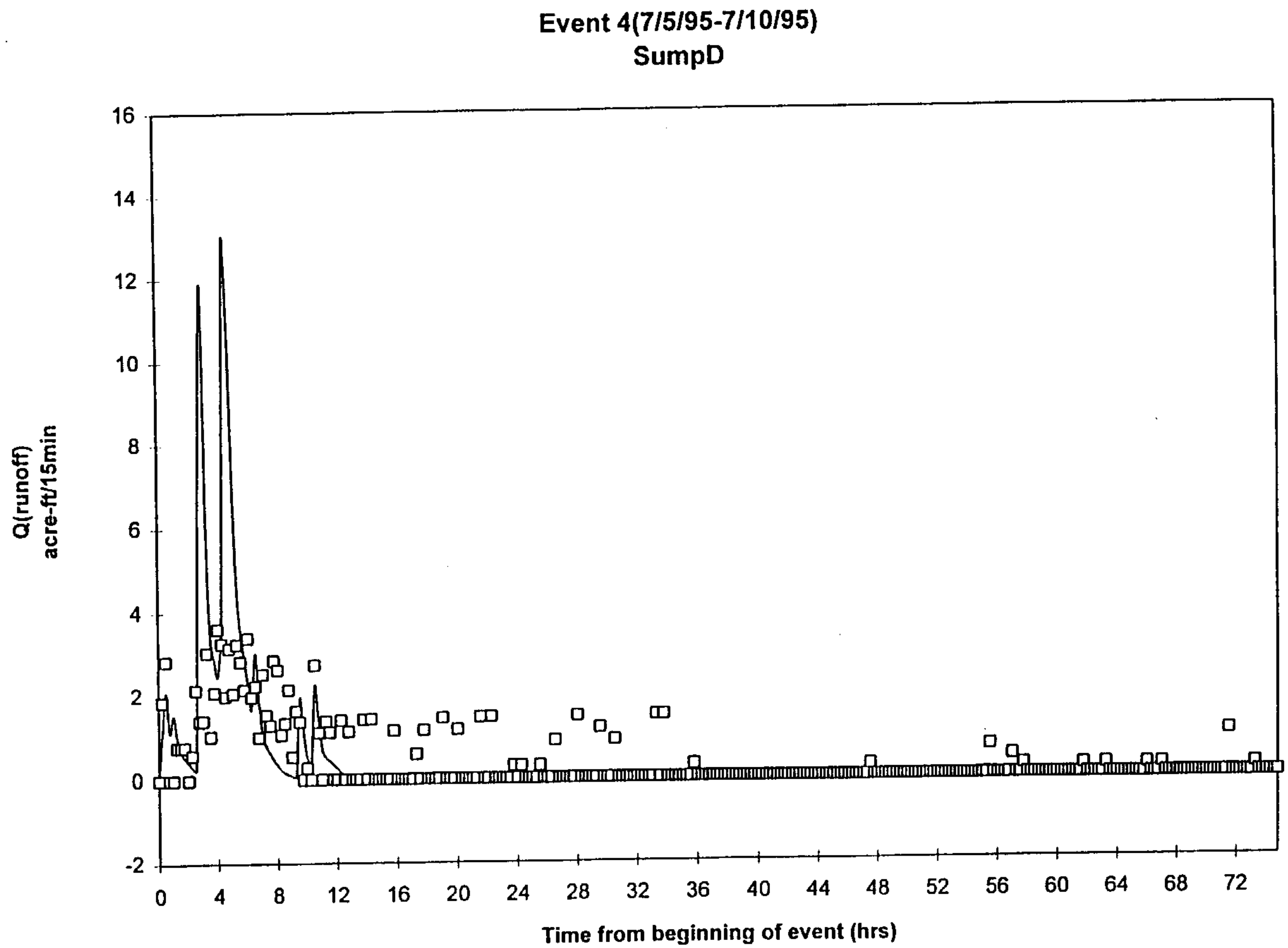


Figure 23: Total Runoff Hydrograph to Sump D for Event 4. Symbols Represent Water Balance Calculation. Solid Line is HEC-1 Simulation.

3.2 Pollutant Analysis

As noted previously, the number of events and parameters sampled was constrained by the budget for chemical analyses of stormwater and sediment samples. To test for the required constituents in a format that might allow estimation the treatment efficiency of the sumps, the number of project events was limited to four, corresponding to Events 1 through 4 described in the hydraulic modeling section above.

3.2.1 Stormwater Quality

Tables 14 through 17 contain stormwater analyses of the four study events for Sumps C and D and the sampled outfalls. A sampling station designation key preceeds the tables. Some observations pertaining to specific stormwater quality parameters are summarized in the following.

pH and Temperature

pH for the four sampled events was in a range typical of natural surface waters with minimum and maximum values of 6.21 and 8.64, respectively. On average, values were slightly higher in Sump D than C, although this difference is not evident in outfall data. The winter-spring events, one and two, exhibited generally higher values than the spring-summer events, three and four. The reasons for this trend are not obvious, but may be related to several processes; for example: (1) more water observed being present in the sump system at the start of the winter-spring events versus the dryer spring-summer period resulting in dilution of more acidic runoff, and (2) increased biological activity during the warmer spring-summer period resulting in increased production of aqueous CO_2 and associated elevated acidity. In addition, the pH in the sumps tended to peak within the first ten hours for the earlier events, while in Event 4 the values appear to sag with the maximum pH attained at the end of the event. Where data is available, there appears to be some correlation between pH and temperature for the sump samples for a given event. This would appear to be most attributable to diurnal variations, and may be related to photosynthetic activity that consumes CO_2, thereby increasing pH, during the day; and the corresponding buildup of aqueous CO_2 at night when photosynthesis is at a minimum. The pH-Temperature correlation is depicted in Figure 24. Temperature values ranged from 11-18, 13-22, and 22-32 °C for Events 2, 3, and 4, respectively.

Solids

Total suspended solids (TSS) concentrations in the sumps exhibited several intuitive patterns. Values tended to peak fairly early in the event when runoff to the sumps was generally highest. The timing of the peak from the start of the event tended to occur later in Sump D than C, doubtless related to the larger size and hydraulic detention time of Sump D. A related phenomenon was higher peak values achieved in Sump C (over the background value) versus Sump D. These trends are similar to those observed from data collected for the target sumps in a 1988-89 stormwater runoff study (Davis, 1994).

TSS peak values in Sump C were proportional to the magnitude of the event with a high of ~1,600 mg/L for Event 2 with a rainfall of 3.8 inches. The only exception to this was Event 1 which had a slightly higher peak value than Event 3 even though the rainfall was considerably less. Possible reasons for this are that: (1) Event 3 occured in the context of substantial antecedent moisture compared to Event 1, and (2) the time intervals between samples are sufficient such that the peak TSS may have been missed, particularly in Sump C (the data from the 1988-89 study referred to above lends support to this possibility). A case could be made for the same trend in Sump D although, as noted above, peak values are greatly dampened by the large volume / detention time of the sump. Event 4 data exhibits the highest TSS values for Sump D, even greater than those attained during the highest runoff event (Event 2). However, the difference between the peak and the background value is approximately the same for the two events. Furthermore, Event 4 occured after a lengthy dry period in the summer, suggesting the greater availability of surface particulates and dust, and the original sump level was lower than usual implying a decreased dilution of stormwater inflows. The rise and fall of TSS versus time is indicative of time-variations in pollutant concentrations in stormwater outfalls to the sump. It may also be evidence of solids removal in the sump as a result of detention.

Outfall values suggest that first-flush samples do not necessarily provide an accurate basis for computing pollutant loads to the sumps. In 7 of 8 cases for the two outfalls sampled for Sump C, the second outfall sample had greater TSS concentrations than the first flush. The relative percent difference between readings ranged from 18 to 196 percent with an average of 116 percent (note that the maximum value by this method is 200 percent). The most extreme values were for the 98-inch pipe at drainage area 12. For Sump D outfalls, RPDs between readings were considerably less, ranging from 14 to 158 percent with an average of 75 percent. The highest variations were always were always at the Fishtrap Channel outfall in drainage area D10. There was no substantive difference in estimate TSS loadings per unit area as given in Table 18.

As anticipated, volatile suspended solids (VSS) measurements followed the general trends of TSS; namely, (1) peaking that roughly coincides with the timing of peak runoff; (2) peak values higher for Sump C than D; and, (3) the highest peak values occuring for Sump C for the highest magnitude event (i.e., Event 2). Figure 25 illustrates the relationship between TSS and VSS for the 90 stormwater samples analyzed.

Total dissolved solids measurements exhibited little in the way of recognizable trends. With some exception in Event 1, sump values appear to sag with time between 10 and 24 hours before increasing over the remainder of the event.

Settleable solids is typically utilized for the assessment of wastewater rather than stormwater. However, since it is hypothesized that the bulk of pollutant removals in sumps is due to particulate settling, settleable solids may lend insight into the nature and extent of this mechanism. Although the magnitudes are relatively low, the sump values indeed suggest a significant correlation between the total solids and the amounts that are readily settleable. Excluding the pre-event samples, the peak settleable solids value corresponded with the peak TSS sample in 8 of 8 cases. With the exception of Event 3, the results suggest that a low level of removal of pollutants *via* settling may continue in the sumps well beyond the termination of appreciable runoff. Figures 26 and 27 illustrate the variation with time and correlation between TSS, VSS, and settleable solids concentrations in Sumps C and D, respectively, for the maximum runoff event (Event 2).

Organics

Surrogate organic parameters in addition to VSS were examined. COD, BOD, and TOC were analyzed for Events 1 and 2, but only COD in Events 3 and 4. Figures 28 and 29 compare the sump concentrations with time for COD, BOD, and TOC for Event 2. The shape of the COD curves is similar to the pattern of solids concentrations, especially in the case of Sump C, with runoff-corresponding peak concentrations followed by decreasing values throughout the remainder of the event that approach the pre-event concentration. Once again Sump C peak values are much greater than those measured in Sump D, while steady-state values are similar. Interestingly, BOD concentrations do not follow either of these trends. In both sumps the peak values do not occur until 40 to 60 hours from the beginning of the event. This is a departure from data collected in the 1988-89 study (*Ibid.* in which the trend of BOD concentrations followed that of TSS. Sump D analyses (Figure 29) do indicate an initial peak corresponding to runoff/solids peak time, but this is only half of the value achieved at 40-60 hours. This phenomenon may be due in part to dilution by pre-event water in the sump and a lag time involved for exertion of BOD; however, this does not seem as feasible for Event 2 in which the large quantity of water keeps the sumps well flushed. The maximum BOD value of 40 mg/L was the same for both sumps. TOC concentrations did not vary significantly over the event. For this event, the trends for Sump C outfall concentrations of COD and BOD tended to follow those of solids concentrations. In fact, Figure 30 illustrates that for the outfall designated C-2, there is a rather strong correlation between COD and TSS using data from all four sampled events. In other cases; for instance, sampling station D-2; COD concentrations demonstrated an inverse proportionality to TSS, illustrating the diverse nature of sources of oxidizable organic material. As with solids, the largest variations between first-flush and later outfall sample concentrations occured in outfall C-3. The observed variabilities illustrate some of the limitations of stormwater monitoring, namely: (1) that the sampled outfalls may be unrepresentative of organic loading over the basin as a whole, and (2) typically the results do not delineate the contributions of stormwater versus other nonpoint and/or point source pollution in the system. Small concentrations of the pesticide chlordane were detected in a few samples in both Sumps and outfalls during Event 2.

Nutrients

Nutrient concentrations in Sumps C and D are presented in Figures 31 and 32 for Event 2. Nitrate levels in both sumps followed a pattern similar to BOD with peak values recorded between 40 and 60 hours from the beginning of the event (Figure 31). Maximum values were between 5 and 6 mg/L, an order of magnitude greater than concentrations measured in the 1988-89 study. Total Kjeldahl nitrogen values remained essentially constant throughout the event. Measured values were between 1.3 and 4.6 mg/L, consistent with the above-referenced study. Nitrite was not detected in any of the samples. Outfall concentrations of nitrogen compounds were consistent with sump values and exhibited no distinctive trends.

Phosphorus concentrations in Sumps C and D for Event 2 are shown in Figure 32. The timing of peak values for total phosphate is more consistent with COD and solids. Moreover, Sump C peak concentrations are about twice those observed in Sump D. Peak values for ortho-phosphate were about 50 percent higher than background values with the observed peak occuring within 15 hours of the start of the event. For the two events in which phosphorus measurements were made, outfall concentrations for nutrients in general, and total phosphate in particular, were greater for sample station C-3 than C-2. This is also the case for station D-3 versus D-2.

Biologicals

Figure 33 depicts sump concentrations for Fecal Coliforms and Fecal Streptococcus for Event 2. Peak concentrations for both organisms are considerably higher and occur earlier in Sump C than D. In the case of Fecal Streptococcus, the difference would appear to be more than simply differences in hydraulic characteristics of the two sumps as outfall concentrations are much greater in Sump C stations than at Sump D outfalls. There is also a large difference between first-flush and later outfall samples for both events in which biologicals were measured; i.e., first-flush samples have little or no presence of fecal organisms versus relatively high counts in later samples. A possible explanation is the presence of substantial pre-event water in the outfall channels. The autosamplers are programmed to collect the first flush sample at a measurable increase in flow in the outfall that is detected by a depth sensor. It is conceivable that the initial runoff "pushes" pre-event water, containing low levels of fecal organisms, ahead of the runoff in the formation of a backwater profile in the channel resulting in the pre-event water predominating in the first flush sample. This suggests the need to collect more outfall samples at more closely spaced intervals in the sampling program. It also illustrates the uncertainty associated with obtaining representative stormwater pollutant loads using a single first flush sample.

Metals

Figures 34 and 35 show metal concentrations (for Pb, Zn, Cu, and As) as a function of time for Event 2 in Sumps C and D, respectively. The concentration-time plots for all four metals exhibit a peaking pattern similar to solids concentrations. For Sump C, the highest concentrations were of As and Zn, followed closely by Pb. This general pattern held throughout all four events. In Sump D, As and Pb concentrations tended to be higher than those for Zn. Overall, metal concentrations were of the same magnitude in both sumps. In only one instance was the Cu concentration above 0.1 mg/L. Lead concentrations in the Sump-D outfall stations tended to be slightly higher than in Sump C stations, with the largest difference occuring in the highest runoff event (No. 2). Sump concentrations compare favorably to Stormwater Pollution Prevention regulations established for Texas under the Clean Water Act. Measured values are all less than single grab limits (e.g., 1.5 mg/L for Pb; 2.0 mg/L for Cu) and even less than daily average limits (e.g., 1.0 mg/L for Pb and Cu) (*Guidance*, 1993). Metal concentrations are also in line with average values for urban runoff quoted in the literature: e.g., 235 μg/L for Pb; 45 μg/L for Cu; and 236 μg/L for Zn (van der Leeden *et al.*, 1990). Moreover, the values reported in this study are for total metals which are known to often be substantially greater than dissolved and bioavailable concentrations (Paulson and Amy, 1993).

Figures 35 through 40 illustrate the relationship of surrogate organics, nutrients, and biologicals to solids concentrations in the sumps for the low flow event (Event 1). Loadings of COD (Sumps C and D), Fecal Streptococcus (Sump C), and, to a lesser extent, Fecal Coliforms (Sump C) were sufficient to generate substantive peaks in the early stage of the event. Other quantities, including metals, did not deviate appreciably from their pre-event levels. Finally, Figures 41 through 45 present data for Event 4, a summer storm after a lengthy dry period. The results follow the general patterns observed in Event 2. Lead concentrations for this event are considerably higher in both sumps than in earlier events.

3.2.2 Sediment Quality

Results of pre- and post-event analysis for sump sediment samples are presented in Tables 19 through 22. It was hypothesized that sediment analyses could provide some verification of solids and other pollutant capture in the sumps. Some of the trends in post-event samples suggest that this is indeed so. Table 23 is a ranking as to which event produced the higher magnitude of respective sediment quality parameters. Referring back to Tables 13 and 18, the maximum runoff and pollutant loading event was, by far, Event 2. Events 3 and 4 had comparable runoff and pollutant loadings approximately one seventh of that of Event 2. Event 1 runoff was very small by comparison to the other three. The rankings of Table 23 illustrate that, in general, Event 2 has the largest sediment pollutant concentrations, corresponding to the maximum runoff and pllutant loading per drainage acre. A composite ranking (1 point for rank 1, 2 points for rank 2, *etc.*) for six parameters measured for each event; namely volatile solids, COD, Pb, Cu, Zn, and As; yielded almost identical results for the two sumps. For Sump C, the composite ranking is: Event 2 (9 points); Event 1 (13 points); Event 3 (19 points) and Event 4 (19 points). For Sump D, the composite ranking is: Event 2 (9 points); Event 1 (14 points); Event 4 (18 points) and Event 3 (19 points). That Event 3 and 4 rankings and actual values are fairly close is consistent with the close runoff and loading associated with these two events. The high ranking of Event 1, however, is somewhat puzzling given the low runoff for this storm. Sediment values for organics and Fecal Streptococcus are particularly high, especially for Sump C sediments, although perhaps organic loading is reflected to some degree in the high stormwater outfall concentrations for Event 1 (Table 15). A major factor is that no pumping was done for either sump during Event 1, meaning that pollutants were retained in the sumps rather than flushed out. This would especially impact pollutant removal in Sump C where retention times for pumping are normally just a few hours or even less. The effect would not be as great in Sump D with its lengthy detention; therefore the fact that no pumping was done for Event 4 in Sump D does not appear to result in elevated pollutant levels in the sediments. Certainly more data is required to derive a more precise relationship between sediment capture of pollutants and the nature of a storm event. Nevertheless, the results here yield evidence that examing the pollutant "signature" left in the sediments may provide a relatively easy method of acquiring more detailed information on pollutant loads and removals with respect to nonpoint-source management structures.

Several comparisons of sediment pollutant levels obtained in this study can be made with results from sediment quality analyses for Sump C and D as part of the TNRCC 1988-89 study (Davis, 1994). With the exception of the high post-event value in Sump C for Event 1, BOD values were the same order of magnitude. Volatile solids and Kjeldahl nitrogen values were very comparable for the two studies. With respect to trace toxic substances, no chlordane was detected in Sump D sediments, while less than 1 mg/kg-dry chlordane was found in Sump C samples. Lead and zinc concentrations were clearly the highest among the heavy metals tested for all four events. This is insightful given that sump water concentrations of As were comparable to Zn and Pb. Apparently, As association with the sediments is not as great as that of Pb and Zn.

Currently, DSS removes sediments for disposal in a regulated municpal landfill. The material is removed periodically, with most of the effort concentrated in the vicinity of the pumping stations where, predictably, the greatest buildup occurs. This procedure appears to work well and maintains sump capacities. While no known standards for stormwater basin sediments exist, there are other regulatory guidelines that provide some perspective on observed sediment pollutant values. For instance, TNRCC's §312 sludge rules for classification of wastewater treatment plant sludges specify limitations on certain pathogens including Fecal Coliforms. The rules specify, for example, that a Class B sludge (i.e., one that may be land applied under certain management restrictions) must have a Fecal Coliform density of less than 2,000,000 cfu per gram of dry solids (Carpenter, 1993). All of the sediment samples tested for Fecal Coliforms had levels less than 50,000 cfu per gram dry solids; i.e., well within the Class B guidelines. With respect to metals, the 40 CFR 503 Subpart B sludge rules are designed to regulate metal concentrations in domestic sewage sludge that is disposed *via* land treatment. The EPA has established soil loading levels that are considered acceptable under current risk assessment guidelines for disposal of these sludges according to several possible exposure pathways. Lead is the metal of significant concern in this study. Lead limits for land treatment for various exposure pathways are (*Part 503*, 1995):

Exposure Pathway	Lead Limit (mg/kg-dry)
Sludge to human	300
Sludge to soil to animal	600
Sludge to soil to plant to animal	5,500
Sludge to soil to groundwater to human	unlimited

The highest Pb concentration measured over the four events sampled was right at the most stringent 300 mg/kg-dry sediment limit (actually 304.5). Concentrations averaged 150-225 mg/kg for the winter-spring events and ~100 mg/kg for the spring-summer events. These concentrations are likely higher than background levels in native soils, indicating some source(s) of potential contamination. Given the current handling and management practices with respect to the sediment, however, these levels would appear to pose no significant exposure risk. It is also interesting to note that the lead levels reported here for sediments are much less than average lead levels in urban street sweepings of greater than 1800 mg/kg (van der Leeden *et al.*, 1990).

3.2.3 Pollutant Removal Calculations

The removal of pollutants in a sump may be estimated from a mass balance. For a given pollutant, the mass removed in the sump, M_{sump}, can be expressed as:
M_{sump} is given by:

$$M_{sump} = M_{in,o} - M_{in,end} + M_{in,storm} - M_{out,ps} + M_{in,gains} \quad (4)$$

where:

- $M_{in,o}$ is the mass of pollutant in the sump at the beginning of the event,
- $M_{in,end}$ is the mass of pollutant in the sump at the end of the event.
- $M_{in,storm}$ is the mass of pollutant entering the sump due to runoff for the event,
- $M_{out,ps}$ is the mass of pollutant leaving the sump during the event at the pumping station, and
- $M_{in,m}$ is miscellaneous pollutant load to the sump via water gains other than runoff,

$M_{in,o}$ is simply:

$$M_{in,o} = C_{o,sump} \times V_{o,sump} \quad (5)$$

where $C_{o,sump}$ and $V_{o,sump}$ are, respectively, the concentration of pollutant and volume of water in the sump at the start of the event. $C_{o,sump}$ derives from field sampling near the pumping station, and $V_{o,sump}$ is calculated from sump-level data from SCADA and depth-volume calibration curve for the sump. Similarly, $M_{in,end}$, is:

$$M_{in,end} = C_{end,sump} \times V_{end,sump} \quad (6)$$

where $C_{end,sump}$ and $V_{end,sump}$ are, respectively, the concentration of pollutant and volume of water in the sump at the end of the event.

$M_{in,storm}$ is :

$$M_{in,storm} = \sum_{i=1}^{N} \left[\sum_{j=1}^{\tau} (C_{of,i,j} \times R_{of,i,j}) \right] \quad (7)$$

where i refers to an individual outfall, N is the total number of outfalls for the sump, j is a time interval during the storm event, and τ is the total number of time intervals, j, used in the calculations. $R_{of,i,j}$ is the runoff from outfall, i, over time interval, j, into the sump, the values of which are determined by HEC-1 modeling of the event. $C_{of,i,j}$ is the concentration of pollutant associated with $R_{of,i,j}$ and obtained by field sampling during the event. Only two samples were collected at an outfall station during an event. This is more than in many stormwater studies, but as suggested by sump data and the timing of outfall samples, it is very likely that the major peak of outfall concentrations was missed in most events for most of the pollutants sampled. The only apparent exceptions to this are some TSS outfall samples in Sump C during Event 3 and possibly Event 1. The best solution would be to perform more frequent sampling at the outfalls to capture the time-variable fluctuations in concentrations, although project constraints prohibited this level of detail in the current study. If enough of these cases were sampled, it may be possible to invoke a stochastic analysis to correlate outfall pollutant concentrations with their corresponding flow hydrographs and and thereby numerically estimate pollutant distributions for events of a given magnitude. This is a potential area for future investigations. For this study, one approach would be to average the two readings taken during the event. However, given the likely underrepresentation of peak values by both measurements and the extreme differences in the two values in some instances, especially in Sump C outfalls, it was thought that this would further underestimate the suspected pollutant loadings to the sump. Therefore, it was decided to simply use the maximum of the two readings as the most representative value of the pollutant concentration at the outfall for an event. For Sump D outfalls, the maximum value is not appreciably different from the averaging approach, and in every case is, by definition, less than double the average value. Since a single value of $C_{of,i,j}$ is used over the event, the subscript j can be dropped from this term making it simply $C_{of,i}$.

Also in Sump D, some additional outfalls were sampled in Events 3 and 4. Maps 5 and 6 show the sump areas assumed to be represented by the various outfall stations for Sumps C and D, respectively. The numbering of the sub-areas follows that of Maps 2 and 3 and Tables 4 and 5. The distribution shown for Sump C (Map 2) was used for all four events. Area 14, the area draining directly to the sump, was divided between the two larger areas for purposes of pollutant loading.

Map 3 for Sump D was used for Events 1 and 2. For Event 3, however, two additional outfalls were sampled, with the represented areas shown in Map 4. Only one of these was retained in Event 4 sampling, and the associated drainage areas depicted in Map 5.

$M_{out,ps}$ is:

$$M_{out,ps} = \sum_{j=1}^{T}(C_{sump,j} \times V_{p,j}) \tag{8}$$

where $C_{sump,j}$ is the pollutant concentration in the sump for the time interval, j, and $V_{p,j}$ is the volume of water pumped out of the sump during time interval, j, of the event. Values of $C_{sump,j}$ are estimated from field sampling data collected in the vicinity of the pumping station as a function of time over the course of an event. $V_{p,j}$ values are from the pumping curve developed from SCADA storm-logging data.

The only $M_{in,m}$ term that was considered was the combination of inflow from neighboring sumps and any backflow from the river. This can be estimated as:

$$M_{in,m} = \sum_{j=1}^{T}(C_{wg,j} \times V_{wg,j}) \tag{9}$$

where $V_{wg,j}$ is the volume of water gained from neighboring sumps and/or backflow to the sump from the river during time interval, j, as estimated according to Section 4.1. $C_{wg,j}$ is the pollutant concentration of this water gain over time interval, j. River and adjacent sump concentrations were not assessed as part of this study, making inclusion of this term rather speculative. However, it could not be neglected since in some instances (e.g., Events 2 and 3 for Sump D) the quantity of backflow over the course of the entire event exceeded the runoff from the sump drainage area itself. Several issues were considered in deciding upon a strategy for assigning values of $C_{wg,j}$. First, the development of differences in river versus sump elevations to produce backflow did not occur until at least the peak of the runoff hydrograph. As noted in sump water quality data, this usually meant that peak sump concentrations had also passed. Second, some existing data suggests that river concentrations of pollutants are of the same order of magnitude as stormwater with the exception of heavy metals and, possible, nutrients, in which cases river concentrations may be an order of magnitude lower (Paulson and Amy, 1993). Note, however, that the "stormwater" values given in the referenced study were from actual outfalls and not necessarily tempered by temporary storage such as might occur in a sump. Therefore, sump values may be even closer to actual river values. Furthermore, in the one case of river versus sump data from the 1988-89 Trinity River Stormwater Survey referred to previously (Davis, 1994), concentrations of measured pollutants in both the river and sumps were of the same order of magnitude. With these considerations in mind, it was decided to simply set $C_{wg,j}$ equal to the (time) corresponding $C_{sump,j}$. The result is an $M_{net,out}$ which is the difference between $M_{out,ps}$ and $M_{in,m}$.

The enormity of this type of problem is evident when reviewing the number and nature of the assumptions utilized in performing pollutant removal calculations. The assumptions include the following.

1) The sump is completely mixed, implying the pollutant concentration in the sump is not a function of position and is equal to the pollutant concentration of water being pumped out of the sump.

2) The value of pollutant concentration for an outfall based upon samples collected during an event represents pollutant concentration for the outfall over the duration of the event.

3) The pollutant concentration measured at sampled outfalls is representative of pollutant loadings at unsampled outfalls in the immediate area.

4) The pollutant concentration in neighboring feed sumps (Sump D) and backflow water from the river is essentially equivalent to the time-corresponding concentration of water leaving the sump.

Tables 23 through 30 present pollutant removal calculations using the above approach. Two additional columns beyond those described previously are included. The first is percent treatment, %T, which was defined as:

$$\%T = \left(\frac{M_{sump}}{M_{in,storm}}\right) \times 100\% \tag{10}$$

for Events 1 and 4 in which there were no appreciable miscellaneous water (or pollutant) gains. $M_{in,m}$ is taken into account in the calculation of %T for Events 2 and 3 using a modified version of Equation 10.

$$\%T = \left(\frac{M_{sump}}{M_{in,storm} + M_{in,m}}\right) \times 100\% \tag{11}$$

Lastly, there is a column in which the loading is expressed in kg/acre for purposes of comparison of the respective sump drainage areas. Some observations from these calculations are presented below.

Event 1: Tables 23 and 24

This was the very low flow event with neither pumping nor backflow in Sump C or Sump D. Percent treatment evaluations are not particularly meaningful here in that the loading due to runoff is of the same order of magnitude or in some cases (e.g., TDS, BOD, nutrients, Fecal Coliforms, and metals) even less than mass of pollutant in the sump prior to and after the event. In such instances the mass of pollutant removed from the sump depends on the difference between the pre- and end-of-event samples and little on the actual loading. The calculations for biologicals and metals (excluding zinc) illustrate this phenomenon. The general high % treatment values, however, are consistent with the complete detention of materials draining to either sump for this event. Estimated pollutant loads per unit area was generally higher for Sump D than C in the cases of solids, surrogate organics (except BOD), and nutrients. Loadings of biologicals and metals were fairly close.

Event 2: Tables 25 and 26

This was the highest flow event and, as such, illustrates best the relationship between hydraulic character of a sump and pollutant removal. An added plus for this event is that pollutant loads due to runoff substantially exceed the difference between the mass of pollutant in the sump at the beginning and end of the event. Pollutant removals in Sump C are mostly low which is consistent with the relatively small volume and high degree of pumping during the event. In other words, the sump is flushed very quickly, with an estimated water detention time of between 2 and 3 hours, even when considering some backflow from the river. The seemingly extreme values for

%T are owing to the "flashy" nature of Sump C hydraulics coupled with substantial differences between peak sump and outfall concentrations for some pollutants. By contrast, Sump D removals are much greater, owing to the large volume and detention of water during the event (average volume in Sump D for Event 2 was 287 acre-ft versus just 4.2 acre-ft for Sump C; detention time in Sump D is approximately 30-40 hours when extra-sump water gain is considered). Once again the percent treatment values are not precise in that they merely are calculated with respect to the mass of pollutant entering the sump due to runoff and do not include mass entering by the miscellaneous water gain. Nevertheless, the results illustrate the contrast between the variable hydraulic characteristics of the respective sumps. As expected, loadings per acre were considerably higher than in Event 1. Solids and surrogate organic loadings were comparable between the two sumps. Sump C had generally higher loadings per acre of nutrients and biologicals, while metal loadings were slightly higher in Sump D.

Event 3: Tables 27 and 28

The results of Event 3 follow those of Event 2 in that Sump D pollutant removals, on average, are greater than in Sump C. There is a glaring exception in the case of COD, although examination of the COD concentration data for this event (Table 16) exhibits a dynamic character much different from the other events for both sumps. Outfall concentrations of TSS and VSS in Sump C outfalls are also high compared to Sump levels. Using maximum outfall concentrations may be overpredicting outfall loads in this case. Total mass loading of solids in Sump C exceeds that of Sump D despite the much smaller drainage area. Another potential contributor to this result was the pre-event detention of water in one of the Sump C basins. Release of this water was accounted for as miscellaneous gain in water balance calculations, but not accounted for in pollutant calculations beyond that described in the previous section. In this regard, it is interesting to note that the total quantity of miscellaneous water gain to Sump C is greater for Event 3 than Event 2 even though runoff is only one-fourth as much. Metal removals were essentially zero in Sump C as before. Extreme values in Sump D may be attributable, in part, to the fact that this was a relatively low-flow event resulting in runoff loads being less than quantities in the sump at the beginning and end of the event. Loadings per acre are comparable for the two sumps with the exception of TSS and VSS, which are unusually higher for C than D as noted earlier.

Event 4: Tables 29 and 30

This second highest flow event also produced mass loadings that were substantially in excess of the difference between the mass of material in the sump at the beginning and end of the event. In fact, for Sump D $M_{in,o}$ and $M_{in,end}$ are very close in magnitude. No pumping was required in Sump D and sump versus river elevations suggested no appreciable miscellaneous water gains. Hence all pollutant loading due to runoff was essentially detained in the sump over the 130 hours of sampling resulting in removals of approximately 100%. Sump removals in Sump C were virtually zero due to the minimal detention (approximately 1.6 hours during the period of runoff). Pollutant loads per acre were very close for both sumps, with the exception of higher copper loadings from Sump D. Perhaps another lesson from this exercise is that pollutant removal calculations seem to improve in terms of consistency of outcome for increasing magnitude of the event.

Key for Tables 14 – 21

Stormwater Sampling Stations

Sump C

C-1: Pumping station

C-2: C1/2/3 drain box off Beckley (at IOSCO)

C-3: C12 – 98-in CIP (concrete channel)

Sump D

D-1: Pumping station

D-2: D33 – headwall, channel from Fishtrap Lake

D-3: Residential area outlet into sump channel at D12

D-4: Westmoreland Bridge at Francis Street at D9

D-5: Residential area outlet into creek at D29

Table 14: Stormwater Quality Data for Event 1[a]

Station	Time (hr)	pH	Temp (degC)	TSS	Set-S (ml/l)	VSS	TDS	COD	TOC	BOD
C-1	0	7.02	–	90	<0.1	19	420	25.4	8.3	17
	2.5	7.18	–	229	1.2	31	440	85.5	10.5	23
	5.8	7.59	–	85	0.5	16	420	50.2	11.5	19
	27.5	7.10	–	82	0.5	61	480	38.4	5.2	3
	50.2	7.05	–	34	0.1	14	660	44.4	5.0	12
	71.5	7.01	–	35	<0.1	9	520	41.1	4.2	7
	144.2	6.92	13.0	28	<0.1	9	530	18.7	4.5	5
C-2	0.5	7.33	–	723	4.5	70	580	100.4	12.9	6
	49.3	6.86	–	103	<0.1	60	520	22.2	7.6	<2
C-3	0.5	7.75	–	68	<0.1	48	430	25.6	8.4	6
	49.3	7.23	–	124	0.6	81	320	104.3	7.9	20
D-1	0	7.25	–	115	<0.1	26	750	44.4	6.4	7
	1.5	7.35	–	171	1.3	25	680	66.3	9.2	15
	4.3	8.20	–	76	0.4	60	1060	28.9	5.0	6
	27.0	7.70	–	85	0.1	42	1080	25.6	5.5	17
	48.8	6.75	–	40	<0.1	31	990	32.1	8.2	7
	70.8	7.51	–	65	0.15	23	870	22.2	4.8	8
	143.4	7.20	13.0	106	0.15	27	960	32.1	5.8	5
D-2	2.7	7.20	–	17	<0.1	7	950	35.3	4.2	<2
	48.3	7.54	–	145	<0.1	85	840	18.7	5.4	<2
D-3	1.5	8.05	–	372	0.8	86	780	32.1	8.5	5
	47.8	7.86	–	109	0.2	19	180	58.5	7.6	5

[a] All quantities in mg/L unless otherwise noted.

Table 14: Stormwater Quality Data for Event 1 (continued)[a]

Station	Time (hr)	NO_3^-	NO_2^-	TKN	Ortho PO_4^-	Total PO_4^-	Fecal[b] Coli.	Fecal[b] Strep.
C-1	0	3.21	<0.5	2.6	0.23	0.28	500	1,200
	2.5	4.05	<0.5	3.0	0.31	0.40	31,000	110,000
	5.8	4.33	<0.5	3.9	0.30	0.35	4,800	84,000
	27.5	2.43	<0.5	1.6	0.01	<0.05	9,100	6,600
	50.2	3.42	<0.5	4.0	0.20	0.28	2,900	14,000
	71.5	2.35	<0.5	4.3	0.17	0.22	3,200	3,200
	144.2	3.47	<0.5	4.0	0.21	0.26	63	12,000
C-2	0.5	1.87	<0.5	2.6	0.11	0.20	10	10
	49.3	1.78	<0.5	1.4	0.09	0.11	10	<10
C-3	0.5	1.55	<0.5	2.0	0.17	0.23	50	<10
	49.3	3.48	<0.5	2.9	0.21	0.37	12,000	38,000
D-1	0	3.80	<0.5	2.7	0.04	0.06	120	<10
	1.5	3.72	<0.5	2.3	0.05	0.08	5,800	2,000
	4.3	1.21	<0.5	2.1	0.02	0.05	2,400	200
	27.0	2.04	<0.5	4.6	0.04	0.17	10,000	9,800
	48.8	4.55	<0.5	1.8	0.01	<0.05	2,900	2,600
	70.8	2.57	<0.5	1.3	0.01	<0.05	2,000	4,600
	143.4	3.55	<0.5	2.4	0.04	<0.05	140	560
D-2	2.7	3.33	<0.5	2.2	0.02	<0.05	90	<10
	48.3	4.17	<0.5	1.9	0.01	<0.05	10	<10
D-3	1.5	1.30	<0.5	1.4	0.16	0.17	<10	<10
	47.8	<0.5	<0.5	1.6	0.18	0.23	150	12,000

[a]All quantities in mg/L unless otherwise noted.
[b]In cfu / 100 mL.

Table 14: Stormwater Quality Data for Event 1 (continued)[a]

Station	Time (hr)	Pb	Cu	Zn	As	Cd	Ca	Chlordane (μg/L)
C-1	0	0.086	0.020	0.182	0.105	0.015	66.90	<0.14
	2.5	0.126	0.019	0.273	0.087	0.027	77.03	<0.14
	5.8	0.060	0.027	0.221	0.105	0.031	65.28	<0.14
	27.5	0.049	0.012	0.111	0.070	0.007	77.00	<0.14
	50.2	0.082	0.004	0.409	0.035	0.020	68.41	<0.14
	71.5	0.016	0.004	0.204	<0.015	0.016	64.69	0.68
	144.2	0.071	0.066	0.241	0.052	0.046	69.88	<0.14
C-2	0.5	0.104	0.058	0.530	0.017	0.038	123.63	0.31
	49.3	0.093	0.012	0.200	0.052	0.033	70.29	<0.14
C-3	0.5	0.071	0.004	0.034	0.035	0.005	85.54	<0.14
	49.3	0.060	0.043	0.280	0.105	0.026	35.34	<0.14
D-1	0	0.065	0.017	0.208	0.143	0.036	112.25	<0.14
	1.5	0.093	0.019	0.163	0.105	0.026	86.62	<0.14
	4.3	0.082	0.019	0.226	0.122	0.018	118.00	<0.14
	27.0	0.082	0.039	0.053	0.087	0.005	149.96	<0.14
	48.8	0.016	0.023	0.200	0.070	0.020	118.64	<0.14
	70.8	0.082	0.012	0.087	0.105	0.031	116.58	<0.14
	143.4	0.093	0.022	0.110	0.131	0.062	110.04	<0.14
D-2	2.7	<0.015	0.016	0.097	<0.015	0.029	132.74	<0.14
	48.3	<0.015	0.004	0.020	<0.015	0.007	137.98	<0.14
D-3	1.5	<0.015	0.039	0.066	0.087	0.020	137.44	<0.14
	47.8	0.060	0.035	0.185	0.052	0.044	30.79	<0.14

[a]All quantities in mg/L unless otherwise noted.

Table 15: Stormwater Quality Data for Event 2[a]

Station	Time (hr)	pH	Temp (degC)	TSS	Set-S (ml/l)	VSS	TDS	COD	TOC	BOD
C-1	0	6.96	14	30	0.15	12	520	11.3	6.0	10.0
	3.8	8.53	18	1597	2.50	289	130	104.3	4.3	13.2
	15.7	8.64	16	620	0.85	102	80	41.4	4.2	21.0
	40.6	7.20	15	47	0.80	10	330	30.5	5.3	40.2
	63.3	7.33	15	57	0.15	10	320	22.2	6.1	41.1
	112.4	7.12	17	76	<0.1	13	440	22.2	6.1	4.2
	304.9	–	–	83	0.55	15	–	45.0	–	–
C-2	0.2	7.35	–	39	0.20	19	640	13.2	4.0	<2
	15.0	7.54	–	90	0.10	20	150	18.7	6.0	8.7
C-3	0.1	7.58	–	8	<0.05	3	610	25.6	7.0	4.4
	11.0	8.06	–	826	0.80	88	160	53.0	4.5	24.3
D-1	0	7.26	11	36	0.12	12	1060	27.7	3.5	7.8
	3.8	8.42	16	251	1.10	36	790	44.4	5.0	20.7
	9.0	7.94	15	218	0.10	34	370	28.9	4.9	8.7
	40.0	7.29	15	55	<0.05	10	310	22.2	5.2	39.9
	62.8	7.52	15	71	0.30	11	340	35.3	6.8	41.1
	112.8	7.05	17	60	0.15	11	440	11.3	6.1	<2
	303.8	–	–	54	0.15	16	–	39.8	–	–
D-2	1.0	7.66	16	55	0.70	16	850	42.9	4.8	4.2
	11.0	7.31	15	321	1.20	50	150	39.9	3.6	11.4
D-3	0.3	7.44	16	276	1.30	45	600	71.3	8.0	9.6
	11.0	8.01	15	151	1.70	26	540	68.8	6.9	17.1

[a]All quantities in mg/L unless otherwise noted.

Table 15: Stormwater Quality Data for Event 2 (continued)[a]

Station	Time (hr)	NO_3^-	NO_2^-	TKN	Ortho PO_4^-	Total PO_4^-	Fecal[b] Coli.	Fecal[b] Strep.
C-1	0	2.3	<0.5	1.6	0.03	0.15	330	500
	3.8	2.9	<0.5	1.2	0.04	0.43	21,000	49,000
	15.7	1.2	<0.5	1.4	0.05	0.53	125,000	130,000
	40.6	5.0	<0.5	1.5	0.03	0.15	96,000	41,000
	63.3	6.1	<0.5	1.2	0.02	0.14	22,000	51,000
	112.4	2.5	<0.5	1.8	0.03	0.25	34,000	220
	304.9	–	<0.5	–	–	–	–	–
C-2	0.2	2.8	<0.5	0.8	0.03	<0.05	<10	220
	15.0	1.1	<0.5	1.0	0.07	0.31	40,000	220,000
C-3	0.1	2.8	<0.5	4.3	0.06	0.59	2,800	1,600
	11.0	2.1	<0.5	1.8	0.04	0.42	29,000	150,000
D-1	0	3.0	<0.5	1.3	0.04	0.20	<10	<10
	3.8	2.4	<0.5	0.9	0.06	0.25	400	8,200
	9.0	1.2	<0.5	1.1	0.03	0.23	7,000	35,000
	40.0	5.2	<0.5	0.6	0.04	0.13	7,800	49,000
	62.8	<0.5	<0.5	1.3	0.01	0.09	10,000	31,000
	112.0	2.7	<0.5	0.7	0.01	0.11	1,100	1,900
	303.8	–	<0.5	–	—	–	–	–
D-2	1.0	2.6	<0.5	2.3	0.01	0.05	<10	63
	48.3	1.2	<0.5	2.0	0.02	0.15	3,200	6,000
D-3	0.3	3.9	<0.5	1.5	0.08	0.23	130	14
	11.0	1.4	<0.5	1.6	0.01	0.56	34,000	47,000

[a]All quantities in mg/L unless otherwise noted.
[b]In cfu / 100 mL.

Table 15: **Stormwater Quality Data for Event 2 (continued)**[a]

Station	Time (hr)	Pb	Cu	Zn	As	Cd	Ca	Chlordane (μg/L)
C-1	0	0.091	0.045	0.054	0.222	0.058	70.42	<0.14
	3.8	0.375	0.142	0.484	0.460	0.149	182.27	0.48
	15.7	0.082	0.029	0.167	0.221	0.069	54.03	0.14
	40.6	0.055	0.032	0.060	0.206	0.069	48.55	<0.14
	63.3	0.055	0.042	0.076	0.222	0.083	39.45	<0.14
	112.4	0.055	0.021	0.245	0.285	0.028	53.50	<0.14
	304.9	0.368	<0.002	0.306	0.405	0.048	71.45	–
C-2	0.2	0.064	0.021	0.053	0.206	0.106	77.32	0.36
	15.0	<0.015	0.034	0.129	0.190	0.051	28.53	<0.14
C-3	0.1	0.082	0.034	0.037	0.222	0.065	77.21	<0.14
	11.0	0.027	0.039	0.294	0.174	0.060	63.92	0.15
D-1	0	0.110	0.032	0.055	0.333	0.114	103.96	<0.14
	3.8	0.174	0.047	0.111	0.222	0.020	83.81	0.74
	9.0	0.255	0.050	0.074	0.269	0.024	48.79	<0.14
	40.0	0.165	0.039	0.102	0.365	0.042	34.65	<0.14
	62.8	0.046	0.045	0.069	0.317	0.026	46.30	<0.14
	112.0	<0.015	0.013	0.039	0.190	0.018	18.87	<0.14
	303.8	0.018	<0.002	0.172	0.239	0.022	72.70	–
D-2	1.0	0.329	0.058	0.108	0.618	0.098	94.63	<0.14
	11.0	0.393	0.071	0.078	0.729	0.098	61.10	<0.14
D-3	0.3	0.155	0.063	0.091	0.412	0.065	94.63	<0.14
	11.0	0.329	0.063	0.100	0.681	0.100	21.61	0.28

[a]All quantities in mg/L unless otherwise noted.

Table 16: Stormwater Quality Data for Event 3[a]

Station	Time (hr)	pH	Temp (degC)	TSS	Set-S (ml/l)	VSS	TDS	COD
C-1	0	7.00	20	122	0.1	27	370	0
	2.0	7.21	18	144	0.1	25	440	0
	10.1	6.55	15	200	0.15	33	320	0
	26.8	7.00	17	65	0.05	18	390	11.3
	49.3	7.20	19	27	<0.1	6	400	44.4
	97.0	6.41	20	67	<0.1	18	430	38.4
C-2	0.8	6.36	18	70	0.4	17	630	10.3
	9.3	7.35	14	304	1.2	45	160	55.8
C-3	0.9	6.68	19	12	<0.1	5	700	-7.5
	9.8	7.15	13	934	2.3	125	370	76.2
D-1	0	6.62	20	171	0.3	28	570	28.9
	2.0	7.36	20	56	<0.1	16	660	15.0
	10.0	7.42	19	70	<0.1	21	710	0
	26.3	6.61	17	90	<0.1	18	510	50.2
	48.9	6.85	19	144	0.1	9	530	47.3
	97.5	6.95	20	68	<0.1	15	600	44.4
D-2	1.3	7.01	19	53	<0.1	19	470	7.5
	9.5	6.66	16	287	0.3	10	550	3.7
D-3	0.8	6.92	21	100	0.1	21	600	25.6
	9.2	6.60	14	86	0.1	24	240	76.2
D-4	1.5	6.50	22	115	<0.1	9	1050	32.1
	9.4	7.03	16	96	0.1	17	390	25.6
D-5	1.8	6.90	19	18	0.1	2	780	0
	9.2	6.50	17	32	<0.1	6	690	11.3

[a] All quantities in mg/L unless otherwise noted.

Table 16: Stormwater Quality Data for Event 3 (continued)[a]

Station	Time (hr)	Pb	Cu	Zn	As	Cd	Ca
C-1	0	0.088	0.057	0.159	0.374	0.040	56.84
	2.0	0.262	0.048	0.143	0.385	0.048	56.54
	10.1	0.070	0.048	0.251	0.291	0.040	61.39
	26.8	0.140	0.053	0.256	0.249	0.060	63.28
	49.3	0.070	0.047	0.186	0.177	0.030	65.33
	97.0	0.175	0.057	0.184	0.249	0.040	56.44
C-2	0.8	0.018	0.048	0.186	0.187	0.018	92.96
	9.3	0.280	0.064	0.308	0.447	0.100	53.36
C-3	0.9	0.298	0.135	0.267	0.343	0.064	101.91
	9.8	0.088	0.070	0.279	0.208	0.034	82.61
D-1	0	0.154	0.078	0.144	0.249	0.038	62.41
	2.0	0.417	0.070	0.023	0.260	0.034	60.54
	10.0	0.202	0.078	0.032	0.249	0.040	56.24
	26.3	0.417	0.088	0.186	0.270	0.060	75.81
	48.9	0.249	0.084	0.077	0.249	0.040	88.30
	97.5	0.487	0.092	0.043	0.322	0.056	94.30
D-2	1.3	0.297	0.083	0.032	0.281	0.066	95.98
	9.5	0.249	0.092	0.085	0.301	0.079	93.38
D-3	0.8	0.487	0.068	0.257	0.249	0.025	100.44
	9.2	0.131	0.060	0.091	0.249	0.075	46.52
D-4	1.5	0.202	0.056	0.229	0.239	0.058	133.97
	9.4	0.059	0.068	0.040	0.208	0.070	56.92
D-5	1.8	0.178	0.056	0.017	0.218	0.054	125.36
	9.8	0.226	0.064	0.043	0.239	0.050	101.43

[a]All quantities in mg/L unless otherwise noted.

Table 17: Stormwater Quality Data for Event 4[a]

Station	Time (hr)	pH	Temp (degC)	TSS	Set-S (ml/l)	VSS	TDS	COD
C-1	0	7.14	29	117	<0.1	47	640	64.8
	3.2	6.35	24	348	1.0	69	180	89.9
	11.2	6.72	22	284	0.5	72	170	83.2
	38.5	6.75	31	87	0.5	26	470	32.1
	57.0	7.18	32	189	1.0	56	620	63.5
	130.7	7.25	32	73	0.5	49	520	71.3
C-2	1.8	6.36	24	62	0.2	28	180	56.3
	10.6	6.79	22	192	0.3	52	330	41.4
C-3	2.2	6.47	24	175	0.5	31	140	55.8
	11.0	6.55	22	209	0.2	40	170	89.9
D-1	0	7.36	29	271	0.4	98	1100	38.4
	2.8	7.10	27	237	1.0	34	290	47.3
	11.5	6.82	27	433	1.5	64	440	51.0
	38.0	7.80	31	230	0.8	40	540	32.1
	56.6	7.58	32	158	0.2	23	540	28.9
	130.0	8.02	32	202	0.4	30	940	35.3
D-2	1.8	6.62	30	183	0.2	45	140	28.9
	10.6	7.67	26	83	<0.1	33	140	53.0
D-3	2.5	6.80	27	52	<0.1	24	990	11.3
	11.2	7.42	27	64	<0.1	16	880	83.2
D-4	2.2	6.65	27	517	1.8	65	340	78.6
	10.9	6.52	27	325	1.0	78	250	41.4

[a]All quantities in mg/L unless otherwise noted.

Table 17: Stormwater Quality Data for Event 4 (continued)[a]

Station	Time (hr)	Pb	Cu	Zn	As	Cd	Ca
C-1	0	0.553	0.037	0.328	0.451	0.138	80.91
	3.2	0.379	0.023	0.425	0.207	0.066	57.41
	11.2	0.706	0.047	0.426	0.432	0.135	54.88
	38.5	0.308	0.029	0.300	0.075	0.067	59.24
	57.0	0.349	0.016	0.267	0.207	0.094	81.48
	130.7	0.328	0.008	0.253	0.113	0.076	71.75
C-2	1.8	0.328	0.023	0.375	0.150	0.070	30.43
	10.6	0.440	0.018	0.369	0.188	0.092	55.66
C-3	2.2	0.308	0.018	0.307	0.019	0.066	35.43
	11.0	0.522	0.042	0.912	0.207	0.107	49.87
D-1	0	0.522	0.023	0.372	0.338	0.100	124.59
	2.8	0.471	0.026	0.348	0.207	0.094	53.89
	11.5	0.593	0.089	0.474	0.244	0.100	61.47
	38.0	0.410	0.021	0.275	0.132	0.084	61.35
	56.6	0.298	0.018	0.262	0.150	0.067	66.94
	130.0	0.379	0.018	0.265	0.226	0.075	106.17
D-2	1.8	0.390	0.026	0.317	0.188	0.095	24.47
	10.6	0.369	0.029	0.250	0.169	0.083	117.25
D-3	2.5	0.542	0.021	0.542	0.338	0.100	131.62
	11.2	0.359	0.034	0.311	0.188	0.075	36.37
D-4	2.2	0.451	0.102	0.433	0.226	0.100	56.49
	10.9	0.379	0.021	0.304	0.132	0.074	23.81

[a]All quantities in mg/L unless otherwise noted.

Table 18: Sediment Quality Data for Event 1
2/28/95 – 3/6/95

Pollutant	Sump C		Sump D	
	Pre-Event	Post-Event	Pre-Event	Post-Event
VS (mg/kg-dry)	82,242	87,579	49,290	56,591
COD (mg/kg-dry)	5,650	42,600	1,600	24,250
BOD (mg/kg-dry)	518	12,236	423	3.977
NO_3^- (mg/kg-dry)	<0.6	<0.6	<0.6	<0.6
NO_2^- (mg/kg-dry)	<0.6	<0.6	<0.6	<0.6
TKN (mg/kg-dry)	826	854	1298	858
O-PO_4^- (mg/kg-dry)	2.4	0.8	1.1	2.3
Total PO_4^- (mg/kg-dry)	253	2.3	254	18.8
Chlordane (μg/kg-dry)	700	980	<140	<140
F. Coli (CFU/100 g-dry)	7,610	7,595	2,993	43,561
F. Strep. (CFU/100 g-dry)	958,904	46,413,502	24,648	107,955
Pb (mg/kg-dry)	118.8	186.1	116.0	183.3
Cu (mg/kg-dry)	32.9	19.6	24.1	16.4
Zn (mg/kg-dry)	168.6	238.1	89.9	155.7
As (mg/kg-dry)	10.6	30.1	4.3	60.5
Cd (mg/kg-dry)	9.0	5.7	8.5	13.2
Ca (mg/kg-dry)	75,236	72,467	31.760	47,780

Table 19: Sediment Quality Data for Event 2
3/12/95 – 3/17/95

Pollutant	Sump C Pre-Event	Sump C Post-Event	Sump D Pre-Event	Sump D Post-Event
VS (mg/kg-dry)	87,579	102,041	56,591	123,092
COD (mg/kg-dry)	42,600	62,900	24,250	59,550
BOD (mg/kg-dry)	12,236	2,205	3,977	969
NO_3^- (mg/kg-dry)	<0.6	3.4	<0.6	6.3
NO_2^- (mg/kg-dry)	<0.6	<0.6	<0.6	<0.6
TKN (mg/kg-dry)	854	727	858	2,781
O-PO_4^- (mg/kg-dry)	0.8	6.2	2.3	8.3
Total PO_4^- (mg/kg-dry)	2.3	1,978	18.8	16.3
Chlordane (μg/kg-dry)	980	990	<140	<140
F. Coli (CFU/100 g-dry)	7,595	43,478	43,561	9,375
F. Strep. (CFU/100 g-dry)	46,413,502	17,701,863	107,955	729,167
Pb (mg/kg-dry)	186.1	304.5	183.3	231.1
Cu (mg/kg-dry)	19.6	13.8	16.4	6.1
Zn (mg/kg-dry)	238.1	490.5	155.7	282.3
As (mg/kg-dry)	30.1	35.6	60.5	68.6
Cd (mg/kg-dry)	5.7	6.21	13.2	14.9
Ca (mg/kg-dry)	72,467	—	47,780	—

Table 20: Sediment Quality Data for Event 3
4/10/95 – 4/14/95

Pollutant	Sump C Pre-Event	Sump C Post-Event	Sump D Pre-Event	Sump D Post-Event
VS (mg/kg-dry)	55,382	60,117	54,587	48,890
COD (mg/kg-dry)	42,500	2,850	27,950	6,050
Pb (mg/kg-dry)	155.4	91.1	100.3	55.2
Cu (mg/kg-dry)	33.4	28.3	22.2	22.3
Zn (mg/kg-dry)	337.2	215.1	80.5	57.2
As (mg/kg-dry)	33.7	24.8	32.6	32.8
Cd (mg/kg-dry)	6.0	6.4	7.9	7.7

Table 21: Sediment Quality Data for Event 4
7/5/95 – 7/10/95

Pollutant	Sump C Pre-Event	Sump C Post-Event	Sump D Pre-Event	Sump D Post-Event
VS (mg/kg-dry)	94,485	53,883	57,621	83,408
COD (mg/kg-dry)	15,050	13,600	6,350	4,900
Pb (mg/kg-dry)	131.1	93.3	99.8	84.9
Cu (mg/kg-dry)	51.6	37.3	30.5	21.4
Zn (mg/kg-dry)	290.6	152.4	85.8	73.0
As (mg/kg-dry)	22.5	20.3	31.6	22.6
Cd (mg/kg-dry)	8.6	8.8	10.7	15.3
Ca (mg/kg-dry)	79,753	81,514	142,849	71,096

Table 22: Ranking of Post-Event Sediment Quality Data by Event

Pollutant	Sump C Rank				Sump D Rank			
	1	2	3	4	1	2	3	4
VS	2	1	3	4	2	4	1	3
COD	2	1	4	3	2	1	3	4
BOD	1	2			1	2		
NO_3^-	2	1			2	1		
TKN	1	2			2	1		
O-PO_4^-	2	1			2	1		
Total PO_4^-	2	1			1	2		
Chlordane	2	1			–	–		
F. Coli	2	1			1	2		
F. Strep.	1	2			2	1		
Pb	2	1	4	3	2	1	4	3
Cu	4	3	1	2	3	4	1	2
Zn	2	1	3	4	2	1	4	3
As	2	1	3	4	2	1	3	4

Table 23: Pollutant Mass Balance Calculations for Event 1 – Sump C

Pollutant	$M_{in,o}$	$M_{in,end}$	$M_{in,storm}$	$M_{out,p}$	M_{sump}	%T	$M_{in,storm}$ (/ac)
TSS	41.7	17.1	125	0	149	120	0.157
VSS	8.81	5.49	18.4	0	21.7	118	0.0232
TDS	195	323	130	0	1.54	1	0.164
TOC	3.85	2.75	2.79	0	3.89	139	0.00352
COD	11.8	11.4	25.3	0	25.7	101	0.0319
BOD	7.88	3.05	2.77	0	7.60	274	0.00350
NO_3^-	1.49	2.12	0.612	0	-0.0178	-3	0.000772
TKN	1.21	2.44	0.674	0	-0.563	-84	0.000849
O-PO_4^-	0.107	0.128	0.0365	0	0.0149	41	4.60E-05
Total PO_4^-	0.130	0.159	0.0653	0	0.0364	56	8.23E-05
Chlordane	6.49E-05	8.55E-05	0.0486	0	0.0486	100	6.12E-05
F.Coli (cfu)	2.32E+07	3.85E+06	1.1E+08	0	1.3E+08	118	1.39E+05
F.Strep(cfu)	5.56E+07	7.33E+08	3.49E+08	0	-3.3E+08	-94	4.39E+05
Pb	0.0399	0.0433	0.0224	0	0.0189	84	2.82E-05
Cu	0.00927	0.0403	0.0130	0	-0.0180	-138	1.64E-05
Zn	0.0844	0.147	0.109	0	0.0460	42	0.000137
As	0.0487	0.0317	0.0178	0	0.0347	195	2.24E-05

All quantities are in Kg except:

1) %T (dimensionless)
2) $M_{in,storm}$ (/ac) (Kg/acre)
3) Biologicals, i.e., F. Coli. and F. Strep., which are in cfu rather than Kg

Table 24: Pollutant Mass Balance Calculations for Event 1 – Sump D

Pollutant	$M_{in,o}$	$M_{in,end}$	$M_{in,storm}$	$M_{out,p}$	M_{sump}	%T	$M_{in,storm}$ (/ac)
TSS	6410	6990	1440	0	860	60	0.79
VSS	1450	1780	639	0	309	48	0.351
TDS	41800	63300	11300	0	-10200	-90	6.20
TOC	357	382	72.2	0	46.3	64	0.0396
COD	2310	2120	405	0	595	147	0.222
BOD	390	330	10.7	0	71.0	665	0.00585
NO_3^-	212	234	44.3	0	21.9	49	0.0243
TKN	150	158	27.2	0	19.4	71	0.0149
O-PO_4^-	2.23	2.64	0.534	0	0.125	23	2.93E-04
Total PO_4^-	3.34	3.30	0.427	0	0.473	111	2.34E-04
Chlordane	0	0	0	0	0	0	0
F.Coli (cfu)	6.69E+08	9.24E+08	7.32E+07	0	-1.8E+08	-248	4.02E+04
F.Strep(cfu)	5.57E+07	3.69E+09	1.28E+09	0	-2.4E+09	-184	7.03E+05
Pb	3.62	6.13	0.0640	0	-2.45	-3820	3.51E-05
Cu	0.947	1.45	0.193	0	-0.310	-161	1.06E-04
Zn	11.6	7.25	0.943	0	5.28	560	5.18E-04
As	7.97	8.64	0.149	0	-0.521	-349	8.19E-05

All quantities are in Kg except:

1) %T (dimensionless)
2) $M_{in,storm}$ (/ac) (Kg/acre)
3) Biologicals, i.e., F. Coli. and F. Strep., which are in cfu rather than Kg

Table 25: Pollutant Mass Balance Calculations for Event 2 – Sump C

Pollutant	$M_{in,o}$	$M_{in,end}$	$M_{in,storm}$	$M_{out,p}$	$M_{in,m}$	M_{sump}	%T	$M_{in,storm}$ (/ac)
TSS	16.6	146	80700	299000	145000	-73400	-33	102
VSS	6.66	25.0	10100	51600	25000	-16500	-47	12.7
TDS	289	846	140000	434000	411000	116000	21	176
TOC	3.33	11.7	1420	7930	7110	592	7	1.79
COD	6.27	42.7	7000	43200	32500	-3740	-9	8.82
BOD	5.55	8.08	3230	39900	36000	-673	-2	4.07
NO_3^-	1.28	4.81	625	5820	5440	241	4	0.787
TKN	0.888	3.46	495	2060	1810	242	11	0.623
O-PO_4^-	0.0166	0.0577	14.8	43.5	35.0	6.23	13	0.0186
Total PO_4^-	0.0832	0.481	92.2	350	263	4.96	1	0.116
Chlordane	7.77E-05	0.000269	63.0	0.0580	0.0176	63.0	100	0.0794
F.Coli (cfu)	1.83E+07	6.54E+09	8.02E+11	8.45E+12	6.67E+12	-9.89E+11	-13	1.01E+09
F.Strep(cfu)	2.78E+07	9.81E+09	4.33E+12	4.67E+12	3.39E+12	3.05E+12	39	5.46E+09
Pb	0.0505	0.106	15.8	101	71.8	-13.7	-16	0.0199
Cu	0.0250	0.0404	7.83	51.7	40.6	-3.31	-7	0.00987
Zn	0.0300	0.471	42.4	203	158	-3.05	-2	0.0534
As	0.123	0.548	47.3	345	292	-6.25	-2	0.0596

All quantities are in Kg except:

1) %T (dimensionless)
2) $M_{in,storm}$ (/ac) (Kg/acre)
3) Biologicals, i.e., F. Coli. and F. Strep., which are in cfu rather than Kg

Table 26: Pollutant Mass Balance Calculations for Event 2 – Sump D

Pollutant	$M_{in,o}$	$M_{in,end}$	$M_{in,storm}$	$M_{out,p}$	$M_{in,m}$	M_{sump}	%T	$M_{in,storm}$ (/ac)
TSS	1990	10500	110000	117000	114000	98500	44	60.3
VSS	664	1930	19200	19000	18600	17500	46	10.5
TDS	58600	77100	293000	449000	440000	266000	36	161
TOC	194	1070	2710	7490	7340	1680	17	1.49
COD	1530	1980	26400	34000	33300	25300	42	14.5
BOD	431	351	4990	36900	36100	4271	10	2.74
NO_3^-	166	473	1160	2830	2770	793	20	0.636
TKN	71.9	123	1350	1230	1200	1270	50	0.741
O-PO_4^-	2.21	1.75	11.3	29.2	28.6	11.1	28	0.00621
Total PO_4^-	11.1	19.3	84.5	167	164	72.9	29	0.0464
Chlordane	0	0	0.0126	0.000315	0.000312	0.0126	98	6.94E-06
F.Coli (cfu)	5.53E+07	1.93E+10	2.32E+11	9.56E+11	9.35E+11	1.92E+11	16	1.27E+08
F.Strep(cfu)	5.53E+07	3.33E+10	3.59E+11	4.22E+12	4.13E+12	2.32E+11	5	1.97E+08
Pb	6.08	2.63	197	145	142	197	58	0.108
Cu	1.77	2.28	37.1	50.4	49.3	35.6	41	0.0204
Zn	3.04	6.84	53.7	96.8	94.7	47.8	32	0.0294
As	18.4	33.3	376	389	381	353	47	0.206

All quantities are in Kg except:

1) %T (dimensionless)
2) $M_{in,storm}$ (/ac) (Kg/acre)
3) Biologicals, i.e., F. Coli. and F. Strep., which are in cfu rather than Kg

Table 27: Pollutant Mass Balance Calculations for Event 3 – Sump C

Pollutant	$M_{in,o}$	$M_{in,end}$	$M_{in,storm}$	$M_{out,p}$	$M_{in,m}$	M_{sump}	%T	$M_{in,storm}$ (/ac)
TSS	72.6	89.6	13900	7620	2209	8500	53	17.5
VSS	16.1	24.1	1930	1430	440	900	38	2.43
TDS	220	575	17000	23700	7844	1000	4	21.4
COD	0	51.3	1640	481	280	1390	72	2.07
Pb	0.0524	0.234	7.43	10.00	2.67	-0.081	-1	0.00937
Cu	0.0339	0.0762	2.34	2.97	1.04	0.370	11	0.00295
Zn	0.0947	0.246	7.71	11.97	4.59	0.183	1	0.00972
As	0.223	0.333	10.6	18.3	5.4	-2.39	-15	0.0134

All quantities are in Kg except:

1) %T (dimensionless)
2) $M_{in,storm}$ (/ac) (Kg/acre)

Table 28: Pollutant Mass Balance Calculations for Event 3 – Sump D

Pollutant	$M_{in,o}$	$M_{in,end}$	$M_{in,storm}$	$M_{out,p}$	$M_{in,m}$	M_{sump}	%T	$M_{in,storm}$ (/ac)
TSS	36100	13300	14100	22200	21600	36300	102	7.74
VSS	5900	2940	1760	4130	3960	4550	80	0.966
TDS	120000	118000	77000	151000	145000	73000	33	42.2
COD	6090	8720	3370	7290	7050	500	5	1.85
Pb	32.5	95.6	17.7	79.4	76.4	-48.5	-52	0.00972
Cu	16.4	18.1	6.02	20.7	19.9	3.69	14	0.00330
Zn	30.4	8.44	9.70	19.7	18.8	30.7	108	0.00532
As	52.5	63.2	21.5	66.0	63.7	8.43	10	0.0118

All quantities are in Kg except:

1) %T (dimensionless)
2) $M_{in,storm}$ (/ac) (Kg/acre)

Table 29: Pollutant Mass Balance Calculations for Event 4 – Sump C

Pollutant	$M_{in,o}$	$M_{in,end}$	$M_{in,storm}$	$M_{out,p}$	M_{sump}	%T	$M_{in,storm}$ (/ac)
TSS	19.0	8.91	9200	11600	-2390	-26	11.6
VSS	7.65	5.98	2210	2780	-568	-26	2.78
TDS	29.3	63.5	12600	12100	466	4	15.9
COD	10.5	8.70	3480	3360	122	4	4.39
Pb	0.0900	0.0400	21.8	24.4	-2.53	-12	0.0275
Cu	0.00602	0.000977	1.39	1.69	-0.296	-21	0.00175
Zn	0.0534	0.0309	26.6	18.4	8.23	31	0.0335
As	0.0734	0.0138	9.05	13.4	-4.26	-47	0.0114

All quantities are in Kg except:

1) %T (dimensionless)
2) $M_{in,storm}$ (/ac) (Kg/acre)

Table 30: Pollutant Mass Balance Calculations for Event 4 – Sump D

Pollutant	$M_{in,o}$	$M_{in,end}$	$M_{in,storm}$	$M_{out,p}$	M_{sump}	%T	$M_{in,storm}$ (/ac)
TSS	18000	13600	42100	0	46500	110	23.1
VSS	6510	2020	6810	0	11300	166	3.74
TDS	73000	63000	60100	0	70100	117	33.0
COD	2550	2380	9970	0	10100	101	5.47
Pb	34.7	25.5	51.5	0	60.7	118	0.0283
Cu	1.53	1.21	39.8	0	40.1	101	0.0218
Zn	24.7	17.8	43.8	0	50.7	116	0.0241
As	22.4	15.2	24.3	0	31.5	130	0.0133

All quantities are in Kg except:

1) %T (dimensionless)
2) $M_{in,storm}$ (/ac) (Kg/acre)

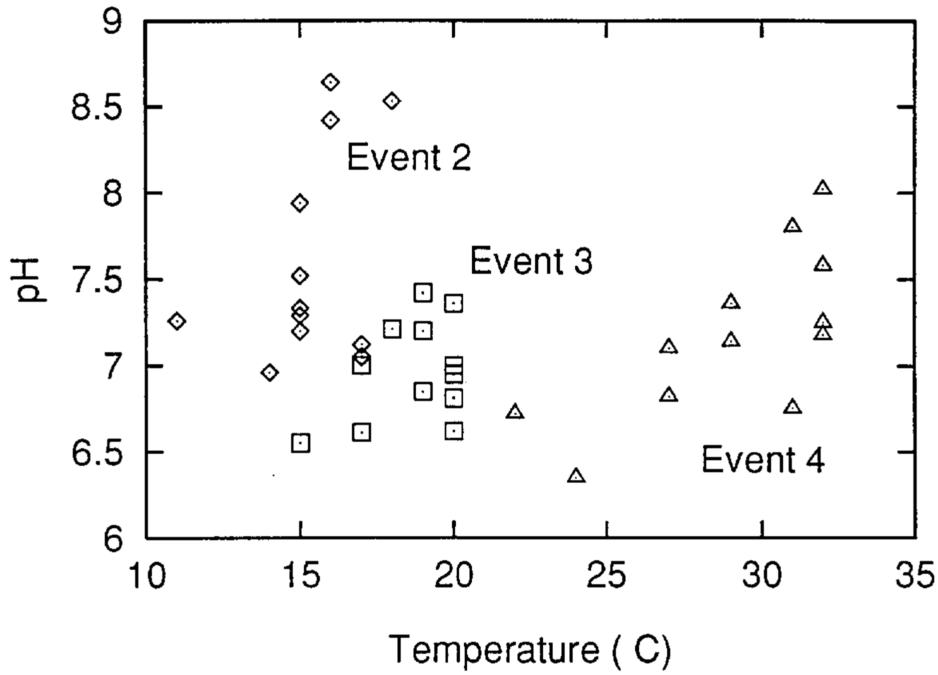


Figure 24: Relationship Between pH and Temperature in Sump Samples.

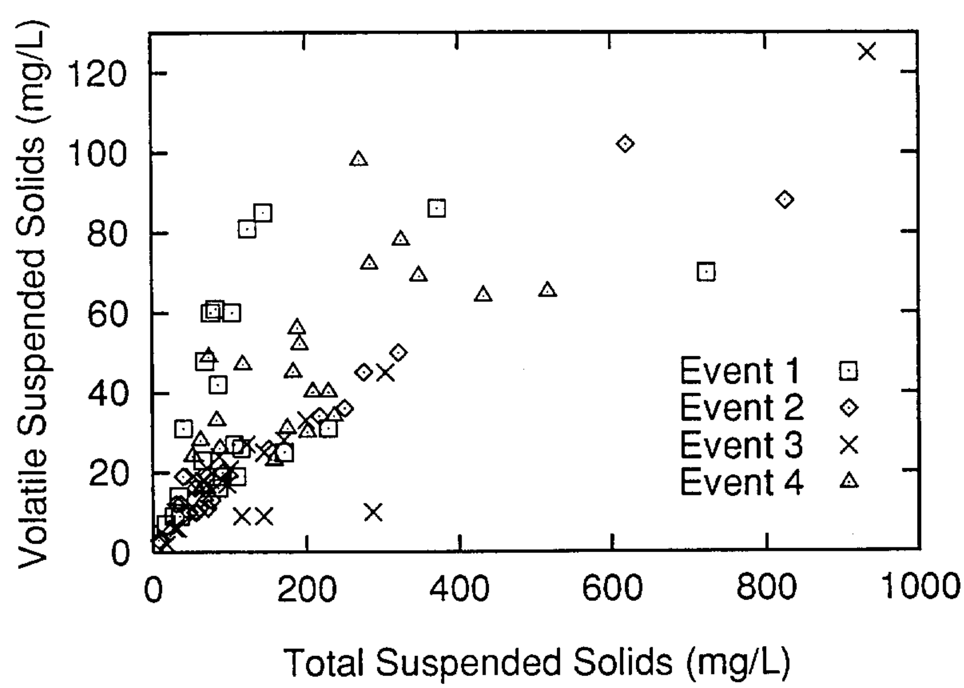


Figure 25: Correlation Between VSS and TSS for All Stormwater Samples.

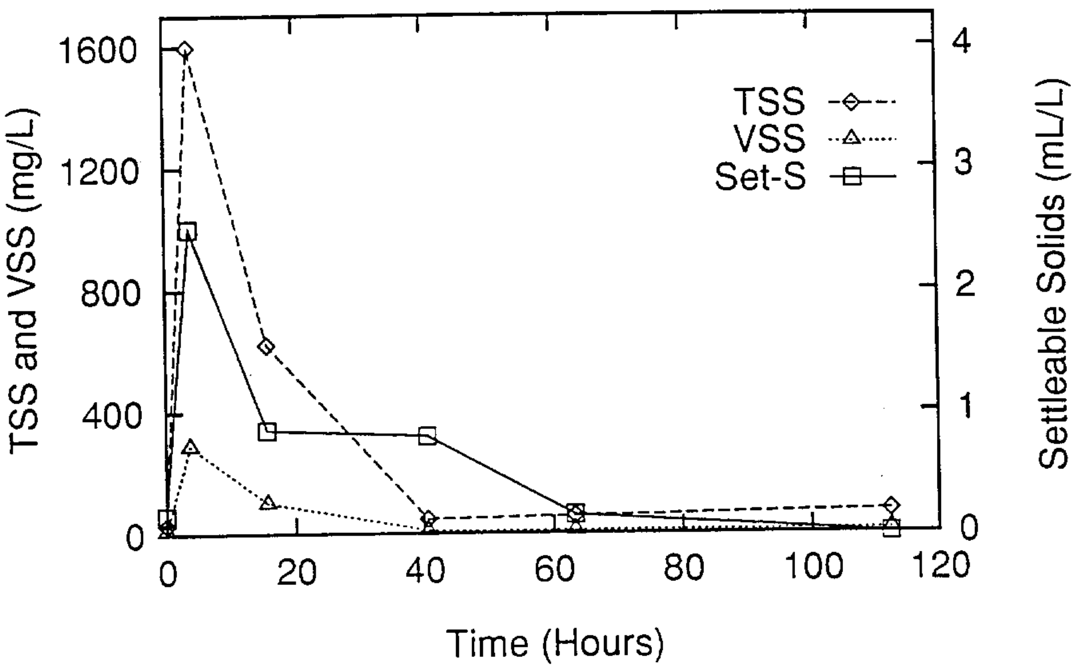


Figure 26: Solids Concentrations Versus Time for Sump C and Event 2.

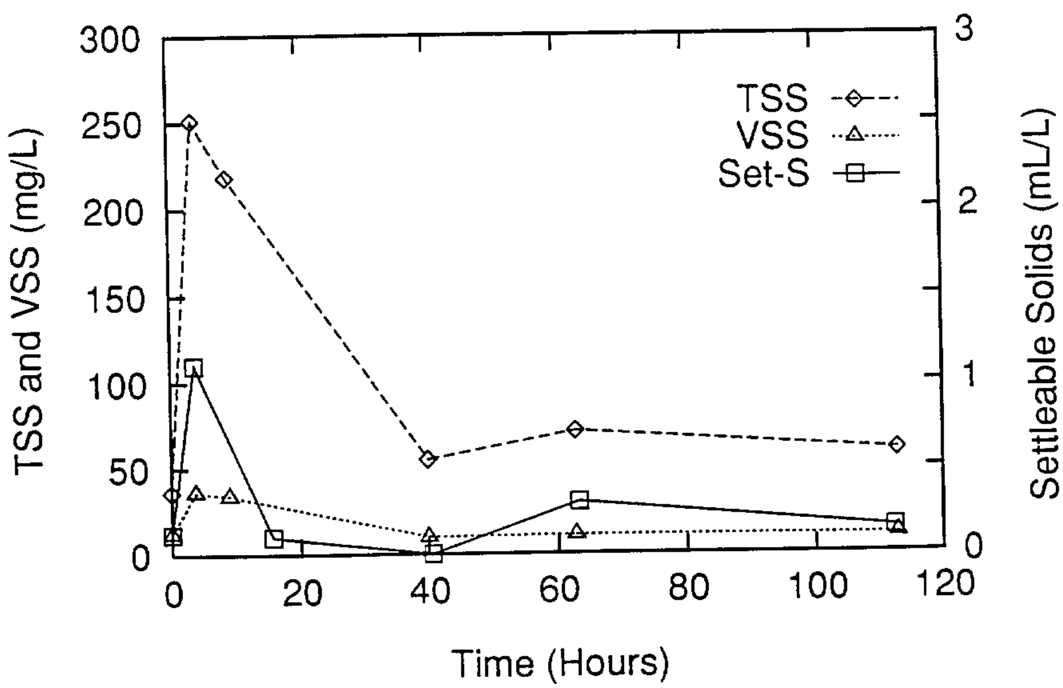


Figure 27: Solids Concentrations Versus Time for Sump D and Event 2.

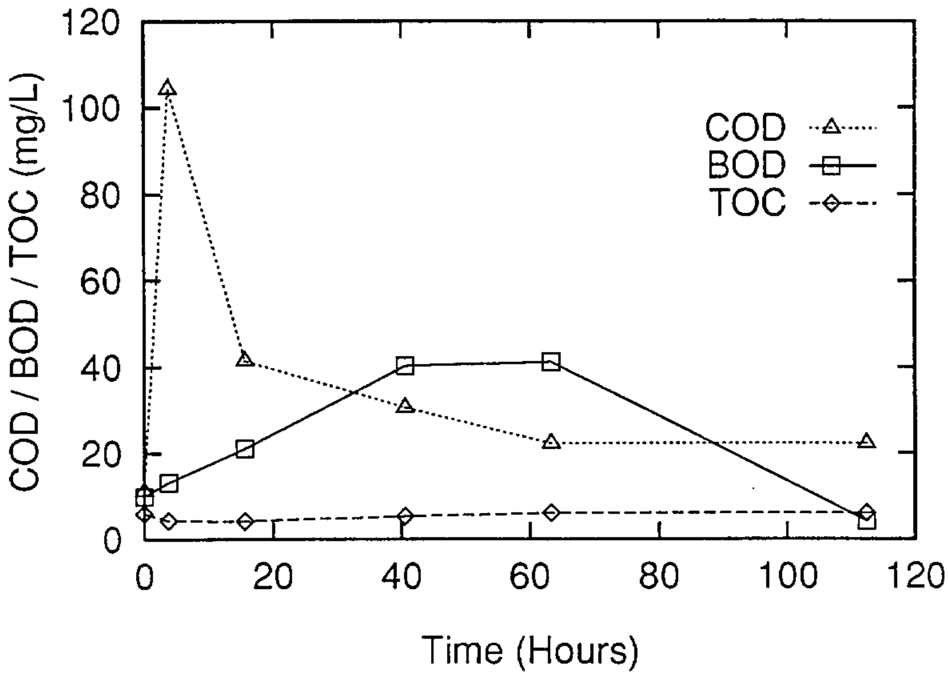


Figure 28: Surrogate Organic Concentrations Versus Time for Sump C and Event 2.

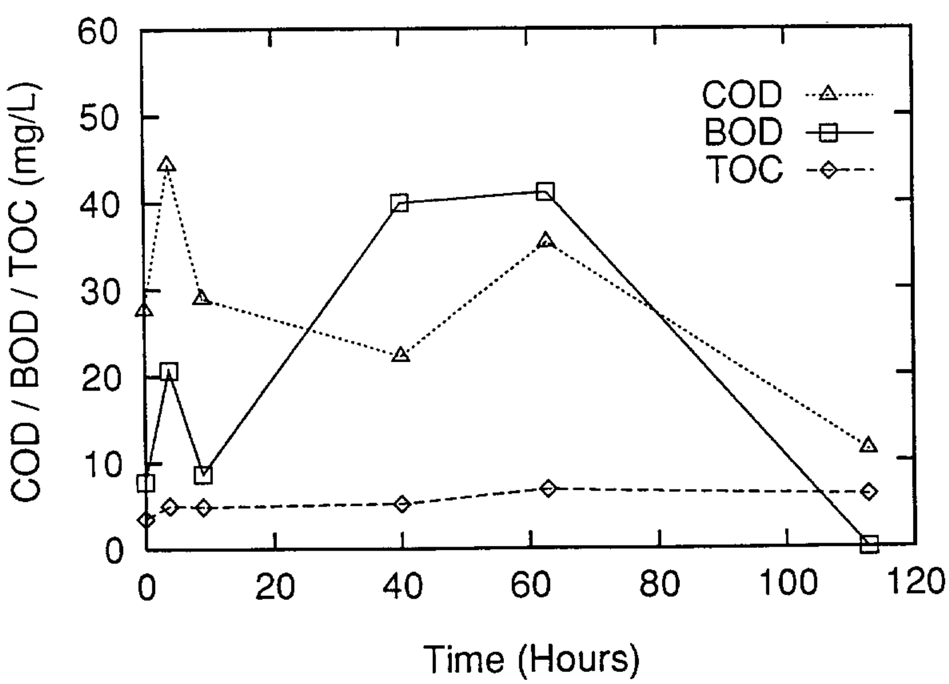


Figure 29: Surrogate Organic Concentrations Versus Time for Sump D and Event 2.

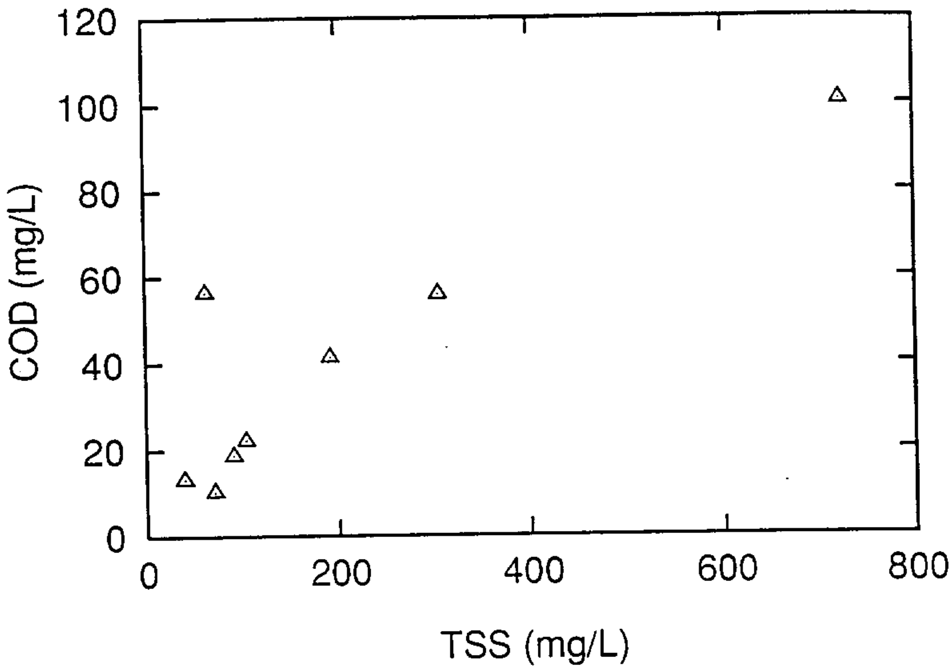


Figure 30: COD Versus TSS for Outfall Sampling Station C-2 (All Events).

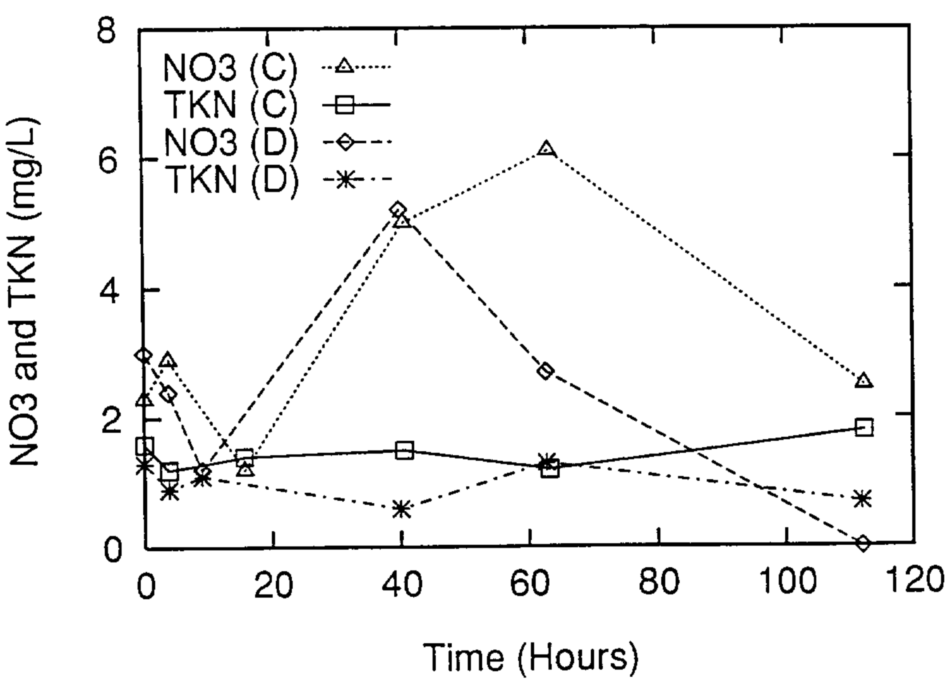


Figure 31: Nitrogen Concentrations Versus Time for Sumps C and D for Event 2.

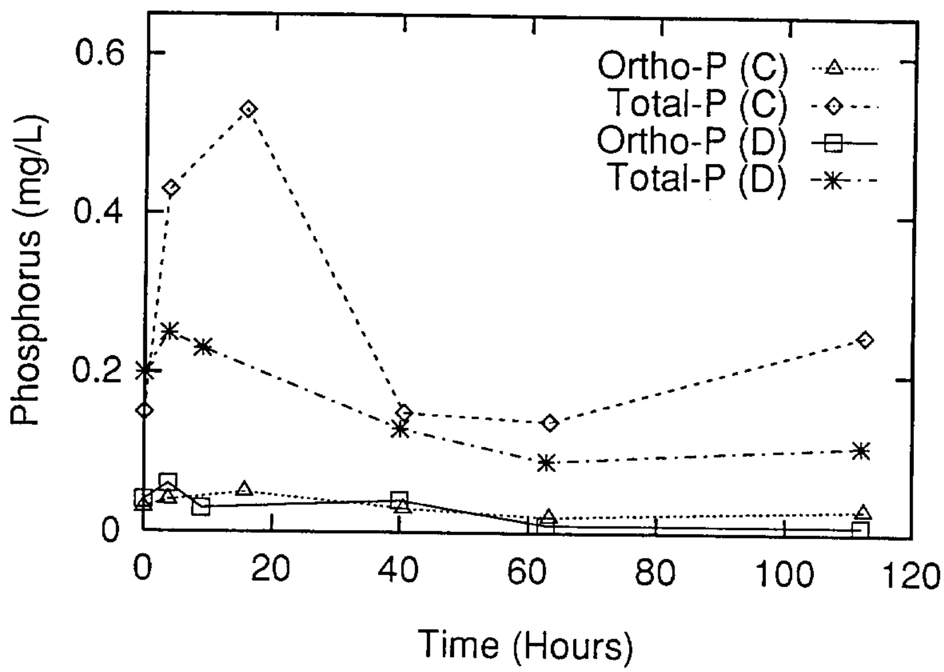


Figure 32: Phosphorus Concentrations Versus Time for Sumps C and D for Event 2.

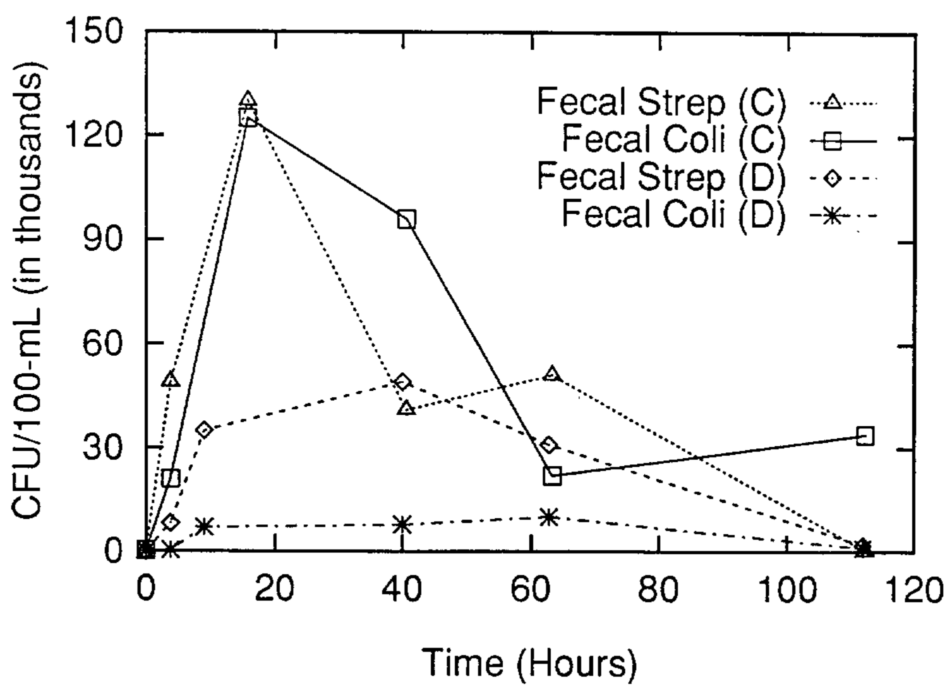


Figure 33: Fecal Coliform and Streptococcus Concentrations Versus Time for Sumps C and D for Event 2.

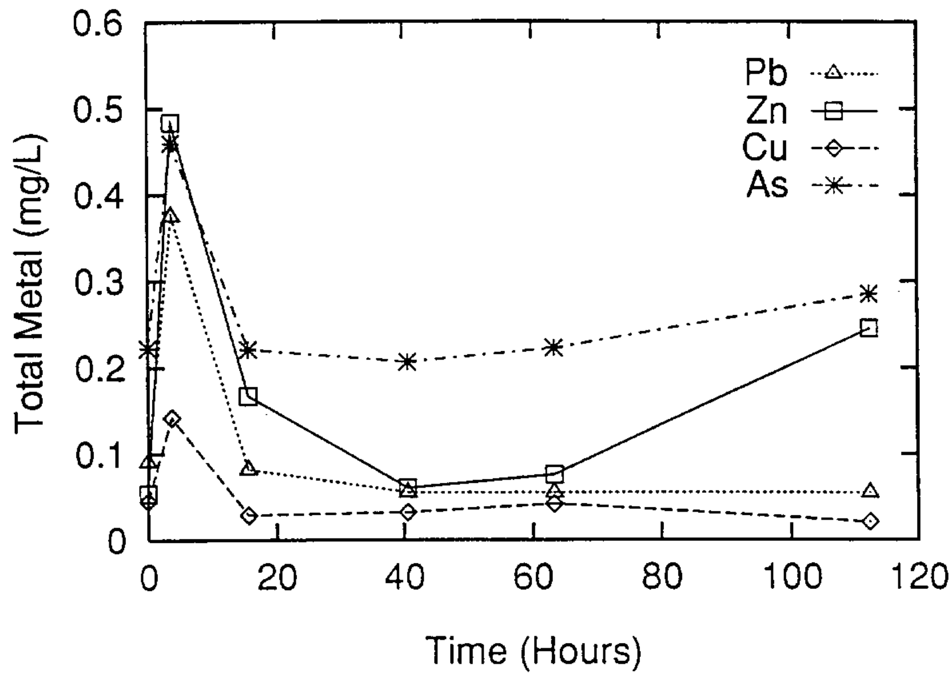


Figure 34: Metal Concentrations Versus Time for Sump C and Event 2.

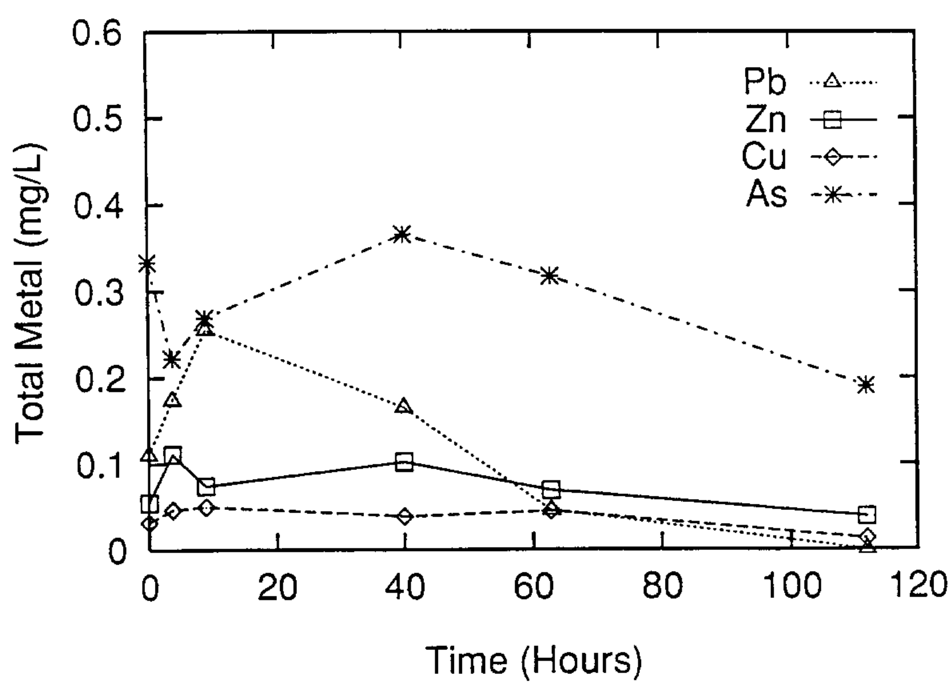


Figure 35: Metal Concentrations Versus Time for Sump D and Event 2.

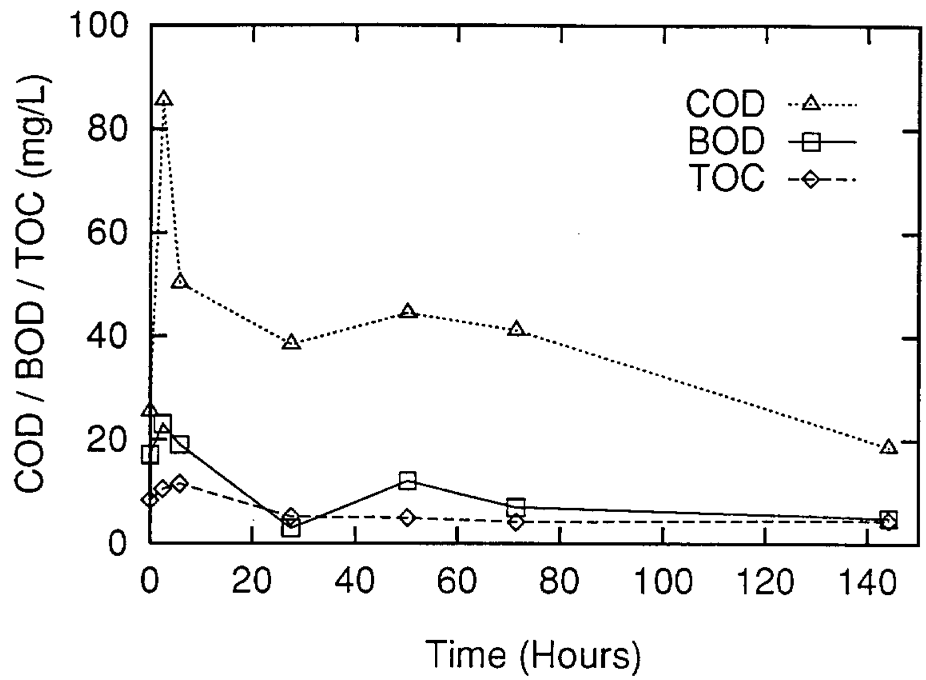


Figure 36: Surrogate Organic Concentrations Versus Time for Sump C and Event 1.

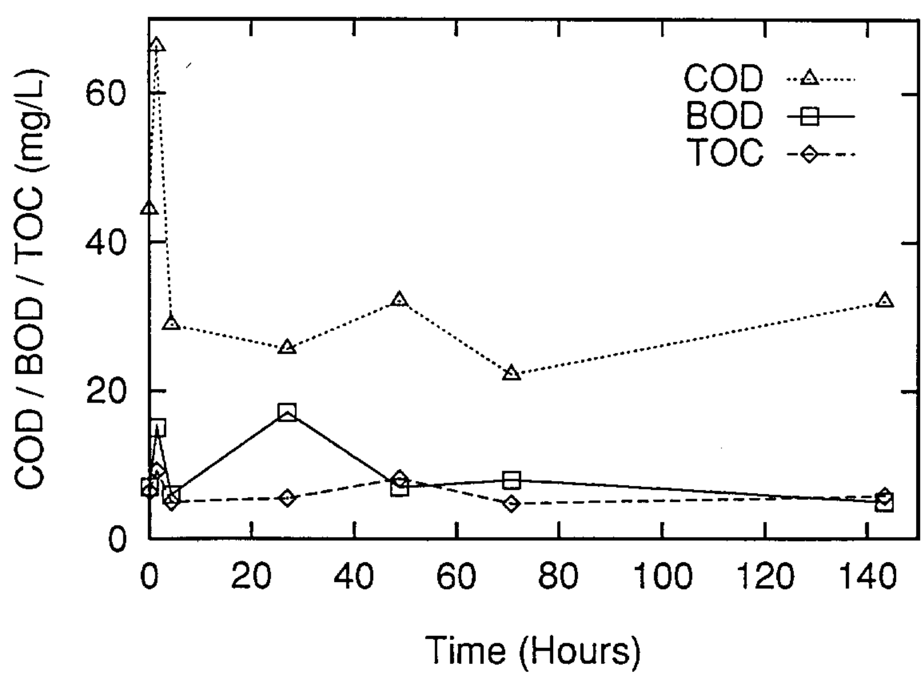


Figure 37: Surrogate Organic Concentrations Versus Time for Sump D and Event 1.

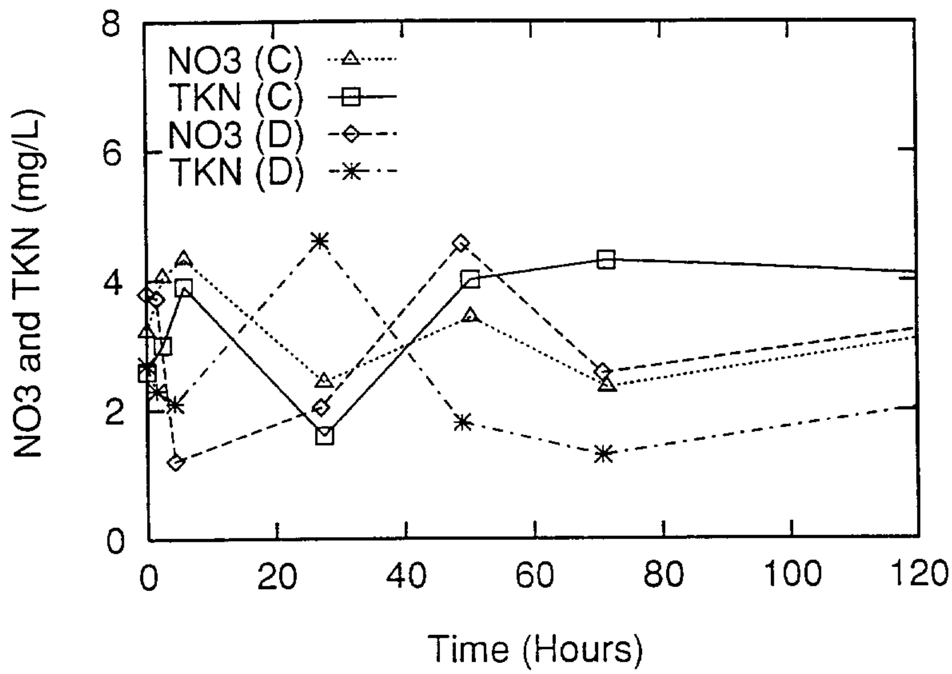


Figure 38: Nitrogen Concentrations Versus Time for Sumps C and D for Event 1.

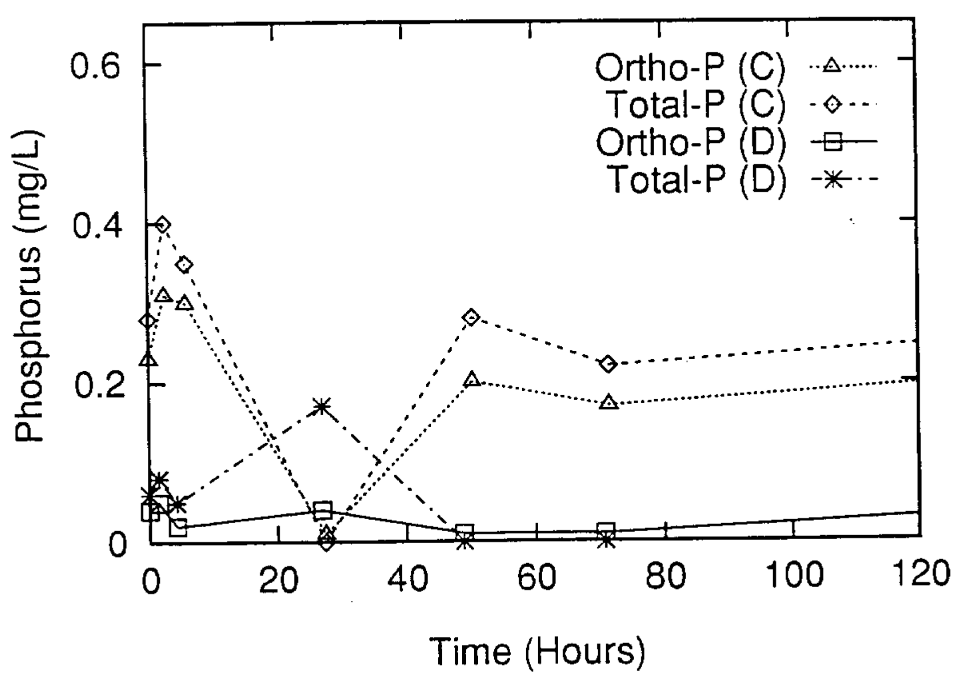


Figure 39: Phosphorus Concentrations Versus Time for Sumps C and D for Event 1.

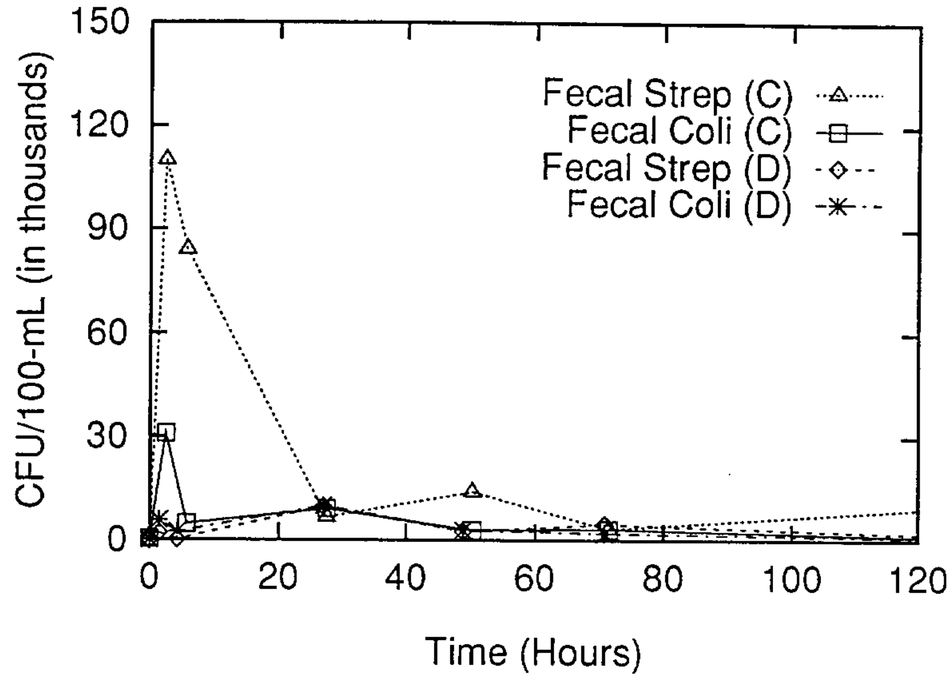


Figure 40: Fecal Coliform and Streptococcus Concentrations Versus Time for Sumps C and D for Event 1.

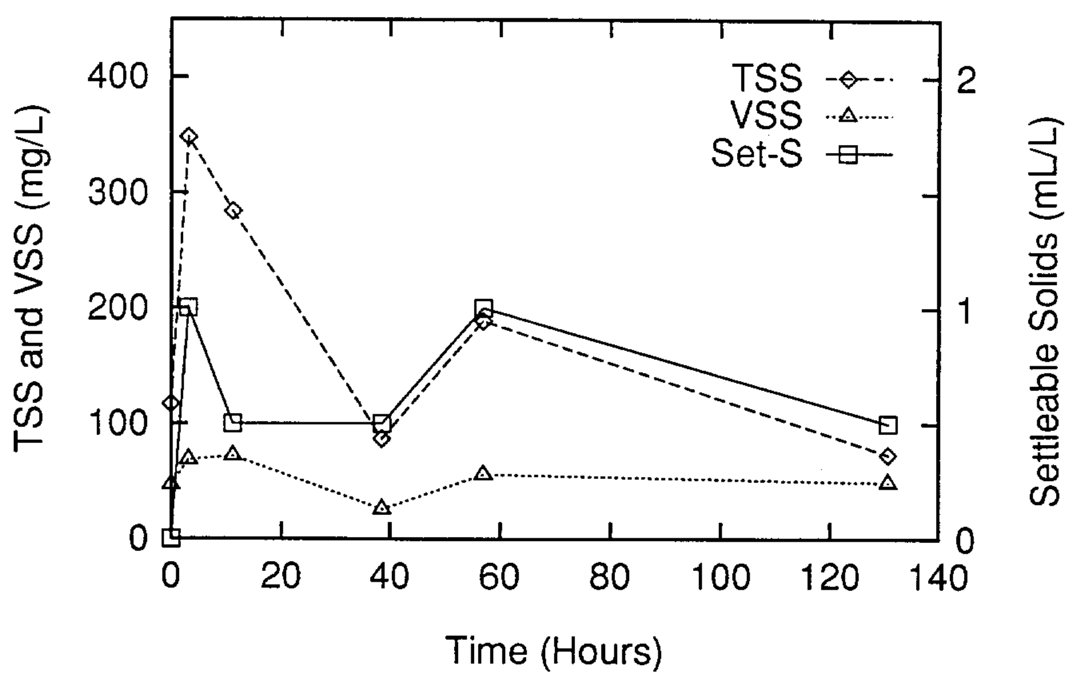


Figure 41: Solids Concentrations Versus Time for Sump C and Event 4.

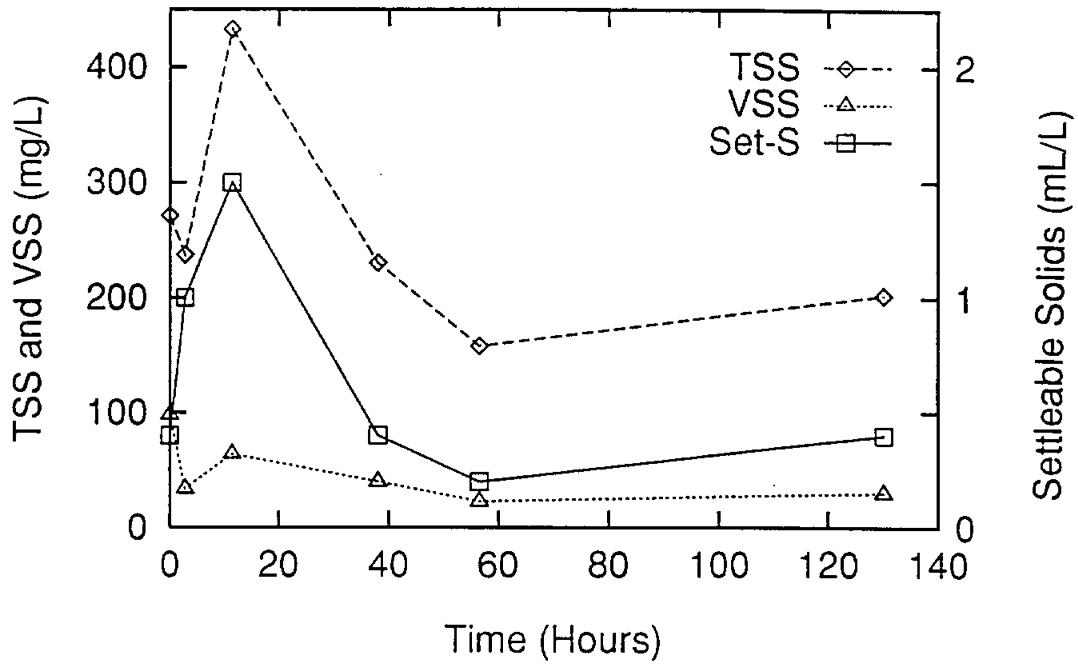


Figure 42: Solids Concentrations Versus Time for Sump D and Event 4.

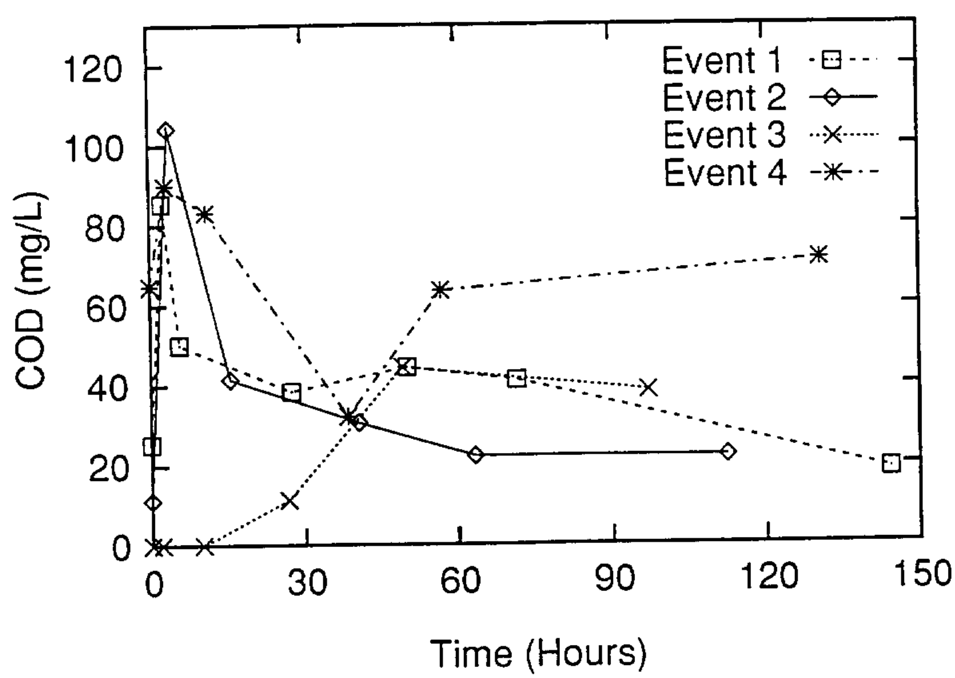


Figure 43: COD Concentrations Versus Time for Sump C (All Events).

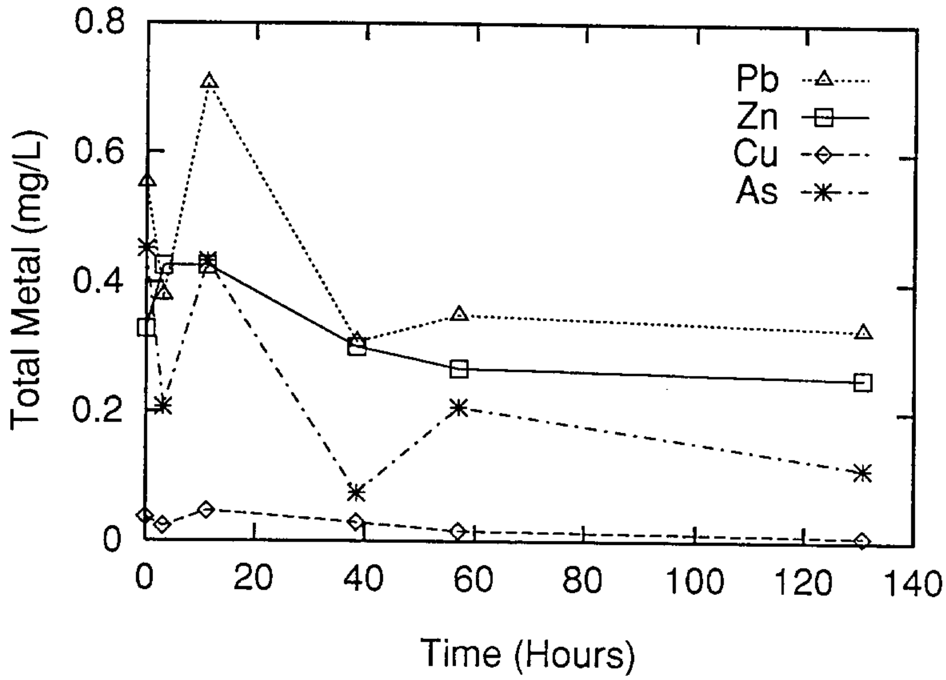


Figure 44: Metal Concentrations Versus Time for Sump C and Event 4.

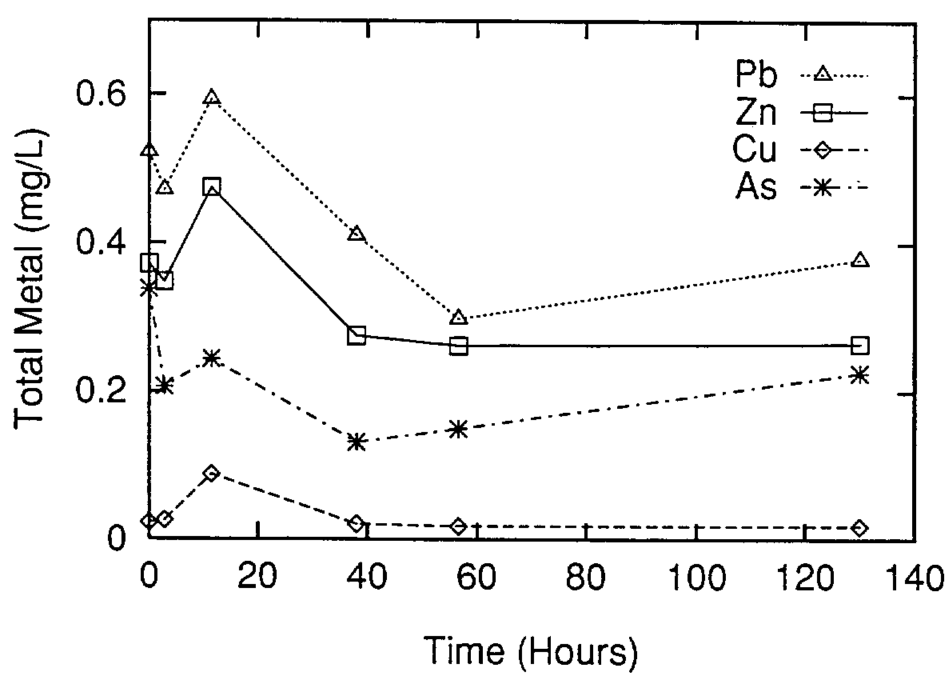


Figure 45: Metal Concentrations Versus Time for Sump D and Event 4.

4 CONCLUSIONS AND RECOMMENDATIONS

4.1 Sump Performance Assessment Procedure

Although assessing the performance of flood-control sumps involves all the complexities and challenges normally associated with nonpoint source evaluation, a potentially useful and transferable protocol is in development as a result of this study. The major tasks in such an assessment procedure are the following.

1) Identification and calculation of all sub-drainage areas for a sump system, location of associated outfalls, and obtaining data on the physical characteristics of the sumps themselves.

2) Conduct a survey of sump management procedures, including the operation of pumps and flow control structures, for different types of events.

3) Design a program for collecting continuous rainfall data, river and sump elevations, pumping activities, and stormwater flows in sump outfalls for test events. In the absence of flow data for individual outfalls, this work demonstrated that HEC-1 calculations could provide a useful estimate of the overall runoff hydrograph to two sumps of highly variable hydraulic character. The total hydrographs were validated by a water balance calculation using independent measurements, lending credibility to the use of HEC-1 generated hydrographs for individual sump outfalls for the purpose of calculating pollutant loads to the sump. The hydraulic modeling exercise also enabled estimation of miscellaneous water gains otherwise difficult to moñitor such as inflows from interconnected symp systems and backflow from the river.

4) Collection of stormwater samples in the vicinity of the sump pumping station and selected outfalls as a function of time will enable estimation of pollutant loads to and discharge from the sump, and estimation of pollutant removal in the sump by settling and other physical-chemical processes.

4.2 Pollutant Runoff and Treatment Efficiency

Important findings with respect to pollutant loads and removals in flood-control sumps are:

1) Results of the stormwater sampling program are mostly consistent with other urban stormwater studies in general, and previous Trinity floodplain studies in particular. A mass balance approach provided a means for estimating pollutant loads and removals with respect to the sumps. The results revealed similar loadings per acre from the two study areas (Sump C and D drainage zones). Sump versus outfall pollutant analyses as well as mass balance calculations also suggest that more rigorous sampling, especially with respect to the outfalls to the sump, is needed to obtain more consistent and reliable results.

2) Substantial removals of several classes of stormwater pollutants do occur in the sumps under the right conditions.

3) As hypothesized, sumps of varying detention provide varying levels of treatment of pollutants. In events of sufficient size to require substantial pumping, Sump D provided a much higher level of pollutant removal than Sump C, a result consistent with the fact that stormwater detention in Sump D is more than an order of magnitude higher. Therefore, from a water quality perspective, sumps are a better stormwater management practice than simple pumping.

4) Post-event sediment analysis provided verification of pollutant capture with sediment pollutant concentrations for various events roughly correlated with the magnitude of and operational procedures relative to the event.

4.3 Recommendations / Proposed Investigations

Key recommendations with respect to sump management deriving from this study are the following.

1) City and regional agencies responsible for stormwater management should recognize that the sumps can indeed provide substantial treatment of stormwater pollutants and take credit for pollutant removals in stormwater management reporting and permit applications. With this in view, they should also continue to pursue studies of this nature in order to more accurately specify pollutant loads to various sump systems and the extent of treatment being achieved.

2) The City should explore methods to enhance pollutant removals in existing sump systems as an alternative to new construction for stormwater pollution control. Some ideas in this regard include the following.

    a) Given the relationship of pollutant removals to sump detention, there may be ways to alter smaller sump systems such as Sump C to increase detention. While enlarging Sump C basins themselves is likely impractical, it may be possible to hydraulically link this system to a larger existing one or with new sump construction to the south. This would increase flexibility in stormwater routing/control and increase detention, thereby improving the removal of pollutants. In certain instances, multiple sump systems may function as treatment reactors in series, providing a high level of pollutant removal.

    b) In general, the guiding principle should be to add sump capacity versus pump capacity.

    c) Certainly, pumping requirements in the system will continue to be substantial. However, to the extent that stormwater quality issues continue to grow in importance, the sump management operations may explore alternatives in their pumping stategy based on better weather forecasting methods in order to increase water detention in the sumps for certain classes of storm events. This is most feasible for sumps such as D that already have a large capacity.

3) The City should carefully examine the possibility and potential pathways of backflow from the river to the sumps and, if discovered, take necessary measures to eliminate these flows as they increase pumping and energy requirements, and can reduce detention of actual storm runoff from sump drainage areas.

4) Sediment removal from the sumps should continue according to its current practice. Perhaps as more outfalls are monitored and certain ones identified as major contributors of solids and associated pollutants, the City may consider installation of sediment forebays at these sites to facilitate greater ease of sediment removal and eliminate the more costly dredging activities near the pumping stations.

5) Follow-up investigations should consider one or more of the following issues:

    a) Testing and verification of some of the major assumptions employed in the current study. For instance, a weir or other flow monitoring device should be installed at a few selected outfalls to compare measured outfall hydrographs with those generated by HEC-1 calculations. More frequent sampling of an outfall during an event should be performed to obtain a more accurate calculation of pollutant loads to the sumps. Once a data base has been developed in this regard, there are stochastic methods that can be invoked to predict the pollutant distribution in unmonitored outfalls or even for future events given the outfall flow hydrograph. Sampling of additional outfalls, including contributions from interconnected sump zones as in the case of Sump D, should also improve pollutant load estimates and sump treatment calculations.

b) The hydraulic modeling schemes developed in the work should be tested for more events. The best method should be sought for integrating HEC-1 calculations with the water balance model to develop a sump management tool that can test, for example, the sensitivity of sump hydraulic parameters to alterations in pumping strategy or manipulation of other flood control structures in a sump system. In the case of Sump D, the adjacent and hydraulically connected sump areas should be studied in detail in an attempt to make better estimates of contributions to the Sump D pumping station during high-flow events and, thereby, accurate estimates of possible backflow from the river.

c) As indicated previously, this study examined two sumps of highly variable hydraulic behavior, most notably in terms of stormwater detention. At least one or two other sumps of intermediate character should be investigated to validate and expand the findings of the current study.

d) Continue to expand the post-event sediment quality data base to determine the extent to which these data can provide an accurate picture of stormwater pollutant loads and sump treatment.

e) Although the attempt was made in this study to test for pollutants deemed important as a result of recent stormwater investigations in the region, limited resources prevented examination of some low-level toxic sustances of importance, most notably, diazinon. Future studies should test for diazinon levels in urban stormwater runoff to and from the sumps.

f) The studies outlined in (a) – (d) above, if performed at sufficient scale, should contribute significantly to floodplain development in general, and to design of sumps in particular, for effective flood control and water quality management. It is suggested that this would best be served by development of an integrated flow and pollutant transport model for sump systems. Once calibrated and verified, the model will serve as a relatively inexpensive design and evaluation tool for numerous aspects of the study. For instance, sensitivity analysis involving model inputs and/or coefficients can assess, quantitatively, the effects of structural or operational alternatives such as sump enlargement, sluice improvements, or pump capacity and scheduling on both flood control and water quality. In short, this would constitute a rational design approach to maximize utilization of the sumps for enhancing water quality in the floodplain while not compromising their performance as flood control structures.

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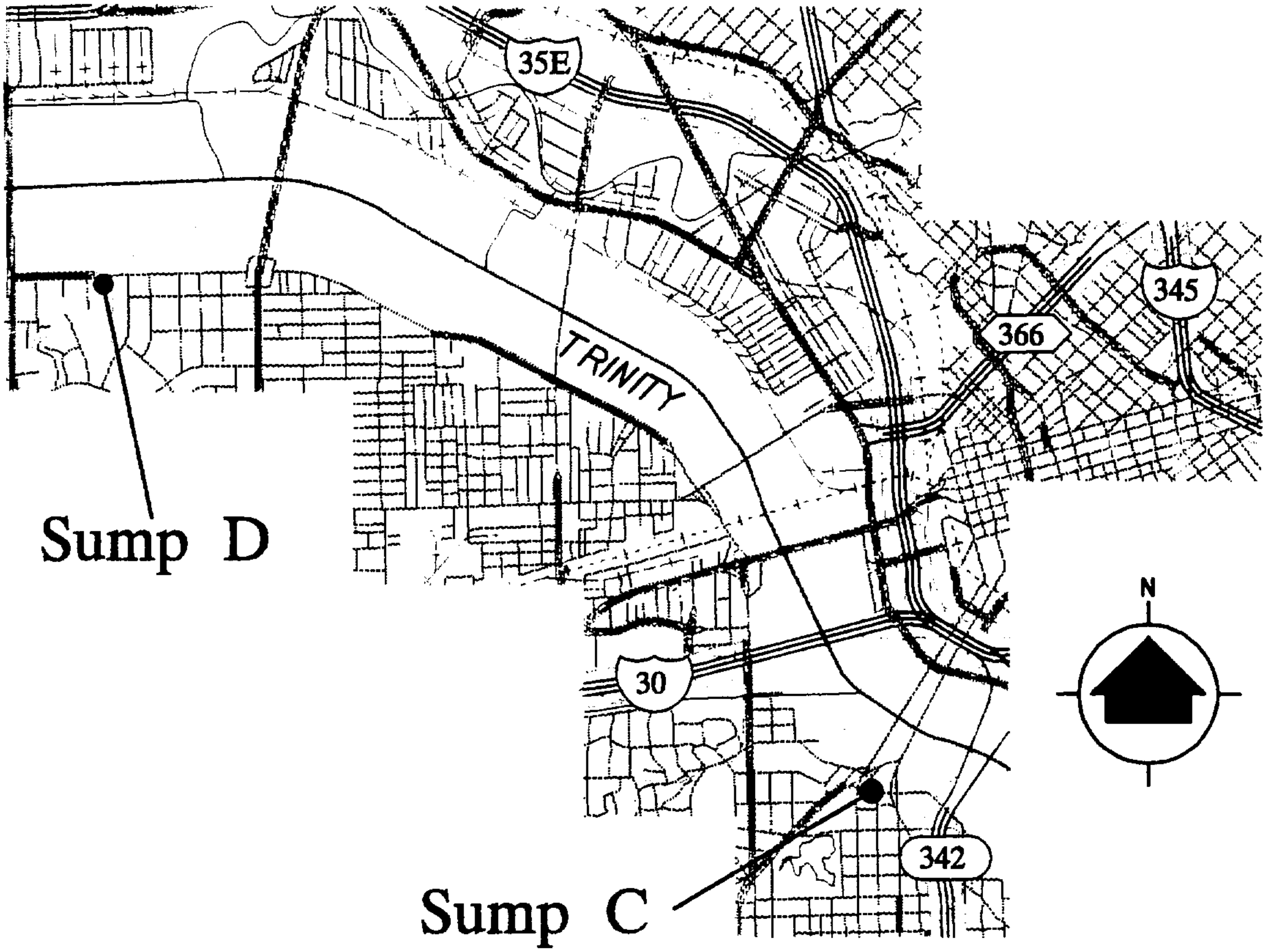
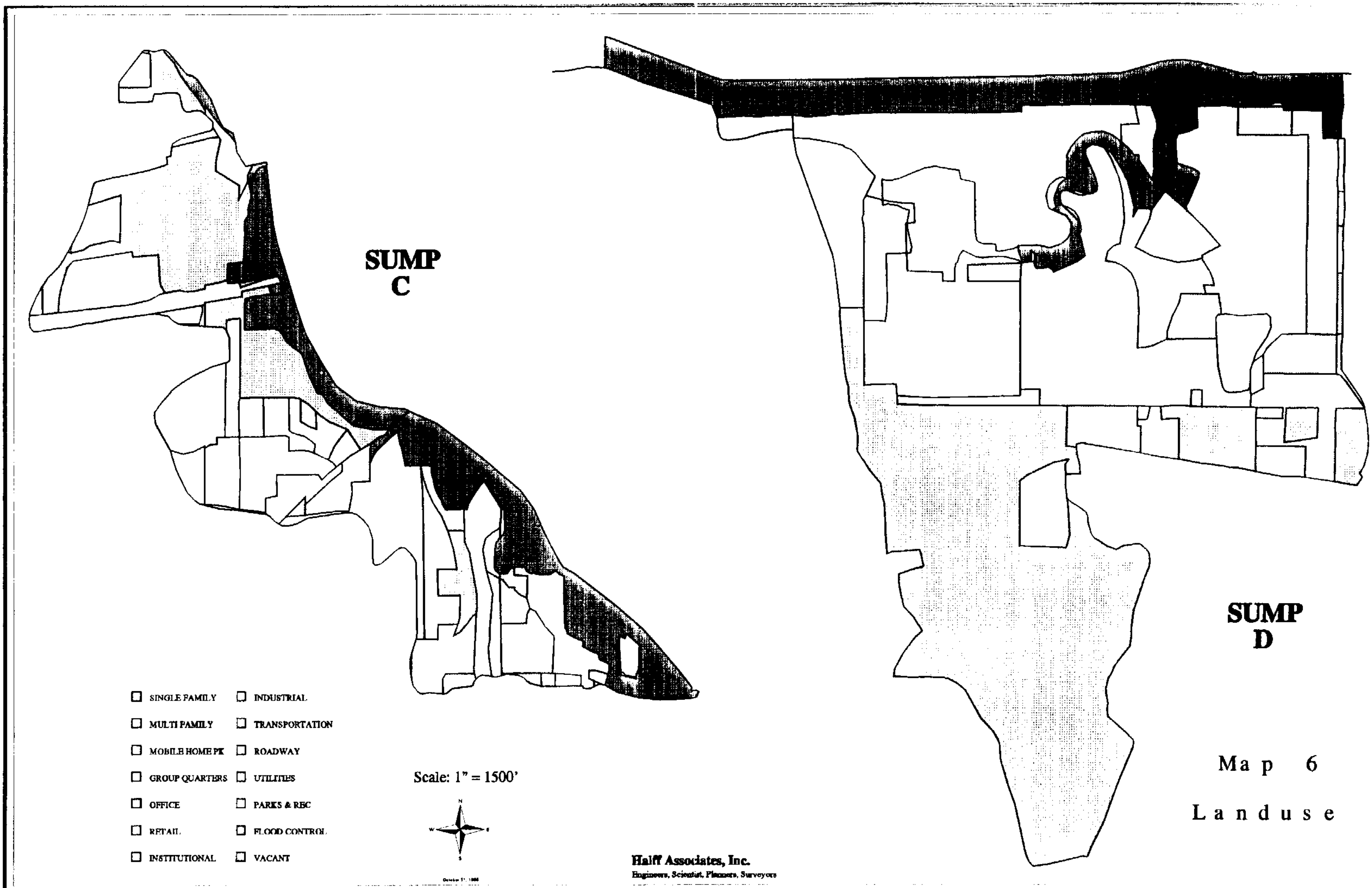
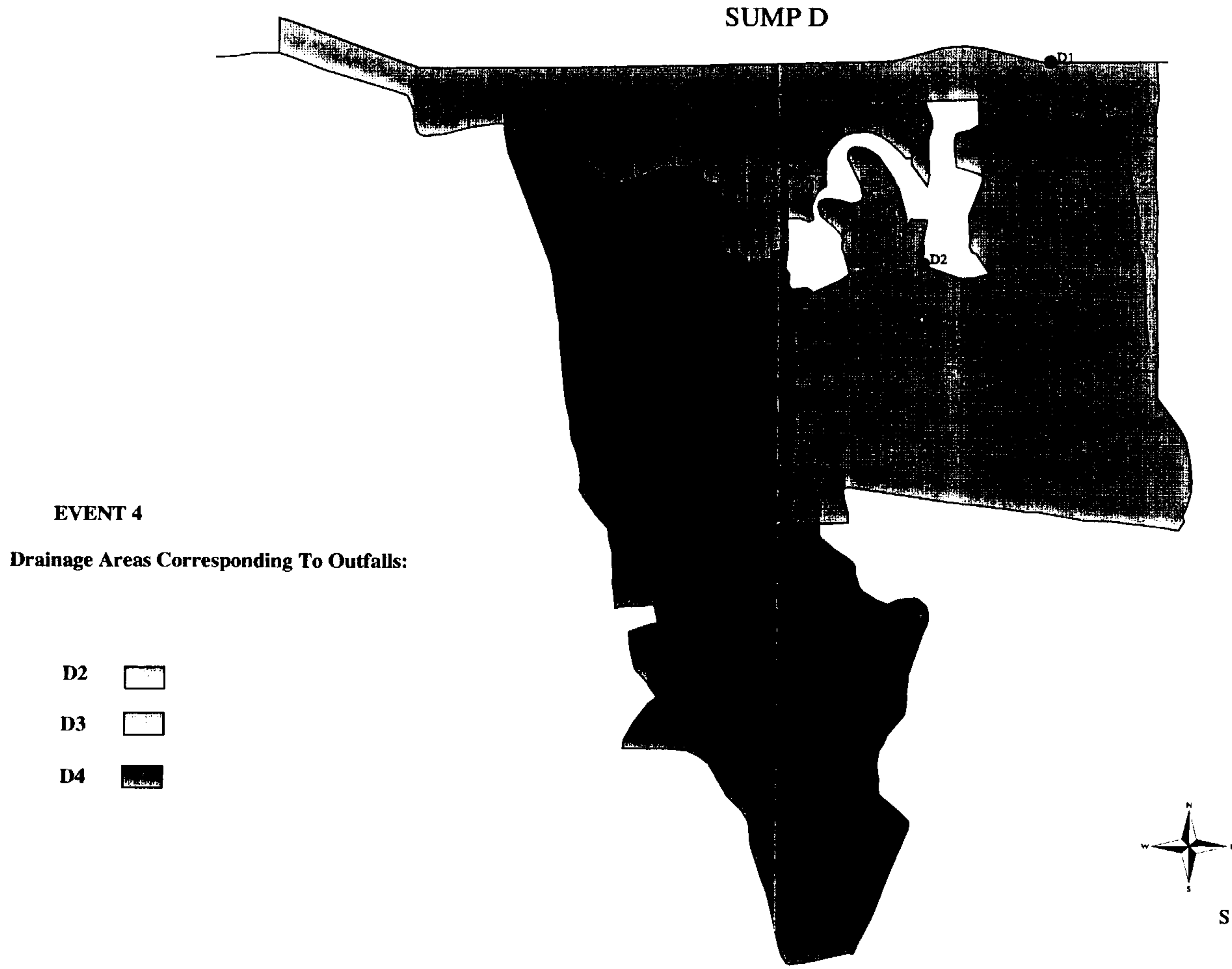


Map 1

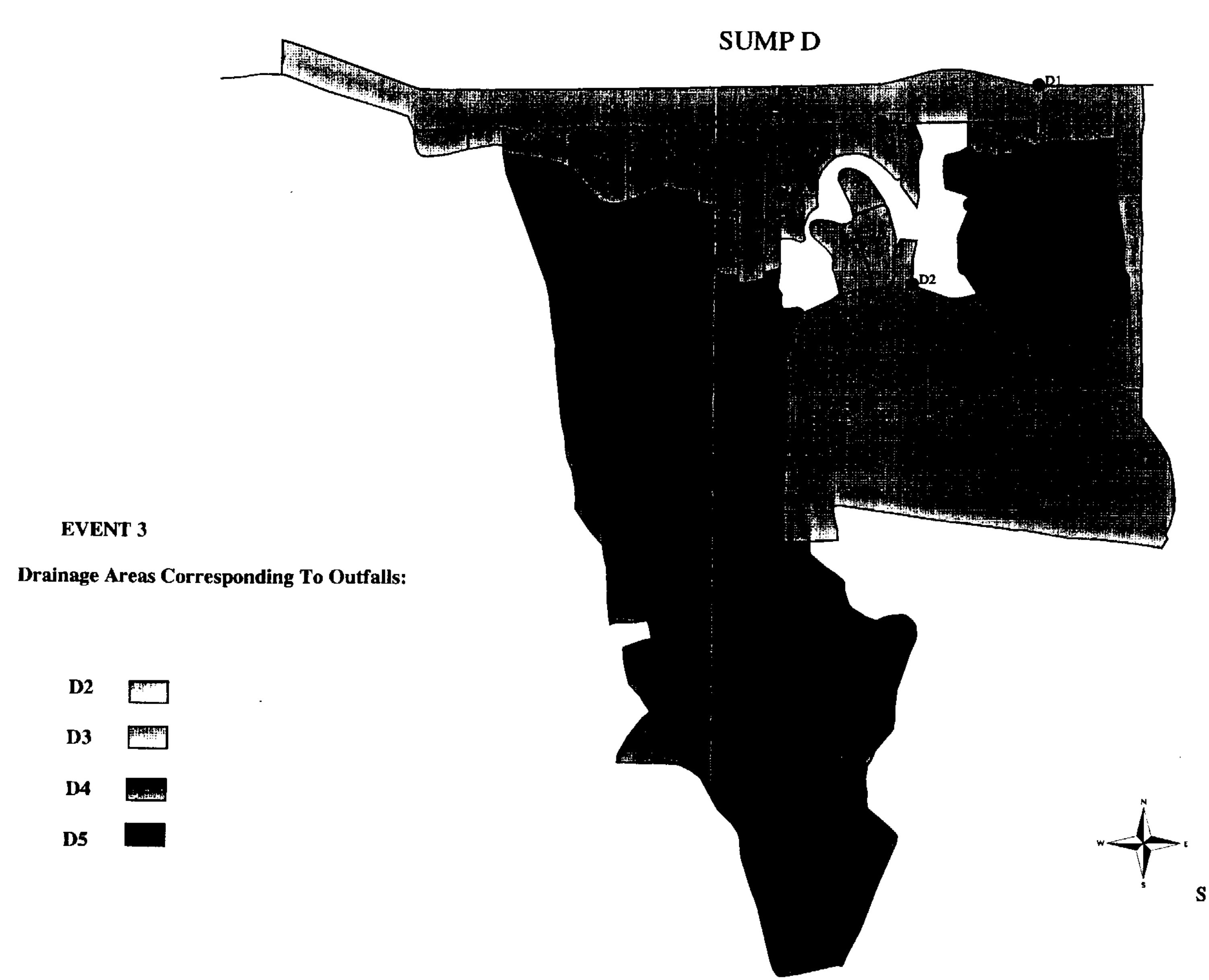
Sump Locations


SUMP
C
SUMP
D
SINGLE FAMILY
MULTI FAMILY
MOBILE HOME PK
GROUP QUARTERS
OFFICE
RETAIL
INSTITUTIONAL
INDUSTRIAL
TRANSPORTATION
ROADWAY
UTILITIES
PARKS & REC
FLOOD CONTROL
VACANT
Scale: 1" = 1500'
N
W
E
S
Halff Associates, Inc.
Engineers, Scientist, Planners, Surveyors
Map 6
Landuse



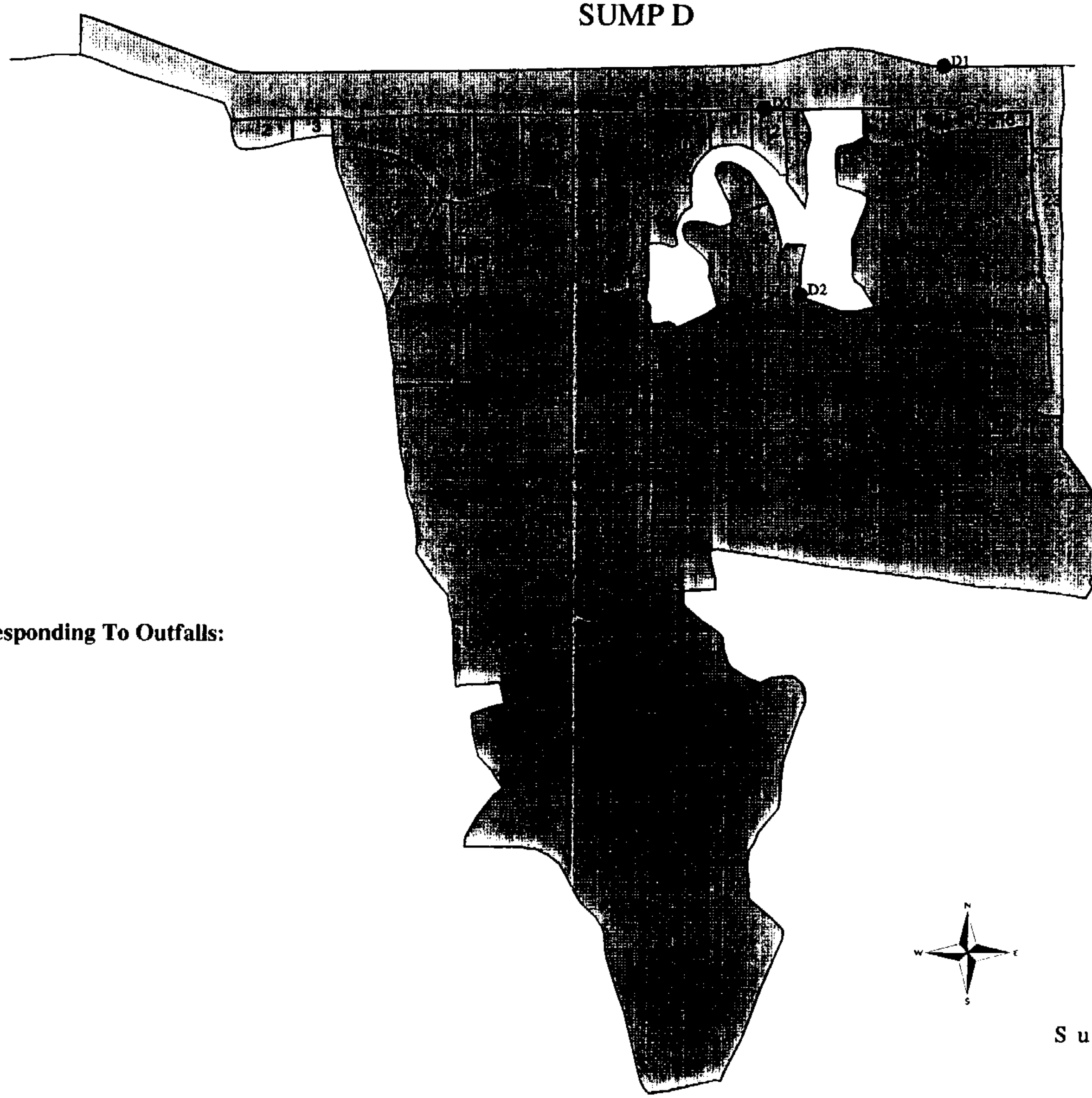
Map 5

Sump D (Event 4)



Map 4
Sump D (Event 3)

SUMP D



EVENTS 1 & 2

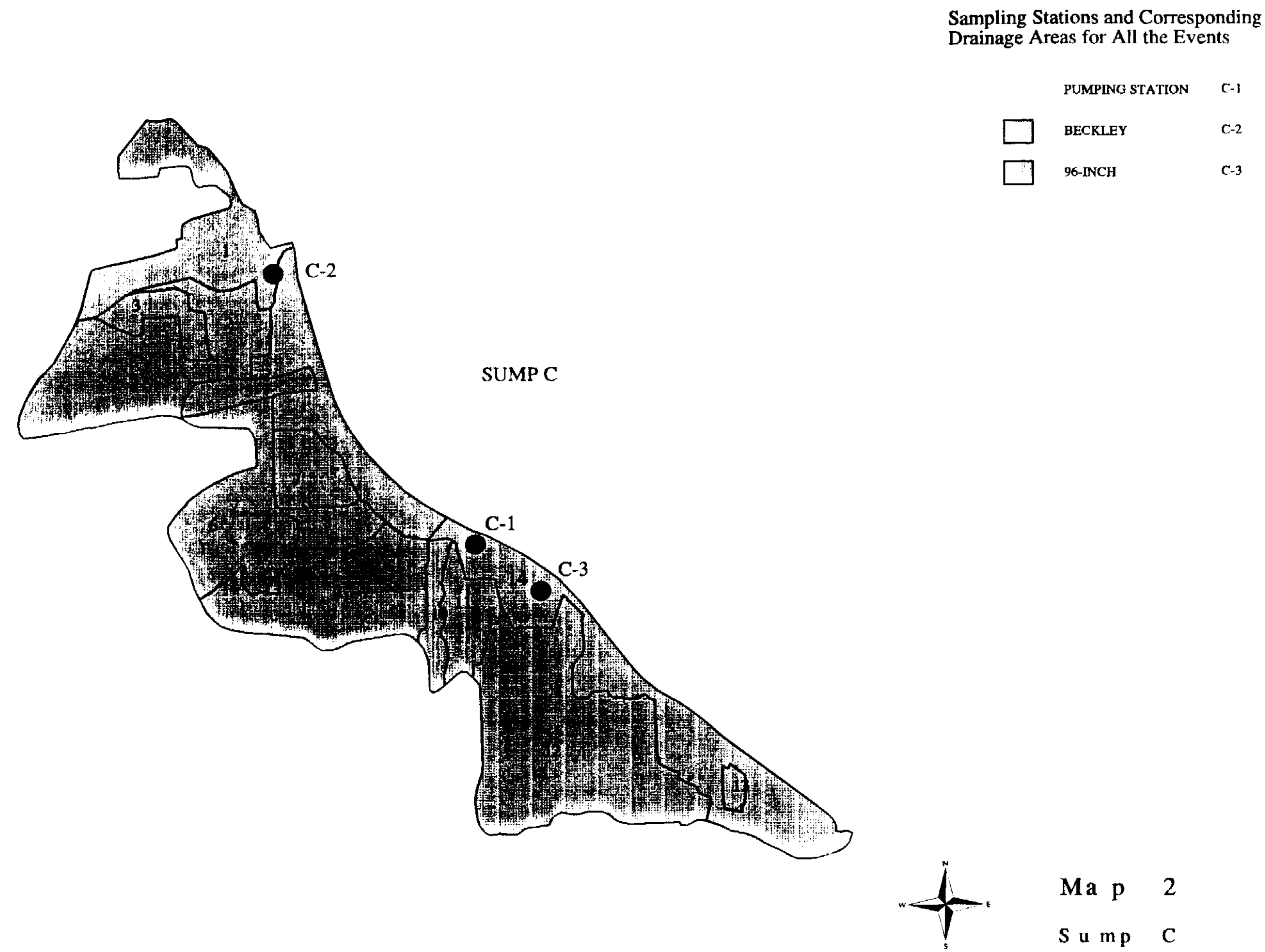
Drainage Areas Corresponding To Outfalls:

D2

D3

Map 3

Sump D (Events 1 & 2)


Sampling Stations and Corresponding
Drainage Areas for All the Events
PUMPING STATION C-1
BECKLEY C-2
96-INCH C-3
SUMP C
C-2
C-1
C-3
N
W
E
S

Map 2

Sump C