Composite Sampling of Highway Runoff: Year 2

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16. Abstract

A composite sampling device was developed that can be installed at less than ten percent of the cost of automatic sampling systems currently used in Federal highway runoff studies. This device was operated for one year, along-side an automatic sampler at the I-5 side, to demonstrate that the two systems provide statistically identical storm composites.

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ABSTRACT

A device has been developed to measure and composite sample stormwater runoff from highways. It has been laboratory calibrated and field tested on a portion of Interstate-5 in Seattle. Performance of the composite sampling device has been compared with conventional discrete sampling instruments. The major discrepancies between the two systems are due to laboratory and flow measurement errors. When these errors are resolved, the performance of the composite and discrete systems are almost identical.

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INTRODUCTION

Stormwater runoff from highways is usually monitored by labor-intensive, manual grab sampling or expensive automatic water quality samplers used in conjunction with flow measuring instruments. These sampling methods usually limit the scope of an investigation because of the large investments in capital or labor necessary to monitor even a single site. Instruments are often unreliable and difficult to maintain, especially in remote locations or during periods of inactivity between storm events. Instrument failure results not only in a repair cost but a loss of data during the down time. Discrete runoff samples can be used to characterize the changes in concentration of various pollutants through a storm, but are usually mixed together in some way to form a composite sample so that average concentrations can be used to calculate total mass loadings of pollutants. Because runoff characteristics are continuously changing, sampling at discrete points in time is limited in accuracy. Small storms may pass unsampled, peaks in concentration may occur between samples or large storms may exceed the container capacity of the sampler. For these reasons, it is desirable to continuously accumulate a composite runoff sample for determination of total pollutant loadings.

If the entire volume of stormwater runoff from a drainage area could be captured in a container, the pollutant concentrations in the container would represent the average characteristics of the entire storm. Since all the runoff from an area can rarely be collected and stored, various methods of obtaining a composite sample are used to determine the average characteristics of the runoff. Wullschleger et al. (1976) suggest four methods of combining discrete samples to obtain a composite according to the time they were taken and the flow rate or volume they represent. Another more direct method is to use a device which continuously removes a fixed fraction of the stormwater runoff, proportional to the flow rate, and automatically accumulates it in a composite sample. Such a device has been developed in this study, and a summary of the composite concentrations observed in samples taken from Interstate-5 in Seattle between February and September of 1979 is displayed in the first two columns of Table 1.

The third column of Table 1 shows complementary data obtained from discrete samples at the same site and indicates that peak concentrations can be several times greater than composite concentrations. For comparison, the fourth column presents highway runoff data obtained by Envirex from several nation-wide sites and the remaining columns present data for raw and treated sewage, drinking water standards and thresholds for toxicity.

THE COMPOSITE SAMPLER

Design Criteria

The highway site monitored in this study was a 1.22 acre area (497.7 m^2) of Interstate-5 located just north of Seattle, Washington, city limits. Four northbound lanes drain to a single collection box with an outlet culvert where apparatus could be located to collect samples. Drainage comes exclusively from the heavily traveled (50,000 ADT) highway surface. The Interstate-5 site provided the opportunity for a side-by-side comparison of discrete and composite sampling methods. A fully automated discrete sampling system was

Table 1 Highway Runoff Water Quality Comparisons

	I-5 Sampling Site, Seattle			Average of Envirex Composites	Seattle Municipal Sewage		EPA Drinking Water Std	Freshwater Aquatic Life	
	Composite Average	Concentration Range	Range of Discrete Sample Concentrations		Raw Sewage	Secondary Effluent		Estimated LC_{50}	Chronic Toxicity
pH	6.1	5.1-6.9	4.5-7.1	-			5.0-9.9		
Conductivity	87. µmho/cm	30.-146.	31.-409.	-					
COD mg/l	137.	75.-211.	8.-914.	147.	550.	50.			
TSS	145.	43.-320.	30.-1120.	261.	350.	13.			
VSS	38.	12.-100.	2.-696.	77.					
TOC	27.	4.-47.	BDL-83.	41.					
Pb	0.8	.2-1.5	0.1-5.5	0.96			< 0.05	0.3	0.03
Zn	0.40	.2-1.0	.03-1.9	0.41			< 5.0	1.0	0.005
Cu	0.03	BDL-.07	BDL-.15	0.10			< 1.0	0.06	0.006
TKN	1.11	.64-1.96	.18-3.96	2.99	34.	17.			
NO_3-NO_2-N	0.82	.52-1.65	.05-2.20	1.14			< 10.0		
Total P	0.34	.20-.55	.12-1.08	0.79	10.	5.			

BDL = Below detectable limit

established there with a mechanical sampler, calibrated flume and companion flow meter. Based on literature surveys and the operational experience with the discrete system, the following were considered to be important design criteria for any new composite sampler:

1. The composite sampler must produce a sample which is representative of the average characteristics of the runoff from an entire storm.

2. The resulting sample volume was to be used to calculate the entire amount of runoff for the storm and no other flow measuring devices were to be required.

3. The sample volume must be small enough to be stored in a reasonable sized container.

4. The sampler must be able to successfully sample solids in the stormwater and must not become incapacitated by litter and debris commonly carried by runoff.

5. The sampler must be suitable for use in remote sampling locations. It should need minimal maintenance, be automatically activated, and should not require electrical power.

6. The cost of the composite sampler should be significantly lower than conventional discrete systems.

The composite sampler actually developed for this highway runoff project was tested at the Interstate-5 site and satisfied all of the criteria to some degree. It has advantages over conventional automatic sampling equipment and provides considerable savings on capital investments and power requirements. It begins sampling by itself, and personnel are only required to collect a single sample after the storm has ended. They do not have to rush to the site to grab sample the initial runoff, nor are they required to restock automatic equipment with clean bottles during the storm. Since the composite sampler produces a single sample, laboratory facilities can analyze many storms with much less effort than in the case of discretes.

The composite sampler is reliable because of its simplicity. There is little that can go wrong,and problems that do occur are easily corrected on site. When problems occur with discrete sampling instruments,they usually must be returned to the factory for repair.

Design of the Composite Sampler

The composite sampling device consists of a rectangular cross-section open-channel with vertical dividers placed parallel to the direction of flow. The dividers divert a fraction of the flow into a container to accumulate a composite sample. The ratio of the opening between the two dividers to the width of the entire channel approximates the fraction removed. Figure 1 shows how a fraction of the flow is "split" from the mainstream and further divided in half once and possibly more times to obtain the volume of composite sample desired. The flow splitting device samples in proportion to the flow rate by removing a larger amount of water as the discharge increases and a smaller amount of water as the discharge decreases. Because the amount of water removed is a fixed fraction of the total discharge, the volume of the composite sample can be used to calculate the total volume of runoff that has occurred.

To maintain an accurate division of flow, the approach to the flow splitting dividers should be the same over the range of flow rates anticipated. Disturbances caused by placing the dividers in the path of flow can be prevented from moving upstream and changing the approach of water by placing the flume on a supercritical slope. There are other advantages to maintaining supercritical-turbulent flow in the flume. Solids are prevented from settling out and are able to pass through and be sampled.

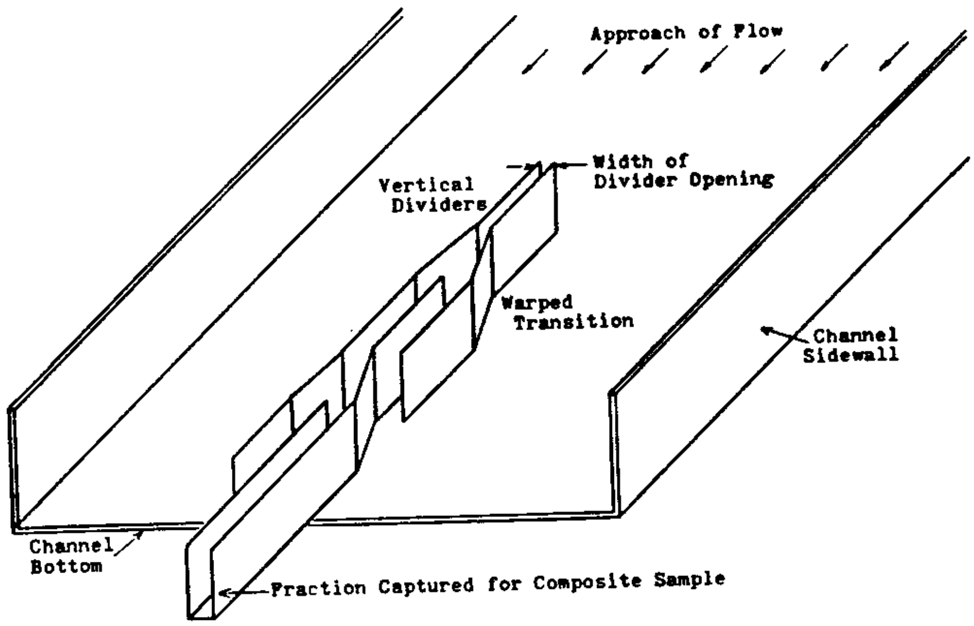

Figure 1: Schematic of Flow Splitting Device.

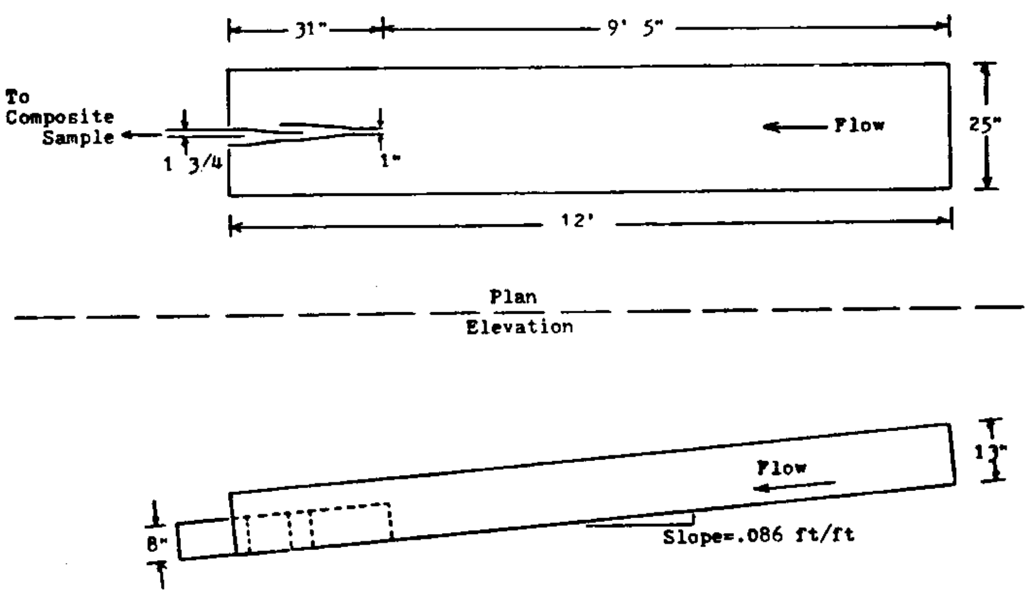

Figure 2: Drawing of the Interstate-5 Flow Splitter.

Sticks, cigarette butts and other debris are usually prevented from clogging the flow splitter by the turbulence.

The size of the drainage area being sampled and the flow rates expected should dictate the size of the composite sampler and storage container. Devices have been constructed to sample from areas as small as 0.099 acres to as large as the 1.22 acre Interstate-5 site. Assuming a runoff coefficient of 1.0, a one-inch (2.5 cm) rain storm would produce about 4,420 cubic feet (125 m^3) of runoff on Interstate-5. The practical maximum composite sample volume was thought to be about 50 cubic feet (1.4 m^3). A sample of this size allowed mixing by hand for uniform subsampling, and could be drained quickly from the container. Disposable plastic tank liners were available in sizes up to 50 cubic feet. Because of these limitations,the Interstate-5 flow splitter was designed to remove approximately one percent of the total flow. This was accomplished by using a channel twenty-five inches wide and an initial divider opening of one inch. This portion of the device isolates about one twenty-fifth of the flow. The dividers make two warped transitions where the isolated flow is split in half twice. The resulting one one-hundredth of the total discharge is captured for the composite sample.

Practical considerations govern the size of the divider opening, width, length and depth used in the composite sampler design. The one-inch divider opening was chosen for the Interstate-5 site because it is capable of passing the majority of debris in the runoff without clogging. A smaller opening becomes difficult to construct accurately. Flumes have been constructed with plywood, polyester boat resin and dividers of flexible one-eighth inch thick masonite. Divider openings larger than one inch for use on smaller drainage area sites are quite easily constructed. The dimensions of the I-5 composite sampler are shown in Figure 2.

The composite sampler was tested to determine how it would actually perform. In addition to testing the flume for the Interstate-5 site, four other flow splitters designed for smaller drainage areas were also examined. The calibrations were performed at the Harris Hydraulics Laboratory,where facilities provided a constant head source of water capable of delivering a wide range of discharges. The tests were conducted so as to duplicate field conditions as closely as possible. A range of flow rates were delivered to each flume in a manner similar to that anticipated in the field. At each rate the amount of water split by the device was carefully measured with a graduated cylinder and stopwatch. Many replicate measurements were made of both the total flow and the fraction split at each discharge. Table 2 summarizes the different flume sizes and their performance.

Several important findings resulted from the flow calibrations. The Interstate-5 flow splitter demonstrated that it could accurately divide a relatively constant fraction two orders of magnitude smaller than the total flow. The actual average fraction split by the flumes (Table 2) was slightly different than that estimated geometrically. This result indicates the necessity for calibrating the devices. The Interstate-5 flow splitter removed an average of 1.15% of the total flow (see Figure 3). The calibration showed that over the range of flows tested the fraction ranged $\pm$ 15% above and below this value. It should be noted that the maximum fraction split in the tests, 1.32% at .076 cfs, differs from the 1.15% average by only 3.5 milliliters per second.

In summary, flow tests have shown that the composite sampler is capable of accurately removing a fixed fraction of the total flow in the channel proportional to the flow rate. Flow splitters having the largest ratio of length

TABLE 2

Summary of Flow Splitter Designs and Flow Calibrations

Flume	% Designed to Remove	Channel Width (inches)	Total Length (ft)	Length of Approach to Dividers (ft)	$\frac{L_{approach}\text{ (ft)}}{\text{Width (ft)}}$	Average % Removed in test
I-5	1.0	25.	12.	9.42	4.52	1.15
#2	20.0	10.	6.	4.50	5.40	20.0
#4	3.75	20.	8.	6.58	3.95	4.42
#5	5.0	15.	8.	6.58.	5.26	5.6
#6	2.0	25.	8.	6.58	3.16	1.14

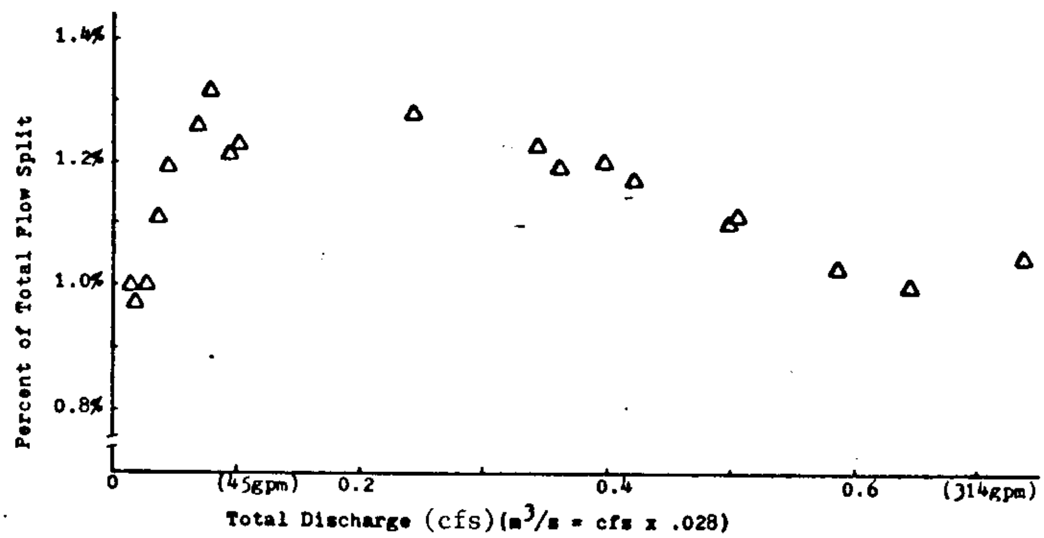

Figure 3: Calibration Curve for the I-5 Flow Splitter.
Note: Each Δ indicates 5 measurements of the fraction split.

(from inlet to the dividers) to width (of the channel) perform best. This is because initial disturbances and shock waves are given time to dissipate before the diversion of flow is made. The laboratory calibration is important to determine precisely how the flow splitter performs. The design of the flume is based to a large degree on practical considerations. The divider opening must be large enough to pass debris, yet small enough to produce a sample volume which can be contained. A steep slope is necessary to maintain supercritical conditions in the channel. The sidewalls should be high enough to contain splash.

<u>Composite Sampling Procedures</u>

Operation of the composite sampling system is quite simple and requires a minimal amount of maintenance. A typical layout is shown in Figure 4. The sample storage tank is lined with a large plastic bag to prevent cross-contamination of samples. After a storm system has passed and runoff has ceased the sample can be measured and collected. The depth of the runoff in the tank is measured to allow calculation of the total volume of runoff for the storm. Then a paddle is used to thoroughly mix the sample and resuspend any particles which have settled. The mixed composite can then be sub-sampled in containers suitable for laboratory use. The remaining runoff in the tank is drained and the old liner disposed of. A new liner is placed in the tank and any debris in the flow splitter is removed. The site is then prepared for the next storm. Other storm data would also be gathered when collecting the composite sample. For example, the rain gauge would be read or the chart changed, traffic counters read, etc.

Approximate Scale 1" = 2.5'

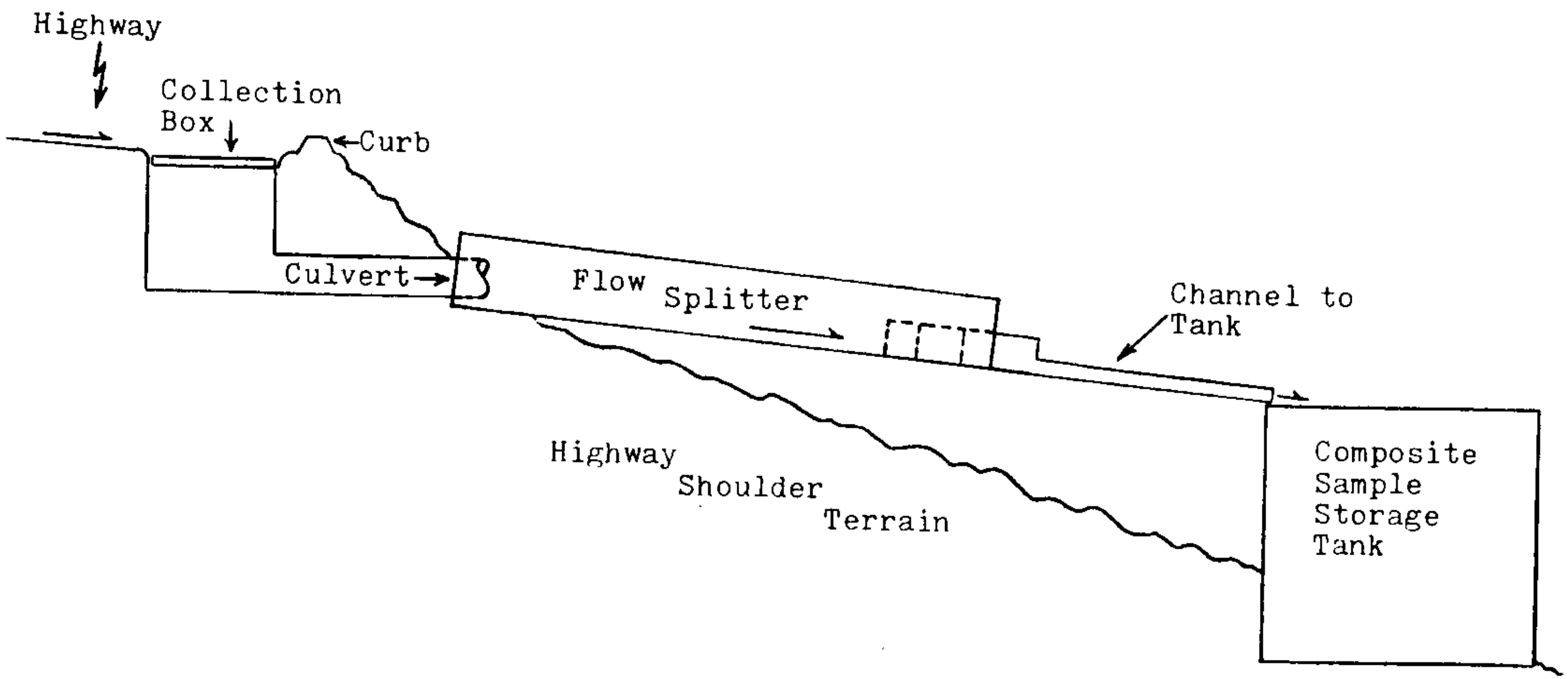

Figure 4: Composite Sampler Layout on a Curbed Highway.

When collecting the composite sample it is important that the tank volume be carefully measured and the sample completely mixed. These steps will insure that the most accurate measure of the total volume of runoff is made and that a representative sample is gathered for calculations of pollutant loadings.

The composite sampler described satisfied the original design criteria. By continuously sampling in proportion to the flow rate it can accumulate a composite sample representative of the average characteristics of an entire storm. Flow tests have shown that the volume of the sample is a known fraction of the total discharge. This finding allows calculation of the total volume of runoff without other flow measurement. Flow splitters have been used to reduce a range of discharges to manageable volumes. They are inexpensive to construct with the materials suggested and do not require electrical power. Table 3 compares the capital costs and operation of the composite and discrete sampling systems on I-5. The composite sampler ($900) is significantly less expensive than the discrete ($6,440) and is also easier to operate.

Any method of sampling may require additional monitoring equipment for a complete highway runoff investigation. For instance, precipitation gauges, traffic counters and dustfall containers may be needed, depending on the availability of data from other sources.

PERFORMANCE OF THE DISCRETE AND COMPOSITE SAMPLERS

Runoff Quantity

Analysis of rainfall and runoff data from the Interstate-5 sampling site yields runoff coefficients (ratio of the volume of runoff to the volume of rainfall) ranging from 0.21 to 1.0. Occasionally, a runoff coefficient

Table 3

Cost and Operation of Discrete versus Composite Systems

CAPITAL COSTS

Discrete		Composite	
H-flume	$ 650	Flow Splitter Material	$150
ISCO Flowmeter	1,700	Construction Labor	300
ISCO Sampler	1,400	Placement Labor	300
ISCO Printer	900	Concrete Tank(in Place)	150
Electrical Service Site Preparation	1,620		
Shelter	170		
TOTAL	$6,440	TOTAL	$900

QUALITATIVE COMPARISON OF OPERATION

	Discrete	Composite
Maintenance	Check at least 2 times per week; change dessicants on instruments; check power supply; clean flow meter bubble tube; check printer paper	Check after storms
During Storm	Reload sampler with bottles; adjust sample interval	Nothing required
Collection of Samples	collect many, both during & after storm; collect flow data	After storm: measure tank depth stir tank collect 1 sample drain tank
Prepare for Next Storm	Re-stock bottles; Re-set sampler	New plastic tank liner
Laboratory	Analyze many samples; wash many bottles.	Analyze 1 sample; wash 1 bottle
Data Analysis	Compute hydrograph; compute pollutograph; integrate pollutograph = Mass	Calculate total volume of runoff; Vol. x Concentration = Mass

greater than 1.0 was obtained, suggesting more runoff than rainfall. This result is impossible, of course, and is caused by instrumentation errors either in measuring rainfall or the volume of runoff. Envirex experienced a similar difficulty in their highway runoff study. A flow meter error of 15% is believed to be appropriate for this study; and, as discussed earlier, the composite sampler has 15% volume measurement errors.

In an attempt to develop a quantitative relationship between rainfall and runoff, Envirex used linear regression to determine the line of best fit for their data. They have used the following equation in their predictive model and suggested that it be used to estimate the amount of runoff from Type 1 (100% paved) sites;

$$Q = 0.969\ TR - 0.019$$

where Q = runoff volume in inches

TR = total rainfall in inches for TR greater than 0.019

For the Envirex data the line of best fit had a correlation coefficient of 0.95 and an R^2 value of 0.91.

The I-5 site fits the Envirex criteria for a Type 1 site, and Figure 5 shows the rainfall and runoff (in inches from the I-5 drainage area) values observed there. The Envirex line of best fit is plotted and tends to significantly overestimate the volume of runoff. Additional fixed data must be obtained to develop a better relationship.

Runoff Quality

The laboratory performed analyses primarily for Chemical Oxygen Demand (COD), total and volatile suspended solids (TSS and VSS), Total Organic Carbon (TOC), lead, zinc, copper, pH and conductivity. A considerable number

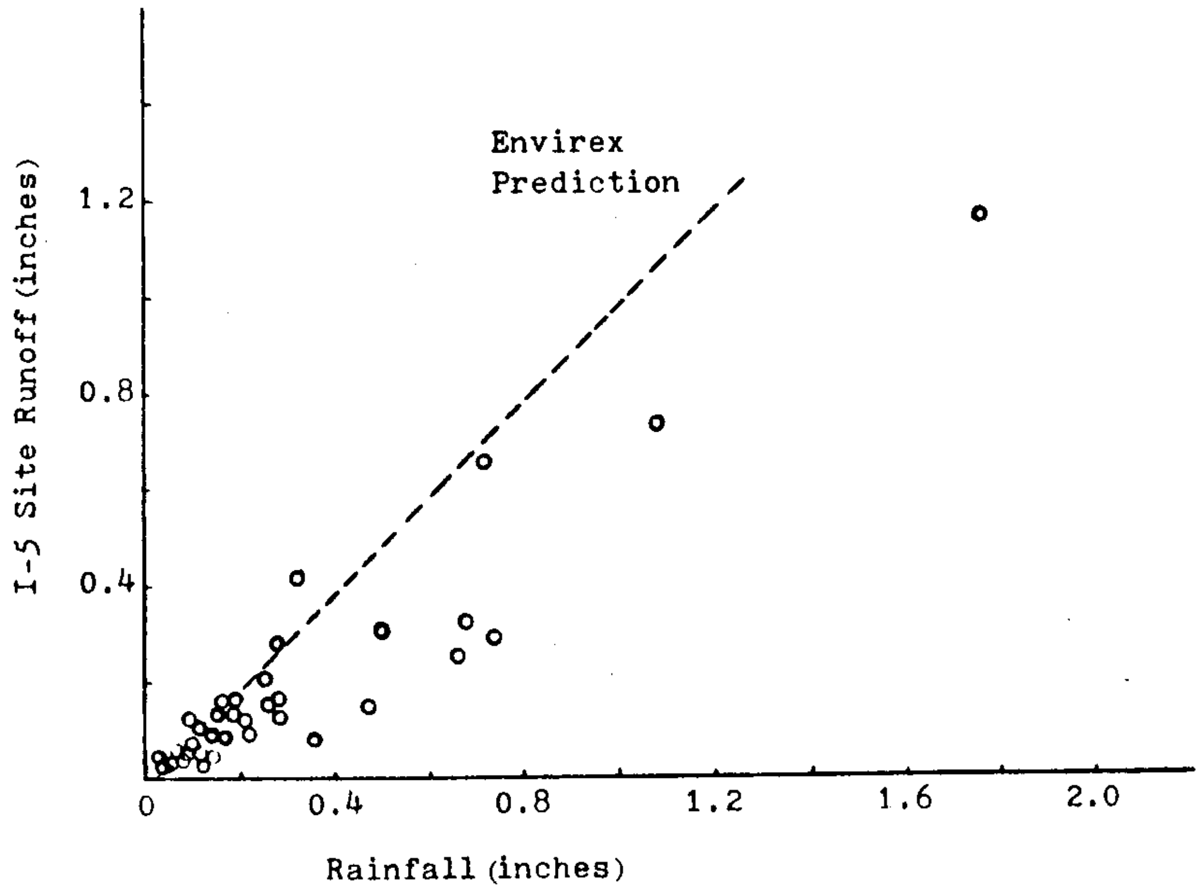

Figure 5: Runoff vs. Rainfall at the I-5 Site.

of Total Kjeldahl Nitrogen (TKN) and some nitrate + nitrite - nitrogen (NO_3 + NO_2 - N) and total phosphorus (Total - P) tests were also run. Analyses were performed in accordance with Standard Methods, metals were analyzed on an Instrumentation Laboratory, Inc., Atomic Absorption Spectrophotometer and TOC on a Beckman IR Carbon Analyzer according to manufacturers instructions.

Errors in laboratory analysis result in uncertainty in the ultimate determination of total mass loadings of pollutants. One of the major errors was associatedwith the proper sampling of sediment in the water samples. Consistent procedures can still introduce systematic errors. The standard error of the mean for all laboratory analyses performed in this study has been estimated at 15%.

Figure 6 shows how laboratory data from four discrete samples are combined with the hydrograph to determine the total mass load of TSS for part of a storm on I-5. The loading pollutograph is a plot of mass loading rates (in this case lbs/minute) at points when samples were collected versus time (hours). The integral of the mass loading pollutograph (area under the curve) yields the total mass of pollutant which was washed from the pavement during that particular hydrograph. In practice the entire procedure was performed on a digital computer by a program which included a routine to integrate the pollutograph geometrically to find the total mass of pollutant.

Error is present in the final estimate of total pollutant loading because of errors in flow measurement, laboratory analysis and the method of calculating the total mass. Several approximations have been made to allow computation by this method. Flow rates are assumed to vary linearly between

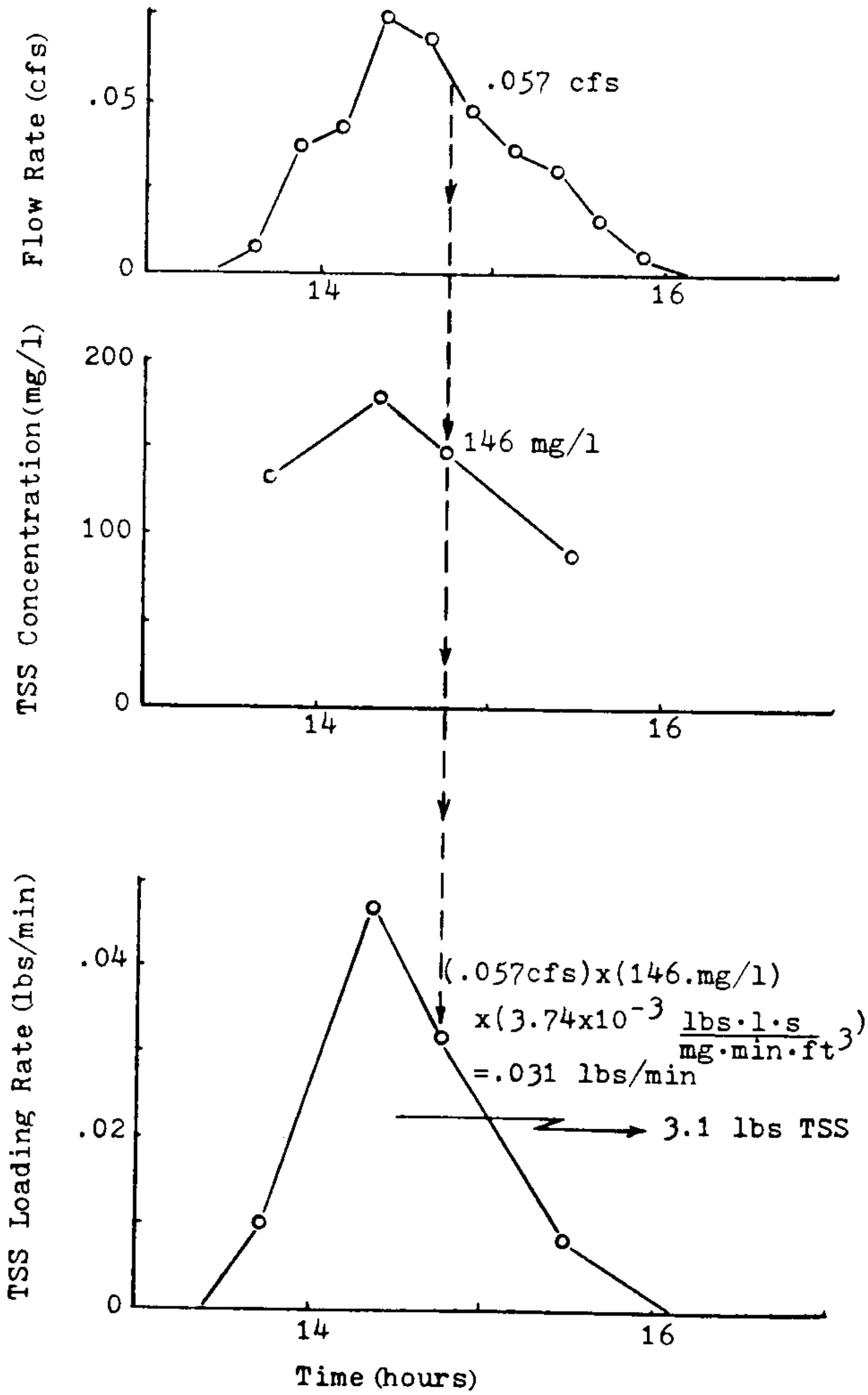

Figure 6: Mass of TSS for Event 47.

observations, and no attempt has been made to shape the pollutograph before integration. Figure 7 shows that the flow data with error bounds actually plot as a step function. The plot of TSS concentration versus time is shown with 15% error bars from laboratory analysis. Finally, the loading pollutograph in Figure 7 shows that there is a possibility that the total mass may actually be larger or smaller than the mean estimate (3.1 lbs) in Figure 6.

Analysis of the composite samples created by the flow splitter is considerably easier than the analysis of discrete data. A subsample of the contents of the composite storage tank is analyzed in the laboratory for the parameters of interest. The total volume of runoff is calculated from the tank volume by dividing by the fraction removed by the flow splitter. For the calibrated I-5 flume;

$$\text{Total runoff } (ft^3) = \frac{\text{Sample Tank Volume } (ft^3)}{(\text{fraction split})}$$

where fraction split = 0.0115 for the calibrated I-5 flow splitter. Having obtained concentration data from the laboratory and computed the total volume of runoff, the total mass of pollutant washed off by a storm is found by:

$$\text{Total Mass} = \text{Concentration} \times \text{Runoff Volume} \times k$$

where k = unit conversion constant

The discrete and composite systems are compared graphically in Figures 8, 9 and 10. In Figure 8 discrete runoff measurements are plotted versus composite measurements. If the two systems were in complete agreement, all of the points would lie on a line extending from the origin at a 45° angle. Similarly, plots of discrete versus composite results for total mass loads of COD

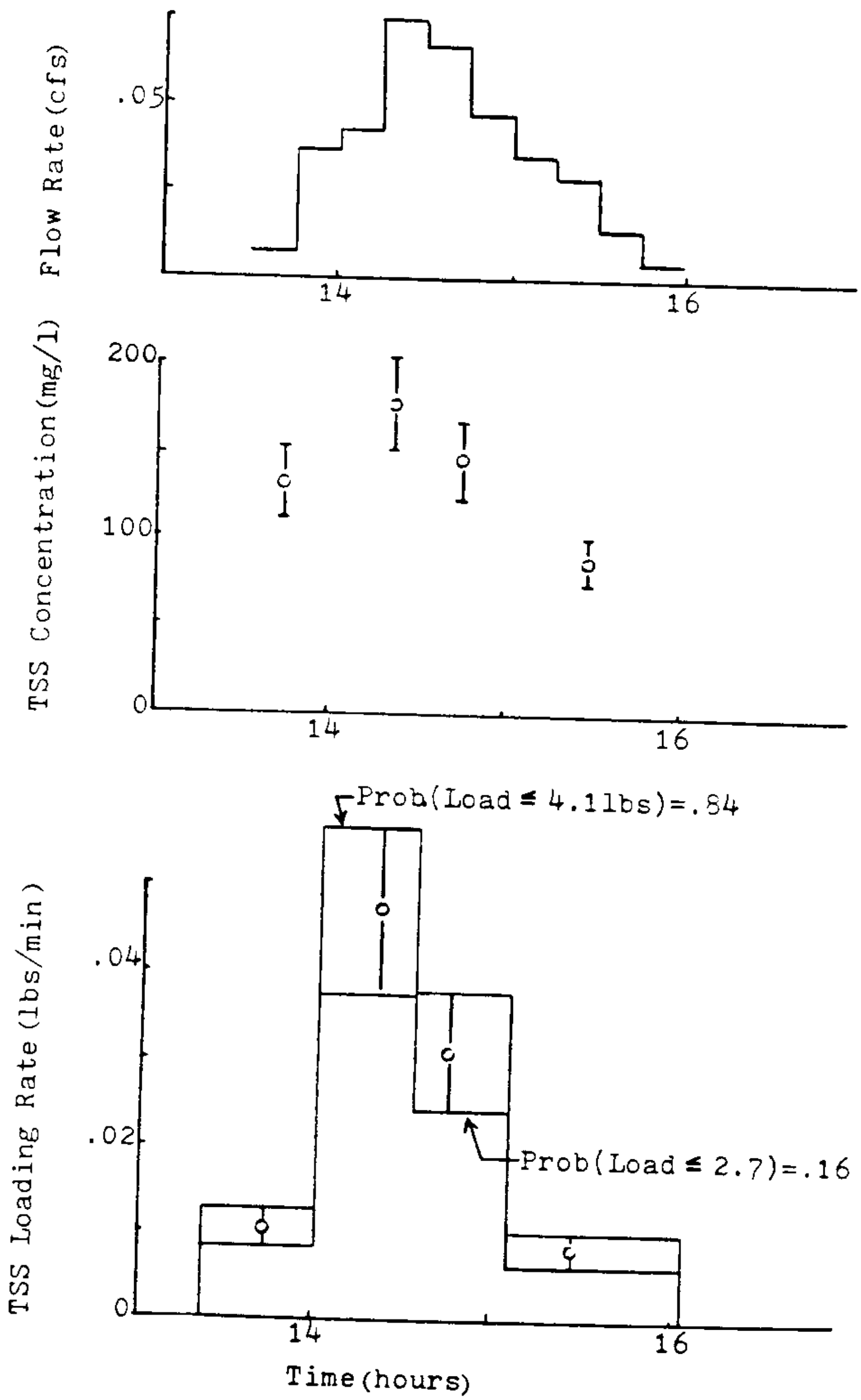

Figure 7: Mass of TSS for Event 47 with error bounds.

and lead are shown in Figures 9 and 10. The mass unit used in the comparison is pounds (lbs) from the I-5 sampling site.

The discrepancy between the total mass of pollutant predicted by the discrete and composite systems varies up to several hundred per cent. The most important factor involved is flow measurement, because the total mass of pollutant is directly proportional to the total volume of runoff. When the difference between discrete and composite flow measurements is large (say greater than 10%), the difference in predicted mass is also generally large. When flow measurements agree, other sources of error predominate and the differences in pollutant mass vary in both positive and negative directions.

Viewing the plots of discrete versus composite mass for various pollutants shows that Event 40 and Event 42 are outlyers. Both storms had composite flow measurements more than 40% lower than the discrete measures; and, consequently, both resulted in underestimates of the mass of pollutants discharged. If the large differences due to runoff volume were corrected using equivalent runoff volumes, the discrete and composite mass estimates would be comparable, as shown by the dotted lines in Figures 9 and 10. The same is true when the composite runoff volume was larger than the discrete, as shown by the corrections for Events 65, 66, 68 and 77 in the figures.

Errors certainly resulted from the approximations made in order to compute mass loadings from discrete samples. They appear, from comparison with composites, to be random when enough discrete samples are available to characterize the pollutograph. Large differences in mass loading estimates also occur when only one discrete sample is available. Small storms will produce a single discrete sample, however, most storms are not continuous and are made up of a series of smaller sub-storms. Depending on the sampling

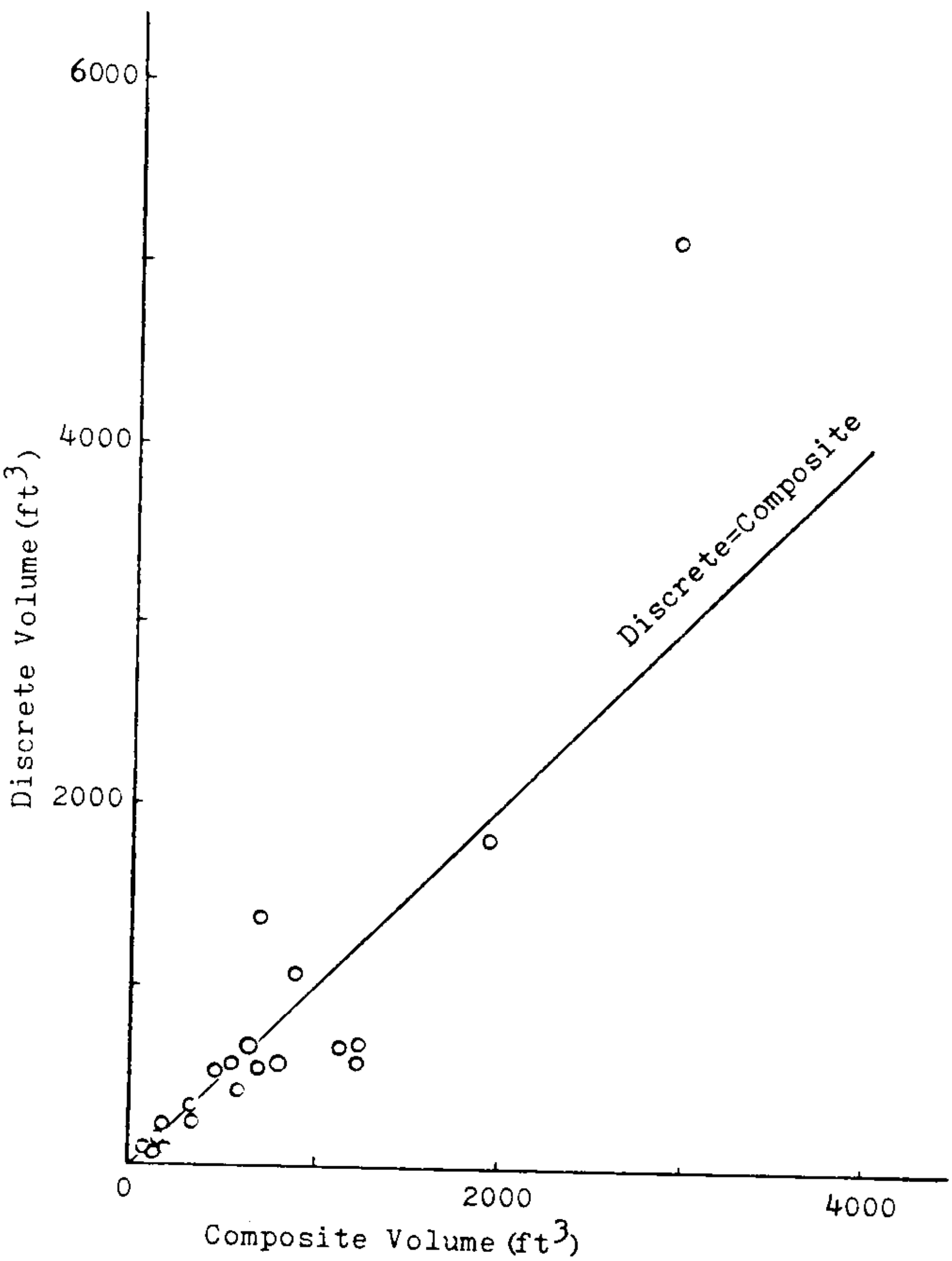

Figure 8: Discrete vs. Composite Runoff Volume (ft^3).

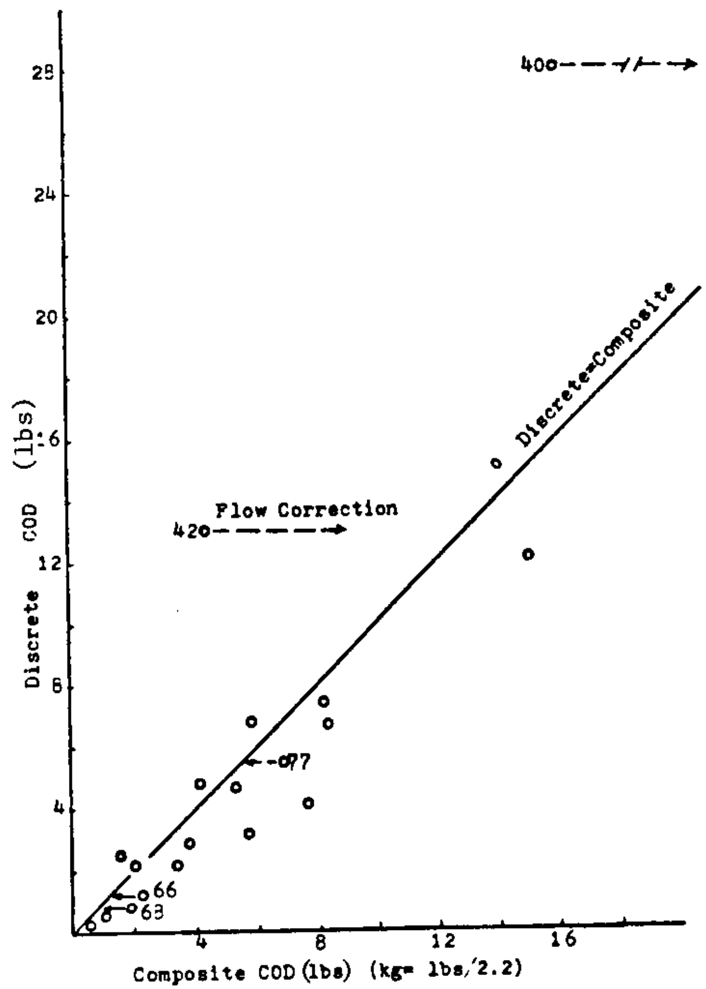

Figure 9: Discrete vs. Composite Results for COD (lbs).

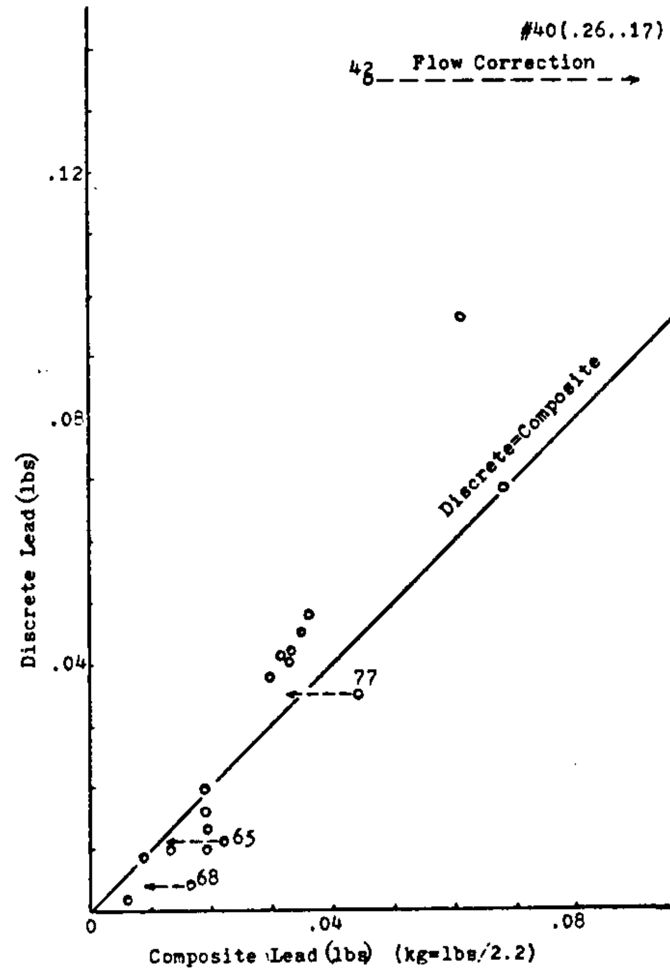

Figure 10: Discrete vs. Composite Lead (lbs).

interval, parts of some storms may have passed the discrete system without being sampled at all. It is difficult to choose an interval which will adequately cover small events and still preserve bottle capacity for large storms. This problem is overcome by sampling continuously throughout a storm as the composite sampler does. Small events are never missed, and large ones are sampled up to the limiting capacity of the storage tank.

CONCLUSIONS

In conclusion, the composite sampling system on I-5 has produced total pollutant loading data which agree with discrete data to varying degrees. To improve the comparison, discrete flow measurements must be refined and errors reduced. The composite sampler has been shown to have many advantages in that it is less expensive, easier to operate and is potentially more accurate than discrete sampling. This is true because it samples continuously and thus avoids problems with selecting automatic sampling intervals. Composite sampling reduces errors because only a single sample is produced. This leaves lab facilities available to perform replicate analyses on all parameters of interest. Because of the simplicity of the composite sampling system, its low cost, low maintenance and ease of operation, it is suitable for use in a network of remote highway runoff sampling stations. Such a network allows compilation of a large set of data on pollutant loads from a variety of locations and storms to be used for model building.

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