PERCENTAGE ENTRAINMENT OF CONSTITUENT LOADS IN URBAN RUNOFF, SOUTH FLORIDA

By Robert A. Miller

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DONALD PAUL HODEL, Secretary

GEOLOGICAL SURVEY

Dallas L. Peck, Director

For additional information
write to:

District Chief
U.S. Geological Survey
Suite 3015
227 North Bronough Street
Tallahassee, Florida 32301

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CONVERSION FACTORS

For use of those readers who prefer to use the International System of Units (SI) rather than inch-pound units, the conversion factors for the terms used in this report are listed below:

Multiply inch-pound units	by	To obtain SI units
inch (in.)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
acre	0.4047	hectare (ha)
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
pound (lb)	0.4536	kilogram (kg)
pound per million gallons (lb/Mgal)	0.1199	milligram per liter (mg/L)

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ABSTRACT

Runoff quantity and quality data from four urban basins in south Florida were analyzed to determine the entrainment of total nitrogen, total phosphorus, total carbon, chemical oxygen demand, suspended solids, and total lead within the stormwater runoff. Land use of the homogeneously developed basins are residential (single familiy), highway, commercial, and apartment (multifamily).

A computational procedure was used to calculate, for all storms that had water-quality data, the percentage of constituent load entrained in specified depths of runoff. The plot of percentage of constituent load entrained as a function of runoff is termed the percentage-entrainment curve.

Percentage-entrainment curves were developed for three different source areas of basin runoff: (1) the hydraulically effective impervious area, (2) the contributing area, and (3) the drainage area. With basin runoff expressed in inches over the contributing area, the depth of runoff required to remove 90 percent of the constituent load ranged from about 0.4 inch to about 1.4 inches; and to remove 80 percent, from about 0.3 to 0.9 inch.

Analysis of variance, using depth of runoff from the contributing area as the response variable, showed that the factor "basin" is statistically significant, but that the factor "constituent" is not statistically significant in the forming of the percentage-entrainment curve. Evidently the sewerage design, whether elongated or concise in plan, dictates the shape of the percentage-entrainment curve.

The percentage-entrainment curves for all constituents were averaged for each basin and plotted against basin runoff for three source areas of runoff--the hydraulically effective impervious area, the contributing area, and the drainage area. The relative positions of the three curves are directly related to the relative sizes of the three source areas considered.

One general percentage-entrainment curve based on runoff from the contributing area was formed by averaging across both constituents and basins. Its coordinates are: 0.25 inch of runoff for 50-percent entrainment, 0.65 inch of runoff for 80-percent entrainment, and 0.95 inch of runoff for 90-percent

entrainment. The general percentage-entrainment curve based on runoff from the hydraulically effective impervious area has runoff values of 0.35, 0.95, and 1.6 inches, respectively.

INTRODUCTION

Problem

In the 1970's much concern relating to stormwater runoff from nonpoint sources developed. This concern resulted in various laws that govern the design of detention (and retention) ponds.

Initially, detention ponds were designed only to affect the rate of stormwater runoff from an urban basin, but later it was realized that detention ponds also affect the quality of water that leaves a basin and enters receiving waters. Detention ponds provide storage for some initial volume of runoff that often contains the highest concentrations of numerous suspended and dissolved chemical substances. Ponds also reduce the velocity of stormwaters and allow suspended sediment and associated constituents to settle out of the water and accumulate on the pond bed. During the time stormwaters are stored within the ponds, biochemical processes may occur which often improve the quality of the stormwaters.

The laws and regulations concerning the design of detention ponds are often ambiguous; those laws that are definitive are sometimes misunderstood by the designer. Some regulations use the term "volume of rainfall," others "volume of runoff," while others refer to "volume of rainfall which becomes runoff." Most regulations are based on the idea of retaining within the pond a defined percentage of one, or several, constituents, thereby prohibiting large amounts of these constituents from entering receiving waters.

The ambiguities of local laws and regulations are due, in part, to the lack of sufficient field-collected data that have been properly analyzed, and then properly presented for the designer's use. Field data that can be used in such an analysis presently exists (1984) for four basins of different, homogeneous land use. These data were collected in south Florida during 1974 to 1978 by the U.S. Geological Survey as part of two separate studies funded by various county and State agencies.

The data from these two south Florida studies were analyzed and used to calculate percentage-entrainment curves (graphs of percentage of constituent load entrained in the basin runoff plotted as a function of basin runoff). With the percentage-entrainment curves available, it is a simple procedure to determine the volume of a detention pond which would contain the specified percentage of a constituent load.

Previous Studies

The data used in this study were originally collected for two studies in south Florida (fig. 1). One study was near Fort Lauderdale in Broward County. It included three basins of different land uses--single-family residential (which in this report will be referred to as residential), highway, and commercial. The second study was near South Miami in Dade County. It had only one land use--multifamily residential, or as used in this report, apartments.

The flow data collected at the four sites were for overland flow only; this because the data were obtained from within stormwater sewers. No natural, earthen channel with its concomitant interflow and base flow was gaged.

Data collected and synchronously recorded at each of the four sites include the quantity of rainfall and runoff and the quality of rainfall and runoff. After processing, the data were stored in a specially designed, computerized data-management system, and are published in site-specific reports (Hardee and others, 1978; Mattraw and others, 1978; Hardee and others, 1979; and Miller and others, 1979).

Basin characteristics associated with the impervious area, the sewer system, drainage, and soils were also determined and published (Miller, 1979). One of the more important findings was that the source of most, but not all, of the runoff observed is the HEIA (hydraulically effective impervious area). Miller (1978) defined the HEIA as the impervious areas adjoining the sewer inlets which contribute runoff to the sewer system as soon as initial abstractions (surface wetting, ponding, and other conditions) are met. For storms having rainfalls of about 1 to 2 inches or less, runoff occurred primarily from the HEIA. For larger rainfalls, basin areas outside of the HEIA contributed runoff to the sewer system. Concepts associated with these source areas of runoff are developed in the section of this report titled "Source area of runoff."

In the analysis of the water-quality data from the residential, highway, and commercial basins, Mattraw and Miller (1981) found that total nitrogen, total phosphorus, and total residue yields from the HEIA were highest in the residential basin, and that chemical oxygen demand and total lead yields from the HEIA were highest in the commercial basin. It was also found that atmospheric contributions to runoff loads on the highway and commercial basins could be 49 percent or greater for the seven constituents considered in the analysis.

Purpose and Scope

The purpose of this study is to determine, from the south Florida stormwater data, the different relations between stormwater runoff and the constituent loads carried by the runoff. This is accomplished by computing, for six water-quality constituents in four basins, the percentage of constituent entrained as a function of runoff. Results of the calculations are presented in both tabular and graphical forms.

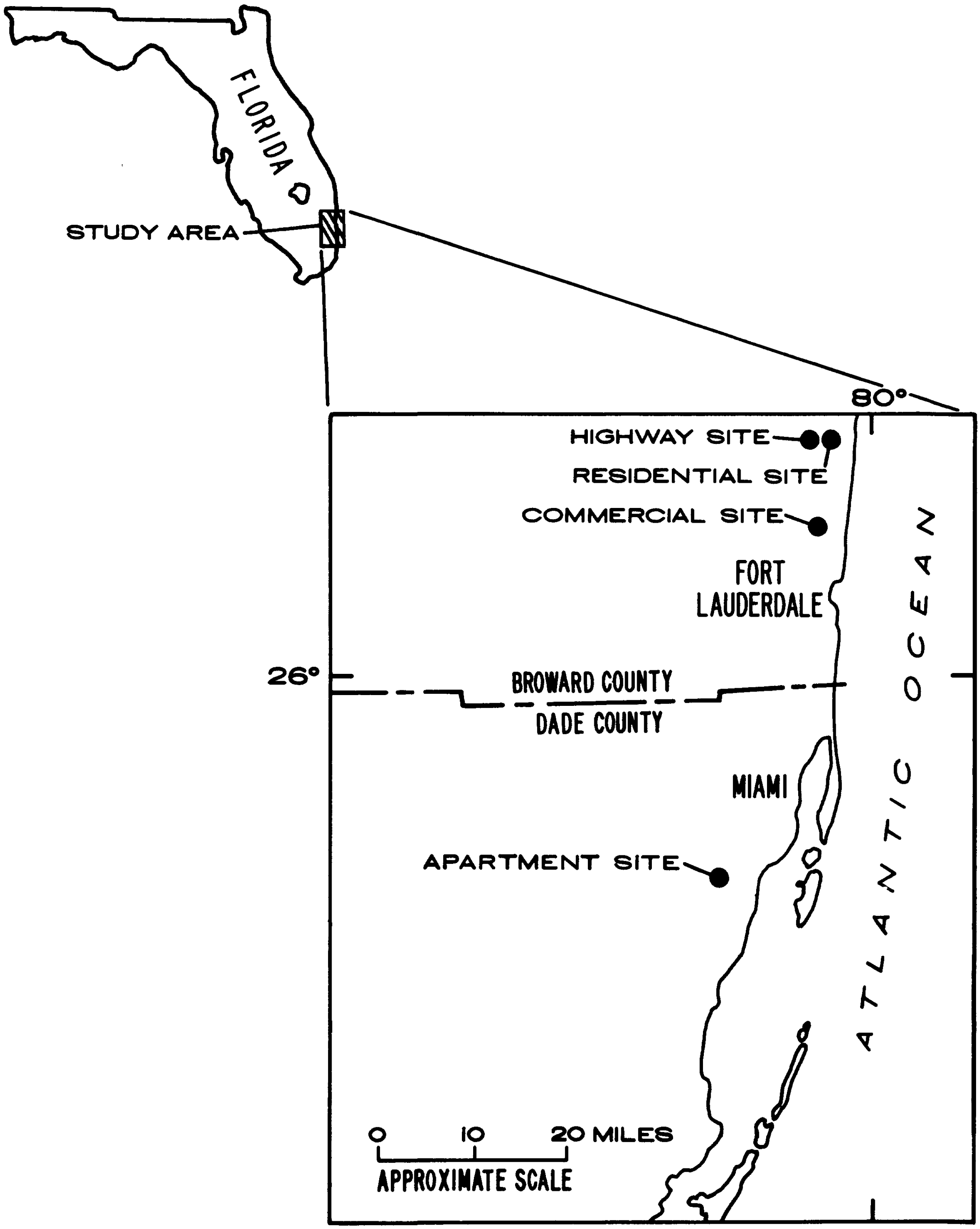

Figure 1.--Location of stormwater runoff sites.

The scope of the study did not include the collection of any new data, and the only data utilized in the study were those collected as part of the two south Florida studies. The analysis of the data consisted mostly of mathematical computations involving the data previously collected. Chemical reactions which might have occurred in the basin were not considered.

BASINS, RAINFALL, AND DATA CHARACTERISTICS

Commercial Drainage Basin

The commercial basin is part of a regional shopping mall, comprised of impervious roof and parking-lot pavement, except for several small tree islands which are pervious. The basin of 20.4 acres is drained through two main collectors, which join near the southwest corner of the basin and empty into a 36-inch pipe. The impervious area is 20.0 acres, all of which is HEIA. Total imperviousness is 97.9 percent.

Highway Drainage Basin

The highway basin comprises 58.3 acres and includes a 3,000-foot long segment of a six-lane, divided highway with curb and gutters. Approximate traffic flow (1978) is 20,000 vehicles per day.

Roadside development is sparse with large areas of unimproved, disturbed sand soil. The sand is fine, single-grained, and loose. Infiltration is very rapid and the available water capacity is very low. Twenty-one acres, or about 36 percent of the area, are impervious due to buildings, streets, and other structures. Approximately 10.5 acres of the impervious area are hydraulically connected to sewer inlets (HEIA), giving an HEIA of 18.0 percent.

Residential Drainage Basin

The size of the residential basin is 40.8 acres; the impervious area is 17.9 acres (43.9 percent) and the HEIA is 2.41 acres (5.9 percent). The basin contains 219 single-family residences built of concrete block around 1959. The average size of the lots is 80 feet by 100 feet.

The basin slopes gently to the east. Shallow, grassy, roadside swales collect the water in the western and central parts of the basin and transport it to the eastern part of the basin where the sewer system is located.

Fifty-six percent of the area is covered by Bermuda grass growing on pervious muck which overlies fine-grained quartz sand. The sand has high permeability and infiltration capacity. The grassy swales through which water is routed generally infiltrate water rapidly.

Apartment Drainage Basin

The apartment basin, which consists of 14.7 acres, is part of an apartment complex. The impervious area is 10.4 acres, or 70.7 percent of the drainage area, and the HEIA is 6.48 acres (44.1 percent). The soil, which is covered by lawn on the pervious parts of the basin, is Perrine marl which has a very low infiltration capacity. The streets have no curbs or gutters, but are formed with the center of the street acting as a swale.

The storm-sewer system in plan view is Y-shaped. One branch starts in the northwestern part of the basin; the second in the northern part. They join in the middle of the basin and then extend to the southern limit of the basin.

Rainfall Characteristics

South Florida experiences a yearly rainfall cycle with a wet season from June through October, and a dry season from November through May. During the summer wet season, when the land is warmer than the air masses coming off the ocean, severe convective thunderstorms produce rainfall that is highly variable in quantity from place to place.

During the winter dry season rainfall is produced by cold, frontal weather originating within the continental United States and Canada. These storms may produce rainfall of low intensity and long duration.

Data Characteristics

Numerous stormwater-runoff samples were collected during the data-collection phase of the south Florida studies. A suite of nutrients, physical characteristics, and six metals, were analyzed with as many as 29 determinations being made for most samples. Bacterial enumerations and biochemical-oxygen-demand analyses were made for several samples.

The number of storms for which data were collected, and the number of water-quality samples collected are as follows:

	Basins			
	Residential	Highway	Commercial	Apartment
Number of storms having rainfall and runoff data	74	108	114	52
Number of storms having water-quality data	33	41	31	16
Maximum number of water-quality samples collected for any constituent	380	440	320	170

The average number of samples collected during each storm, depending on the constituent, was about 10. The data and the laboratory methods used are provided in the previously cited site-specific reports.

From the data available, it is possible to calculate the instantaneous constituent load for a particular storm by multiplying constituent concentration in milligrams per liter, stormwater discharge in cubic feet per second, and the proper units-conversion factor. The function of instantaneous load versus time (or runoff) is commonly called the loadograph; accumulation of this function provides the accumulative loadograph; and the final value of the accumulation is the total load for the storm.

For this study, the accumulative loadographs for six constituents were analyzed for each of the four basins. The constituents are total nitrogen, total phosphorus, total carbon, chemical oxygen demand, suspended solids, and total lead.

COMPUTATIONAL PROCEDURE

Approach

A computational procedure was developed which consists of three basic steps. These steps were followed separately for each constituent on each basin. First, the accumulative loadograph, the accumulation of a particular constituent load (in pounds) as a function of runoff (in inches), was developed for each runoff event on each basin.

The second step consisted of interpolating the accumulative loads at increments of 0.05 inch of runoff for each loadograph. These data were then placed into a matrix, or table within the computer.

The third step provided the percentage-entrainment curve for each constituent from each basin. The accumulative loads for all storms were summed at each depth of runoff (increments of 0.05 inch). The last value of this calculation is the total load washed off by all storms. Next, the percentage of load entrained in each depth of runoff was determined by dividing the accumulative load for that depth by the total load. This produced an array of percentage of load against depth of runoff. The plot of these two variables is the percentage-entrainment curve.

Assumptions

The computational procedure just described was used for all storms sampled as part of the south Florida studies. If the results are to be extrapolated to any time basis, say a yearly basis, one assumption is inherent; that is, the statistical distribution of the storms sampled is the same distribution as for all storms occurring on the basin. Included within the meaning of "storms" are the variables associated with storms such as amount, intensity, and duration of rainfall, and the available constituent load on the basin at the start of runoff. These variables taken collectively probably constitute an additional variable described in the literature: washoff rate of a constituent.

Also, it must be understood that the chemical reactions and the settling of suspended solids that may take place in the runoff process were not considered in the analysis. Therefore, the results as presented may be unique to the basin sampled due to the transport hydraulics (velocity of flow and particle size) of the basin.

Some consideration should be given to the transferability of results given in this report to urban basins in other areas of the country. The data used in the analysis are field-collected data which are site specific. The basins are small (less than 100 acres) and flat. It is hoped that the transformation of discharge data to depth of runoff will ensure transferability, but this is not certain. Therefore, results of this study should be used with caution, and perhaps be compared to similar analyses performed elsewhere.

SOURCE AREA OF RUNOFF

Rainfall-Runoff Data

Three different combinations of curves (Miller, 1984) are needed to fit the runoff-rainfall data observed at the four basins (figs. 2, 3, 4, and 5). They are:

1. a one-curve function,
2. a two-curve, intersected function, and
3. a two-curve, disjointed function.

The one-curve relation, linear throughout, occurred for the commercial basin (fig. 2). Approximately 98 percent of the basin is HEIA, hence the reason for a linear function for all rainfalls observed.

The two-curve, intersected relation occurred for the highway basin (fig. 3)--a linear curve for the low and medium events observed and a second-degree curve for high events observed. The two curves intersect at a runoff of about 0.4 inch and a rainfall of about 2.1 inches. As shown, the two segments of the runoff-rainfall relation intersect and cross because the data were separated into two groups and each group fitted separately. The data could have been fitted so that the two curves were continuous at their intersection; that is, the slopes of the two curves are equal at the point of intersection.

The two-curve, disjointed function occurred for two basins--the residential and the apartment, as shown in figures 4 and 5. The discontinuity appears between 0.8 and 1.3 inches of rainfall for the residential basin, and between 1.6 and 2.1 inches of rainfall for the apartment basin.

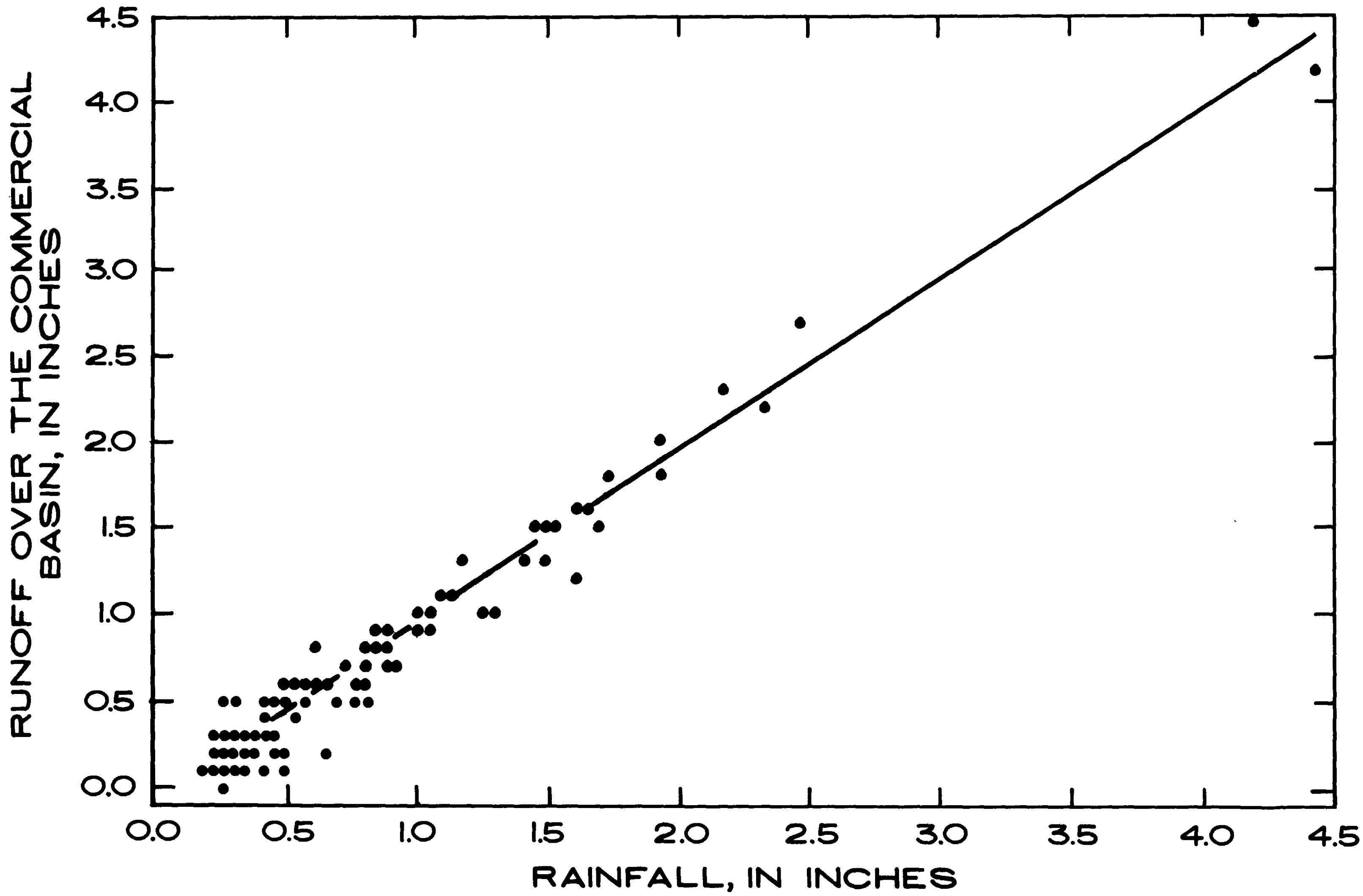

Figure 2.--Runoff-rainfall plot for the commercial basin.

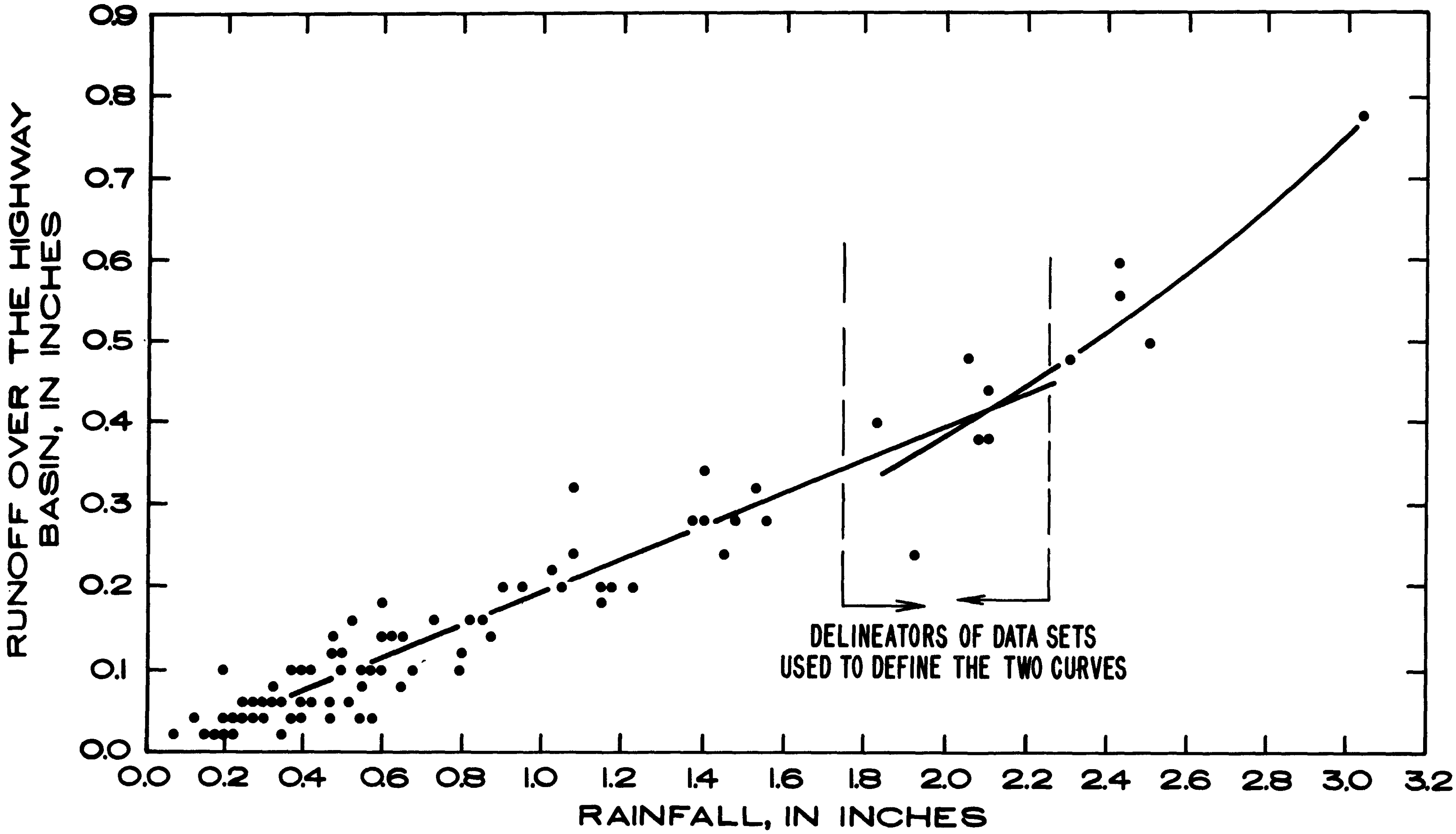

Figure 3.--Runoff-rainfall plot for the highway basin.

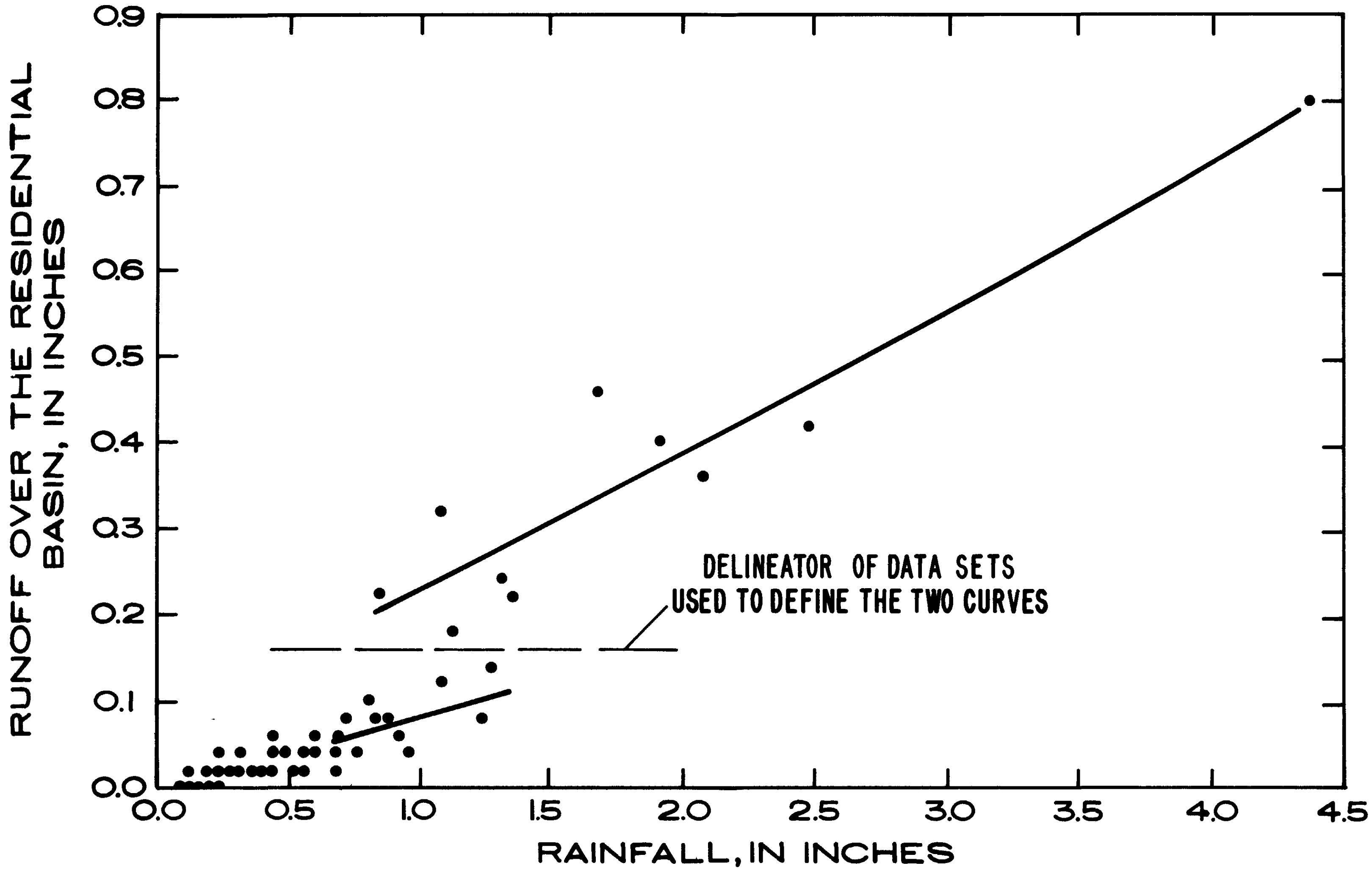

Figure 4.--Runoff-rainfall plot for the residential basin.

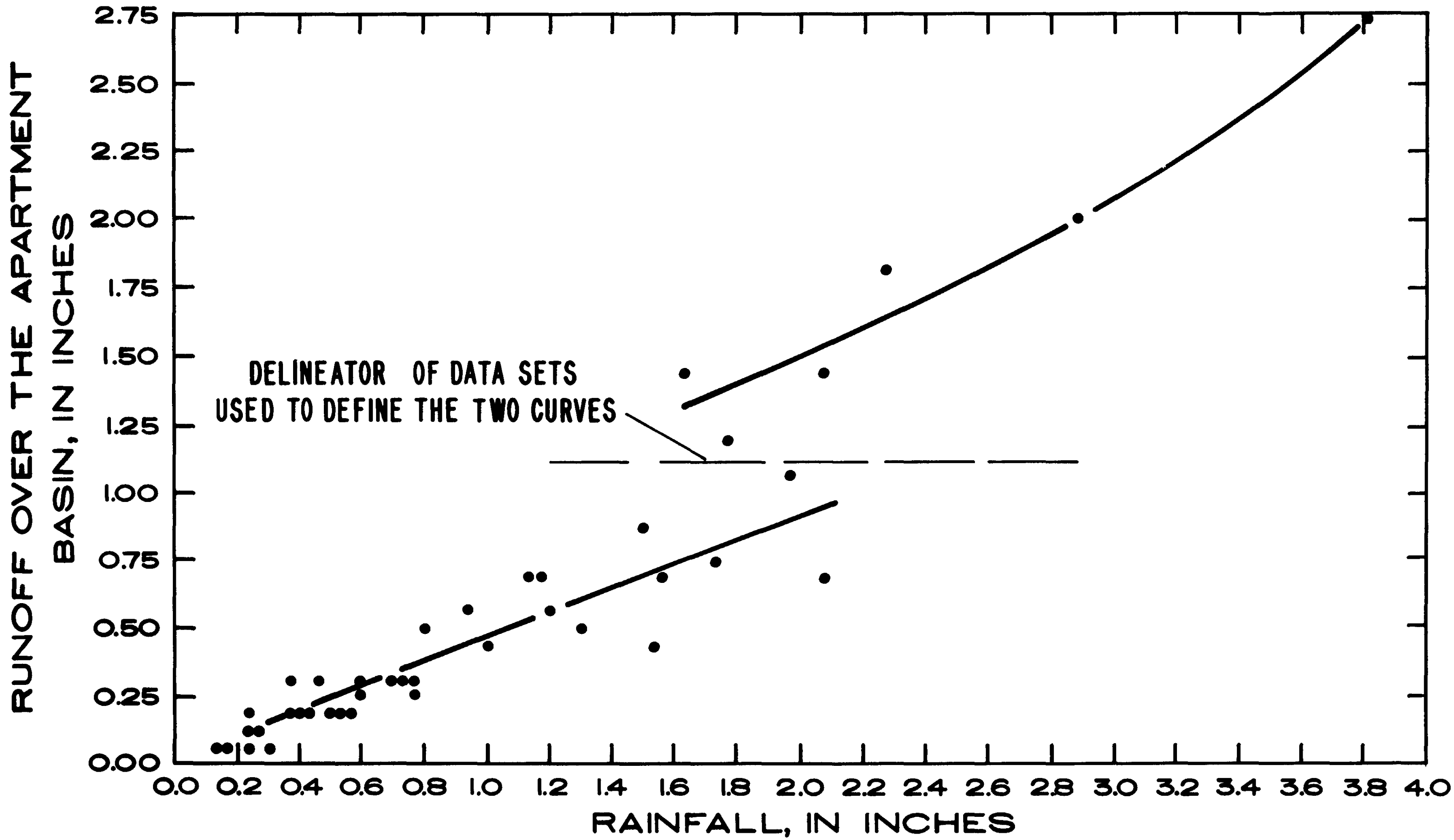

Figure 5.--Runoff-rainfall plot for the apartment basin.

The explanation of the three combinations of curves is rather straightforward. Runoff is routed to the point of observation from three separate, physical areas of the basin--the hydraulically effective impervious area (HEIA), the noneffective impervious area, and the pervious area. The HEIA is defined by Miller (1978) as "that impervious area which contributes runoff to the drain immediately after surface wetting takes place" (or, after initial abstractions have been met). The authors of the model ILLUDAS (Terstriep and Stall, 1974) called this basin characteristic the "directly connected paved area." In the U.S. Geological Survey's model (Dawdy and others, 1978) the characteristic is termed the "effective impervious area."

When the runoff is from the HEIA only, it originates as rainfall on the HEIA, and is proportional to the rainfall so that a linear runoff-rainfall relation exists. If the runoff originates on noneffective impervious area and is routed over pervious area, or if the runoff originates on the pervious area, a relation exists between runoff and rainfall which is nonlinear because of the varying amount of rainfall which becomes infiltrate. The resulting runoff-rainfall plot will be curvilinear with the slope being maximum at the larger rainfalls, and minimum at the smaller rainfalls. The maximum slope is 100 percent, when no additional infiltration can take place and all additional rainfall becomes runoff. The minimum slope may be, or at least appears to approach, that of the linear part of the runoff-rainfall relation.

Whether the linear and nonlinear curves intersect, or are disjointed, depends on the nature of the runoff process when runoff is first contributed from the area outside of the HEIA. Obviously, the intersected function represents a process where the change in runoff increases gradually, whereas the disjointed function represents a process where the change in runoff is abrupt. The severity of the offset of the disjointed function is due to the hydraulic connection of noneffective impervious areas and pervious area with the HEIA, and in some lesser amount to antecedent soil-moisture conditions in the pervious area, and rainfall intensity and duration. On the residential basin, the offset occurs after the swales along the streets fill to capacity and discharge water onto the HEIA. On the apartment basin this offset occurs when the soils on the flow paths between the downspouts of the apartments and the HEIA cannot receive the water as part of the infiltration process, and flow is transmitted from the noneffective impervious area (apartment buildings), across the pervious area, to the HEIA.

Importance of Source Area of Runoff

Runoff is treated as an independent variable in the development of the percentage-entrainment curves. In order to relate the volume of runoff to an expression involving basin size, runoff is expressed as a depth (in inches) over the source area. Three different source areas, the hydraulically effective impervious area, the contributing area, and the drainage area, were considered in the analysis. These are explained in the following sections and shown schematically in figure 6. With runoff expressed as a depth, basin size

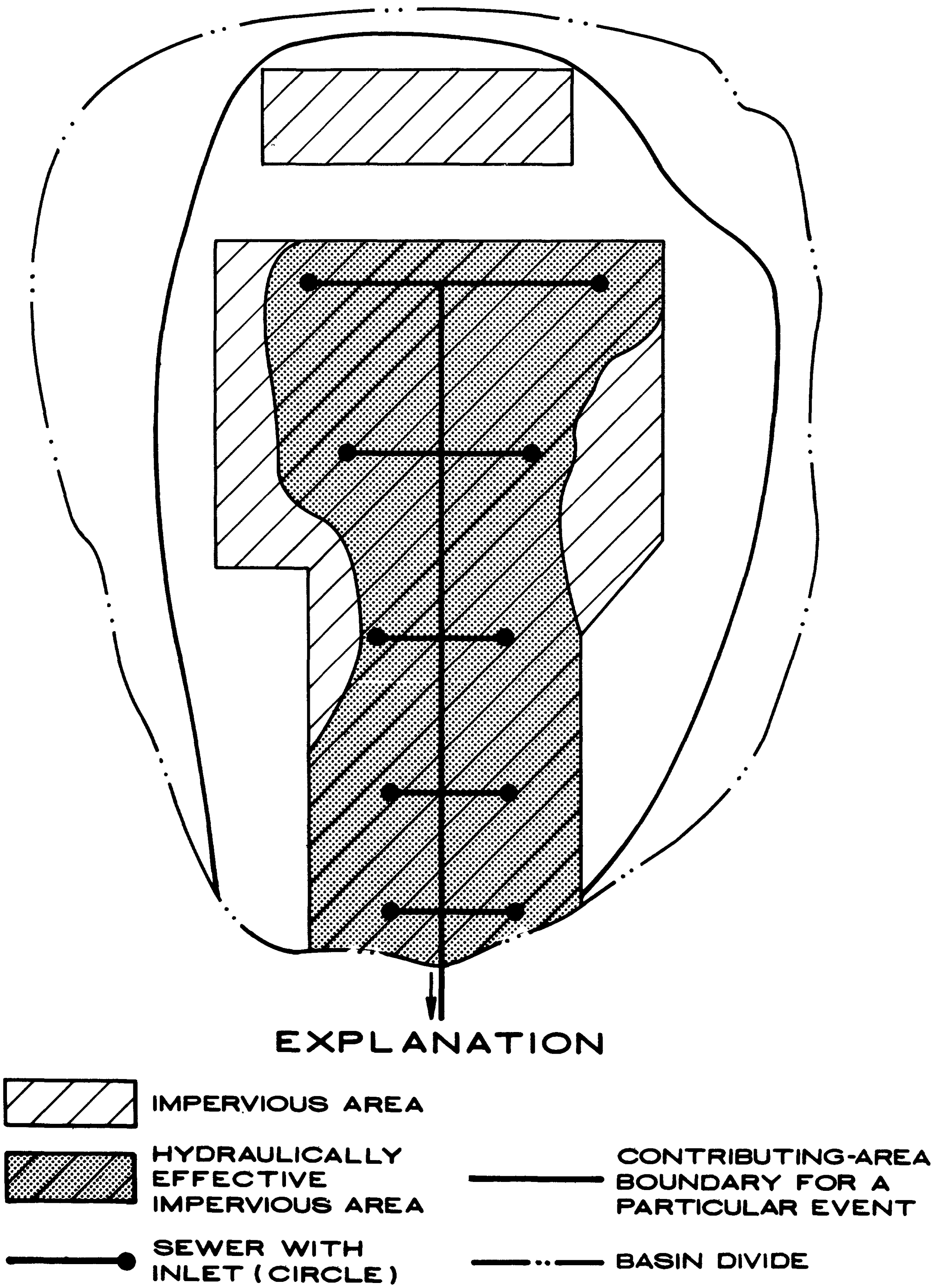

Figure 6.--Concepts of hydraulically effective impervious area and contributing area.

is eliminated as a parameter in the results of the analysis. This should make the results of this study transferable to basins having source areas of runoff different from those used in this study.

In the initial development of the percentage-entrainment relations, basin runoff for each basin was assumed to originate on the HEIA. But it was found that when the percentage-entrainment curves for a specific constituent for the four basins were superimposed, the variation, or spread of the curves was quite large, and, furthermore, that the curve for the commercial basin, which is nearly 100-percent impervious, was always found to the upper left of the other three basin curves. It was reasoned that the curve for the commercial basin represented some sort of upper maximum relation because the basin was nearly fully impervious. Furthermore, it was observed that the three remaining curves sometimes reached the point where runoff, in inches from the HEIA, exceeded the rainfall depth. These latter results inferred that the calculated depths of runoff were excessive for the basins other than commercial, and, therefore, that runoff was being contributed from areas on the basin other than the HEIA.

Methods were then developed for estimating the contributing area of the basin. When the percentage-entrainment curves calculated for runoff from the estimated contributing area were superimposed (as shown in a later part of this report), it was observed that variations in curve shapes and ranges were small. This closeness of fit was taken to be an indirect confirmation that the estimated contributing area was a better estimator than the HEIA of the source area of runoff from the four basins.

Hydraulically Effective Impervious Area

Several steps are necessary to determine the HEIA. First, the sewerage map, the layout of the storm sewer along with the inlet locations, is needed. Second, a contour map of the basin, preferably with a 1-foot contour interval, must be developed. Third, the drainage map, showing the drainage area for each inlet and the paths of overland flow, is constructed by superimposing the sewerage map and the contour map. Fourth, the pervious areas, noneffective impervious areas, and HEIA, are delineated by superimposing the drainage map and a photomosaic of the basin. The three areas are then measured and the percentage of HEIA determined.

The percentage of basin which is HEIA as derived from the procedure described above should be about the same as the slope (in percent) of the lower part of the runoff-rainfall curve for the basin. Miller (1978) and Miller and Mattraw (1982) found that the slope of the lower part of the runoff-rainfall curve correlates well with the percentage of basin measured as being HEIA. This is because, for small rainfall events, the only runoff that occurs is coming from the HEIA. Data pertaining to the HEIA and slopes of the runoff-rainfall curves for the four study basins are given in table 1.

Table 1.--Summary of area characteristics and slope of the runoff-rainfall curves for the four basins

Basin	Total area (acres)	Impervious area (acres)	Hydraulically effective impervious area (acres)	Hydraulically effective impervious area (percent)	Slope of linear part of the runoff-rainfall curve (percent)
Residential	40.8	17.9	2.41	5.92	9.07
Highway	58.3	21.1	10.5	18.1	19.9
Commercial	20.4	20.0	20.0	97.9	101.5
Apartment	14.7	10.4	6.48	43.9	44.2

Contributing Area

The contributing area for surface runoff is that surface area, or part of the basin contributing runoff from the basin during a storm. For most basins, the contributing area is a variable, dependent upon storm rainfall and infiltration, and at least conceptually, varies in size during individual storms. The contributing area is at a minimum at the beginning of a storm when accumulative rainfall is small and infiltration is occurring on most pervious parts of the basin. For urban basins, the minimum contributing area, once initial abstractions have been met, is the HEIA. The contributing area approaches a maximum when rainfall is large and infiltration is no longer occurring. For both natural and urban basins, the maximum contributing area is the topographically-determined drainage area.

The contributing area of a basin varies not only with rainfall amount and intensity, but also depends upon the soil-water interaction. When the soil of a basin is dry, it is capable of accepting sizable amounts of rainfall, the process referred to as infiltration. As more and more water infiltrates, the capability of the soil to accept more water decreases, and finally at some point in the infiltration process, a nontrivial amount of rainfall is rejected as infiltrate and thus becomes stormwater runoff. As rainfall continues with time, or as rainfall intensity increases, proportionally smaller quantities of rainfall infiltrate the soil and larger quantities of stormwater runoff are generated.

If overland flow is generated at some upgradient point on the pervious surface while infiltration is still occurring at some downgradient point on the flow path, the stormwater may simply infiltrate upon reaching the downgradient point. Therefore, if the volume of water passing the stormwater-measuring station is to be increased, the additional stormwater must come from a combination of increased runoff within the contributing area, and an increase in the size of the contributing area.

Concepts analogous to the above description have appeared in the literature for large, natural-basin hydrology (Betson, 1964; Hewlett and Hibbert, 1967). These concepts, and, in particular, the part of the basin on which the runoff originates, have been variously referred to as the variable source area, the partial area, or the contributing area. In this report the term contributing area will be used.

To date (1984), the ideas associated with a dynamic source area of runoff are more conceptual than quantifiable. A deterministic model has been developed by Engman and Rogowski (1974) which, as a part of the computational procedure, determines the source area. But no simple approach exists for calculating the source area of runoff.

A simplified approach was taken in this study to estimate the contributing area. For some low range of rainfall which is dependent on the basin's characteristics, the ratio of runoff to rainfall is equal to the ratio of HEIA to drainage area, as explained in the previous section,

$$\frac{RO}{RN} = \frac{HEIA}{DA}$$

where

RO = runoff from drainage area, in inches,
RN = rainfall, in inches,
HEIA = hydraulically effective impervious area, in acres, and
DA = drainage area, in acres.

When the runoff-rainfall relation is linear, the ratio of runoff to rainfall is the slope of the runoff-rainfall curve.

Therefore,

$$HEIA = S_{RR} \times DA$$

where

S_{RR} = slope of the linear part of the runoff-rainfall relation.

The contributing-area equation is assumed to be analogous to the HEIA equation,

$$CA = S_{RR} \times DA$$

where

CA = contributing area, in acres, and
S_{RR} = slope of the runoff-rainfall curve at the rainfall depth of interest.

The contributing-area functions for the four basins are shown in figure 7. These were calculated from the relation in the previous paragraph, the product of the slope of the runoff-rainfall curve at the rainfall of interest, and the drainage area. Because the slope of the runoff-rainfall curve is the derivative of the equation fitted to the runoff-rainfall data, the form of the contributing-area curve is determined by the form of the runoff-rainfall curve. That is, a second degree runoff-rainfall curve will produce a linear contributing-area curve and a linear runoff-rainfall curve will produce a constant for the contributing-area curve. The reverse is also true--if the contributing-area function is a constant, the runoff-rainfall curve must be linear, and if the contributing-area function is linear, the runoff-rainfall curve must be second degree. Therefore, equations of degrees larger than first for the contributing-area function can hardly be warranted because of the necessity of larger-than-second-degree curve required for the runoff-rainfall plot.

The calculated contributing-area function for the commercial basin is a constant, 20.8 acres, because the runoff-rainfall plot is linear. The HEIA for the commercial basin was measured to be 20.0 acres.

For the highway basin the contributing-area curve is a constant of 11.6 acres for rainfalls up to about 2 inches and then increases linearly (slope $\simeq$ 17 acres per inch) reaching about 60 acres at 5 inches of rainfall. The HEIA was measured to be 10.5 acres. A break in the contributing-area function occurs because the slopes of the two runoff-rainfall curves were not made equal at the point of intersection.

The contributing-area functions for the residential basin and apartment basin are similar in form to that of the highway basin. They have contributing areas equal to 3.71 and 6.50 acres, initially, and then increase linearly (slopes $\simeq$ 0.6 and 2 acres per inch, respectively) until reaching the size of the drainage area. The HEIAs for these two basins are 2.41 and 6.48 acres, respectively.

The range in rainfall over which the contributing area varies should be noted. On the highway and apartment basins, the contributing area begins to increase at a rainfall depth of about 2 inches. Based on the curves fitted to the runoff-rainfall function and then extrapolated, the contributing area reaches a maximum (the drainage area) at about 5 inches of rainfall on the highway basin and about 6 inches on the apartment basin.

The contributing-area curve for the residential basin is radically different from the other three curves in the amount of rainfall necessary to produce the maximum contributing area. Although the contributing area begins to increase at about 1 inch of rainfall, calculations show that the contributing area will not reach drainage-area size until an atypical value of about 63 inches of rainfall is reached. This extremely shallow contributing-area function may be due to several causes. The runoff-rainfall plot is poorly defined above 2.5 inches of rainfall, having only one datum point at a rainfall of nearly 4.5 inches. Therefore, the equation of the curve is probably poor, and the extrapolation needed to complete the contributing-area function is concurrently poor. Another explanation is one associated with the design of

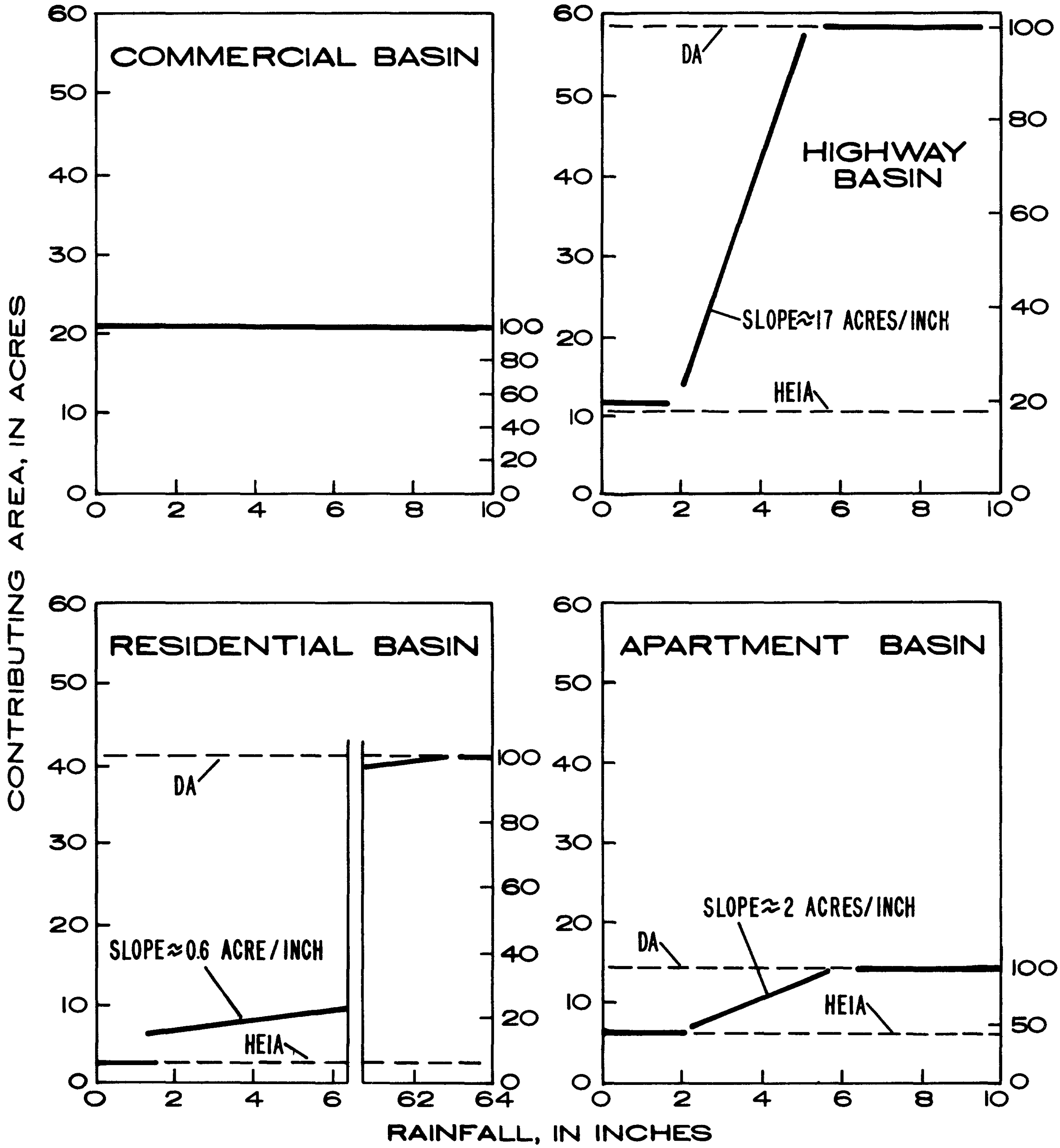

Figure 7.-- Contributing-area functions for the four basins.

the sewerage system, which is located in the eastern part of the basin only. Drainage for the central and western parts of the basin is provided by swales routing flow to the sewerage. This atypical design produces a small slope on the runoff-rainfall curve for the rainfalls observed, and the expected upward curvature of the function at larger depths of rainfall was not observed.

The rainfall depth at which runoff is first contributed from the area outside of the HEIA on any given basin is termed "breakpoint rainfall" in this report. This value is the depth at which the offset, or intersection, occurs on the runoff-rainfall functions, figures 3, 4, and 5. As seen on these figures, there is some range of rainfall depths that could be chosen, not just one definitive value. When this range of values for each basin is plotted against the HEIA of the basin, a casual relation is formed (fig. 8). For the basins in this study there appears to be an increasing function, whether linear or nonlinear, between breakpoint rainfall and the HEIA. This relation is probably due to the increased runoff needed, as the HEIA increases, to effect an offset in the runoff-rainfall relation.

RESULTS OF THE COMPUTATIONS

Analysis Using Hydraulically Effective Impervious Area as Source of Runoff

The percentage-entrainment curves produced when the HEIA is considered as the source of runoff are shown in figures 9 through 11 for the six constituents considered in the analysis. In each figure, the curves for each of the four basins are superimposed. The data used to plot the curves are given in tables 2 and 3.

The figures show a wide range in curve locations, especially for total phosphorus (fig. 9). At 1 inch of runoff from the HEIA, the percentage of total phosphorus entrained in the runoff ranges from slightly less than 70 percent to slightly more than 90 percent. For all constituents, the curve for the commercial basin lies to the upper left, and the curves for either the apartment or residential basins usually lies to the lower right. Typically, the curve for the highway basin lies in the middle of the curves for the other three basins at larger runoffs.

The envelope curves for all constituents (the uppermost curve or curves and the lowermost curve or curves) for the analysis using the HEIA are shown in figure 12. Also superimposed on this figure are the average curve for all the entrainment curves, and the average curve for the commercial basin. The latter curve is shown because it shows the entrainment from an almost totally impervious basin, and should be directly transferable to other nearly impervious basins.

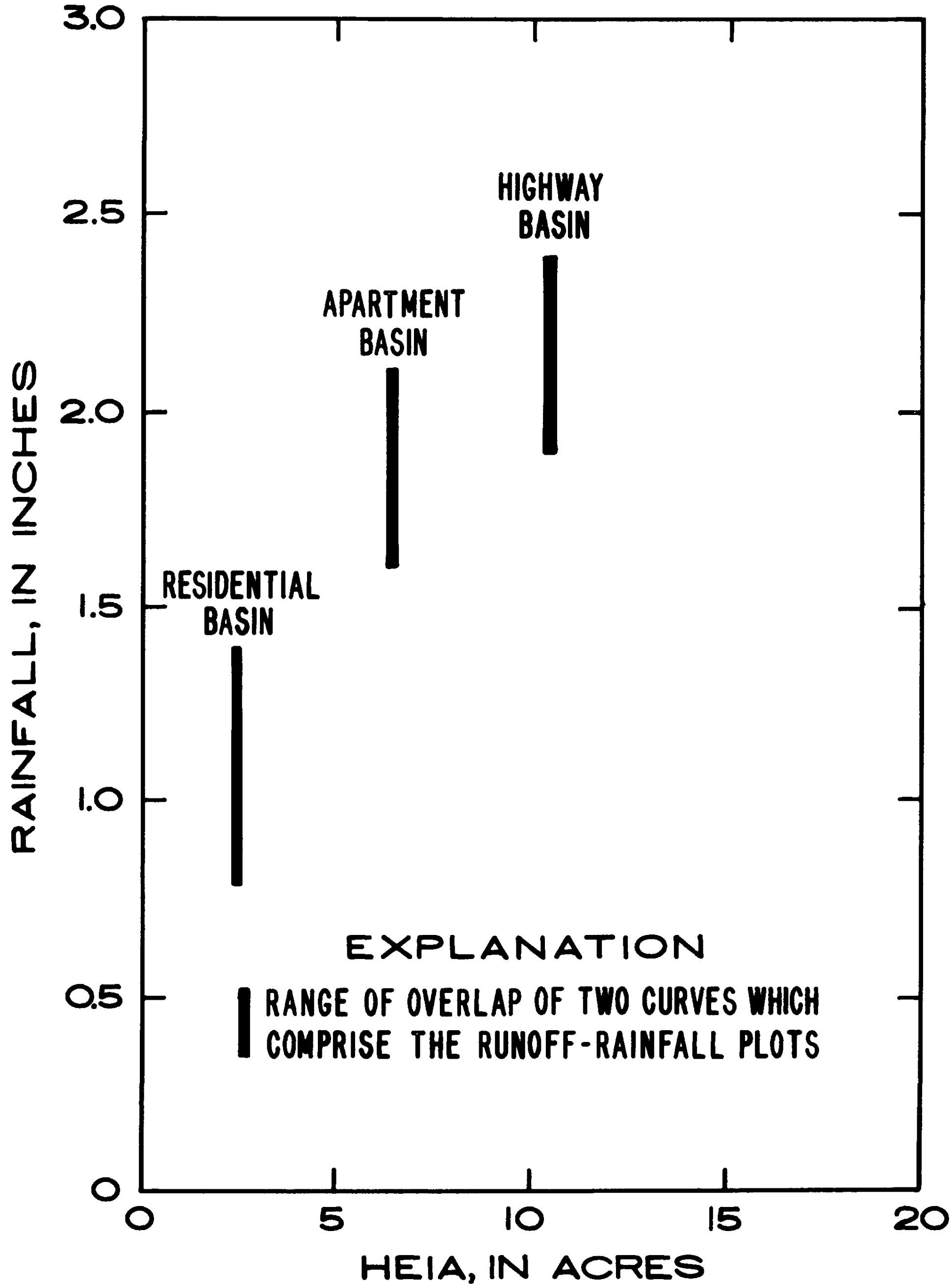

Figure 8.--Relation of breakpoint rainfall and hydraulically effective impervious area.

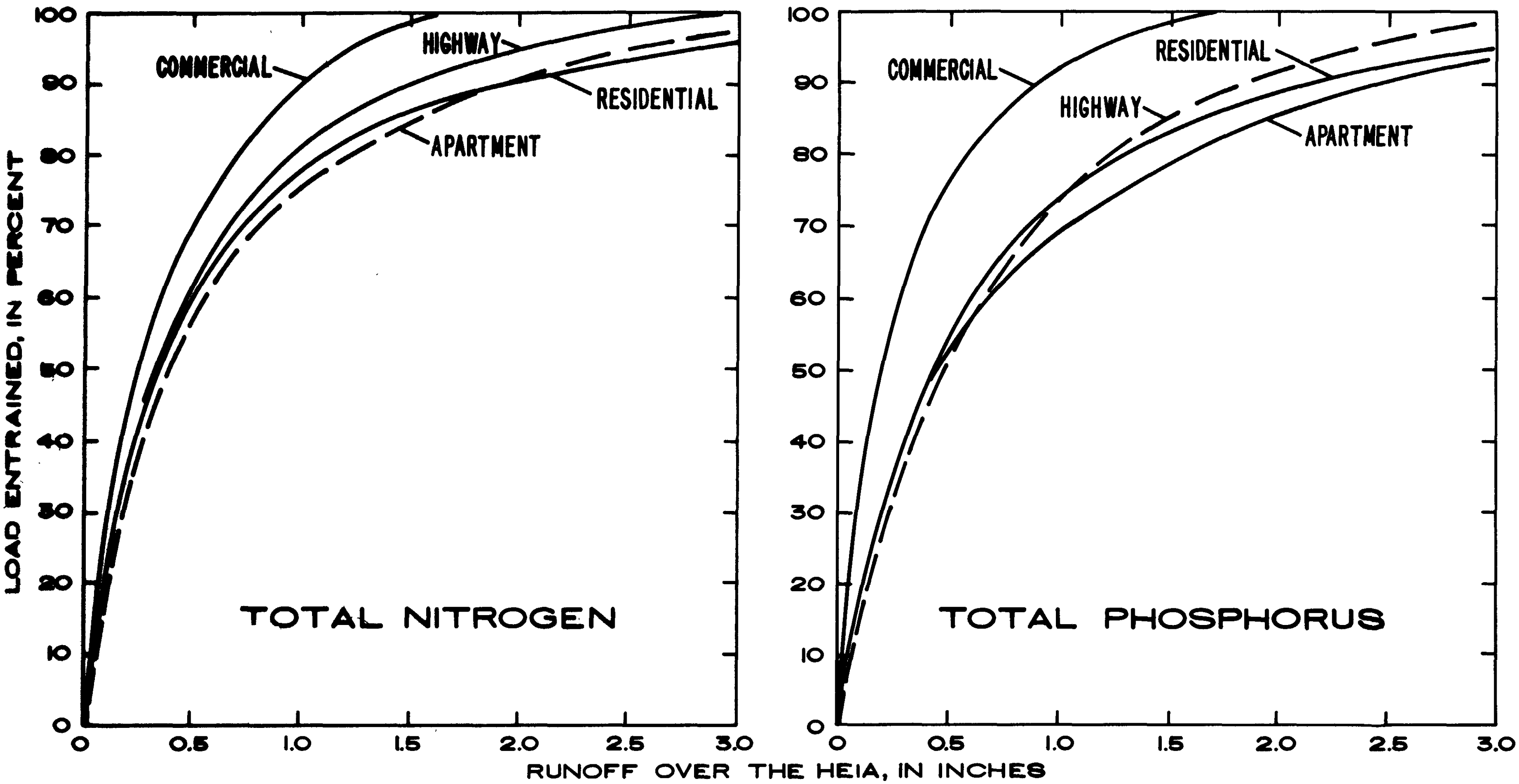

Figure 9.--Percentage-entrainment curves for total nitrogen and total phosphorus when the hydraulically effective impervious area is considered as the source of runoff.

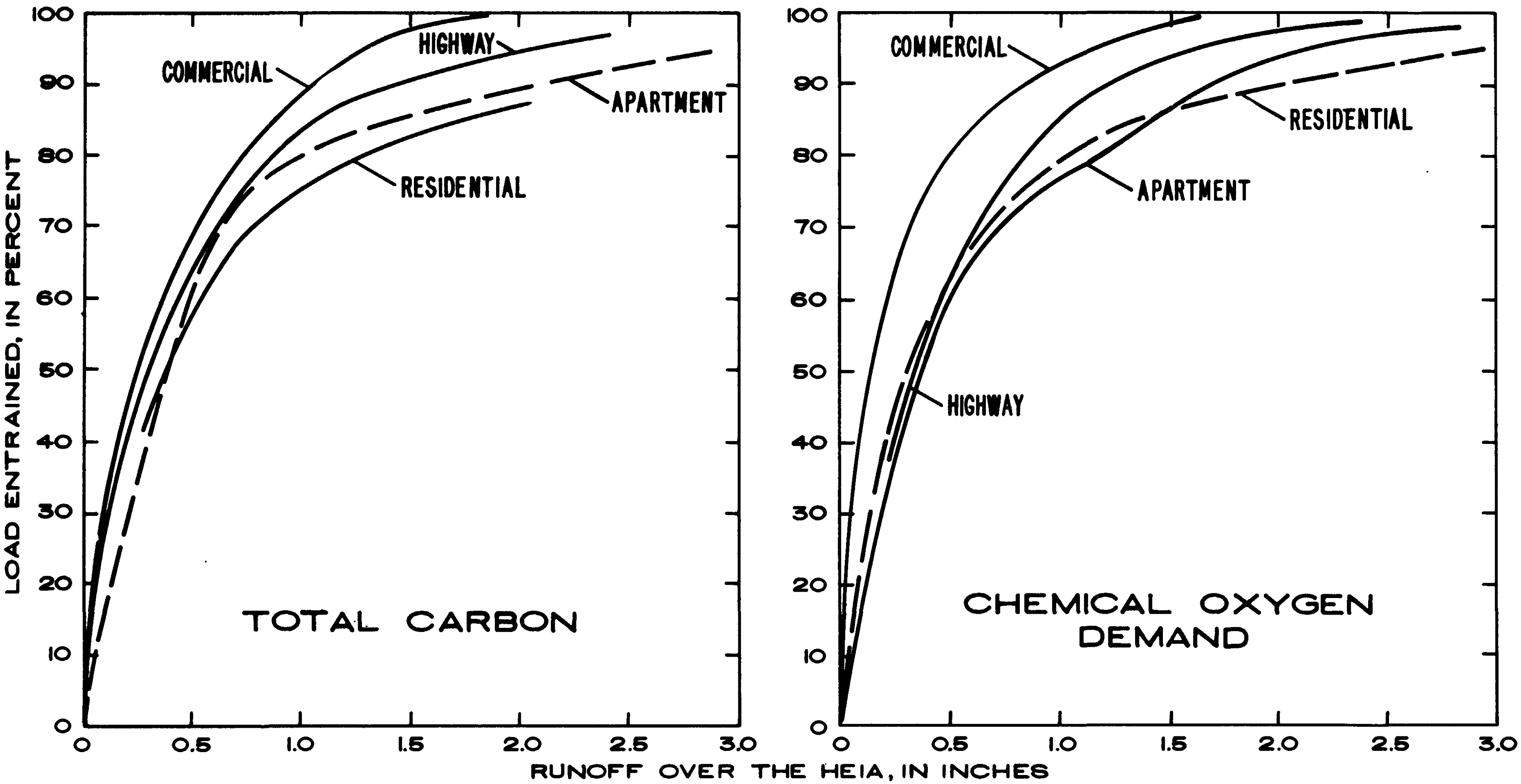

Figure 10.--Percentage-entrainment curves for total carbon and chemical oxygen demand when the hydraulically effective impervious area is considered as the source of runoff.

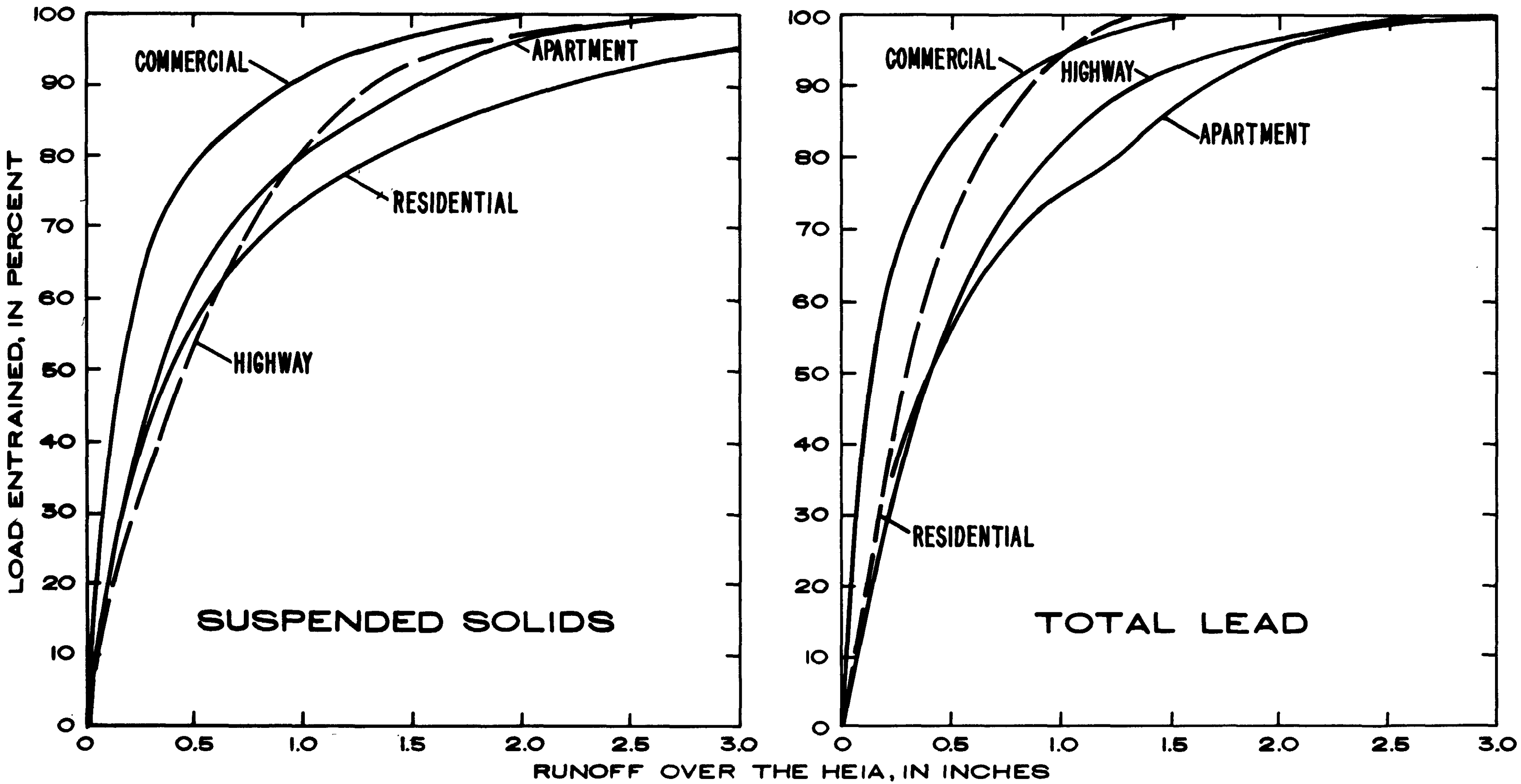

Figure 11.--Percentage-entrainment curves for suspended solids and total lead when the hydraulically effective impervious area is considered as the source of runoff.

Table 2.--Percent entrainment of total nitrogen, total phosphorus, and total carbon from the hydraulically effective impervious area

[HEIA, hydraulically effective impervious area]

Runoff from the HEIA, in inches	Percent entrainment of total nitrogen				Percent entrainment of total phosphorus				Percent entrainment of total carbon			
	Residential	Highway	Commercial	Apartment	Residential	Highway	Commercial	Apartment	Residential	Highway	Commercial	Apartment
0.1	20.4	21.2	27.3	16.6	15.5	15.6	29.9	14.4	17.3	24.1	27.8	13.6
.2	36.1	36.4	44.4	31.8	30.9	27.5	49.4	28.1	32.3	39.0	44.7	26.5
.3	46.3	47.7	56.3	43.0	40.9	36.7	62.1	38.9	42.3	49.3	55.7	38.2
.4	53.1	55.4	64.9	51.8	47.8	44.3	70.8	47.7	49.3	56.8	62.9	49.3
.5	59.7	62.0	71.4	58.2	54.2	51.3	76.8	53.4	56.2	63.5	69.1	59.5
.6	65.6	66.9	76.4	63.2	60.2	56.9	81.2	57.8	62.4	68.7	74.1	67.0
.7	69.9	71.4	80.5	67.1	64.8	62.2	84.6	60.9	67.1	73.2	78.4	71.6
.8	72.8	75.3	84.3	70.4	68.3	66.8	87.4	63.7	70.3	77.1	82.2	74.9
.9	75.3	78.6	87.6	73.3	71.4	70.8	89.9	66.4	73.1	80.4	85.4	77.6
1.0	77.8	81.5	90.4	75.7	74.6	74.2	92.0	68.7	75.8	83.0	88.2	79.8
1.1	79.7	84.0	92.8	77.3	76.7	77.2	93.8	70.4	77.4	85.4	91.1	81.1
1.2	81.8	85.7	94.7	79.1	78.9	79.4	95.3	72.2	78.9	86.9	93.4	82.3
1.3	83.7	87.3	96.4	81.0	80.9	81.5	96.7	74.3	80.3	88.3	95.6	83.5
1.4	85.7	88.8	97.3	82.9	83.2	83.5	97.4	76.4	81.8	89.6	96.7	84.7
1.5	86.7	90.1	98.1	84.9	84.2	85.2	98.1	78.5	82.7	90.6	97.5	85.9
1.6	87.4	91.1	98.8	86.4	85.1	86.6	98.7	80.2	83.4	91.5	98.3	86.8
1.7	88.1	92.3	99.2	87.7	86.0	88.0	99.1	81.7	84.1	92.4	98.8	87.4
1.8	88.8	93.4	99.6	88.8	86.8	89.5	99.4	83.0	84.8	93.5	99.2	87.8
1.9	89.5	94.2	99.8	89.9	87.7	90.6	99.5	84.3	85.5	94.1	99.5	88.3
2.0	90.1	94.9	99.9	90.8	88.5	91.7	99.7	85.4	86.3	94.8	99.9	88.9
2.1	90.7	95.5	99.9	91.6	89.3	92.6	99.8	86.4	87.1	95.3	100.0	89.5
2.2	91.4	96.1	100.0	92.4	90.1	93.4	99.9	87.3	87.8	95.8		90.1
2.3	92.0	96.7		93.0	90.8	94.2	100.0	88.2	88.6	96.4		90.8
2.4	92.6	97.2		93.7	91.5	95.0		89.0	89.4	96.9		91.4
2.5	93.2	97.8		94.3	92.2	95.8		89.9	90.1	97.4		92.0
2.6	93.8	98.4		94.9	92.9	96.6		90.8	90.9	97.9		92.7
2.7	94.3	99.0		95.4	93.5	97.5		91.6	91.7	98.4		93.3
2.8	94.9	99.4		95.8	94.2	98.1		92.8	92.4	98.9		93.9
2.9	95.5	99.5		96.2	94.9	98.5		92.9	93.2	99.1		94.5
3.0	96.1	99.6		96.6	95.6	98.9		93.7	94.0	99.3		95.0
3.1	96.7	99.8		97.1	96.2	99.3		94.5	94.7	99.6		95.6
3.2	97.1	99.9		97.6	96.7	99.6		95.4	95.4	99.8		96.3
3.3	97.5	100.0		97.9	97.1	100.0		96.1	96.0	100.0		96.9
3.4	97.9			98.2	97.5			96.7	96.5			97.3
3.5	98.2			98.5	98.0			97.2	97.1			97.8

Table 3.--Percent entrainment of chemical oxygen demand, suspended solids, and lead from the hydraulically effective impervious area

[HEIA, hydraulically effective impervious area]

Runoff from the HEIA, in inches	Percent entrainment of chemical oxygen demand				Percent entrainment of suspended solids				Percent entrainment of total lead			
	Residential	Highway	Commercial	Apartment	Residential	Highway	Commercial	Apartment	Residential	Highway	Commercial	Apartment
0.1	21.0	22.0	36.7	17.5	18.9	15.9	36.9	18.7	17.8	17.8	36.1	16.3
.2	39.0	36.7	55.9	33.3	33.7	27.5	56.5	36.0	35.7	29.8	57.9	30.9
.3	48.9	47.6	67.1	44.2	44.3	38.1	67.0	48.2	49.5	39.2	69.5	41.3
.4	55.7	55.9	74.5	52.5	51.2	47.4	74.2	56.8	59.6	47.4	76.3	48.4
.5	62.1	63.2	79.2	58.8	57.5	55.3	78.8	62.9	69.4	55.3	80.8	54.6
.6	67.2	69.1	82.7	63.8	62.4	61.9	82.1	67.7	77.3	62.0	84.5	60.1
.7	71.0	74.3	85.6	67.6	66.0	67.7	84.7	71.3	82.7	68.1	87.5	64.6
.8	73.8	78.7	88.0	70.9	68.8	72.7	87.1	75.2	86.7	73.2	89.9	68.2
.9	76.4	82.4	90.0	73.6	71.2	77.0	89.2	78.3	89.9	77.5	92.1	71.3
1.0	79.2	85.3	91.6	75.7	73.5	80.9	91.0	80.3	93.0	81.0	93.5	73.7
1.1	80.7	88.0	93.0	77.1	75.7	84.5	92.5	81.6	95.6	84.3	94.6	75.5
1.2	81.9	89.8	94.4	79.0	77.6	87.2	93.8	83.0	97.2	86.5	95.7	77.7
1.3	83.2	91.5	95.9	81.2	79.4	89.8	95.4	84.8	98.5	88.4	97.0	80.3
1.4	84.8	92.9	96.7	83.4	81.4	92.0	96.4	86.8	99.8	89.9	97.9	83.0
1.5	85.7	94.0	97.4	85.6	83.0	93.2	97.3	88.8	100.0	91.1	98.7	85.6
1.6	86.3	94.5	98.1	87.5	84.3	94.1	98.0	90.6		92.1	99.2	87.8
1.7	86.9	95.3	98.5	89.3	85.3	94.9	98.4	92.4		93.0	99.5	89.9
1.8	87.5	96.1	98.9	91.0	86.2	95.8	98.8	94.1		94.0	99.7	91.7
1.9	88.1	96.5	99.2	92.4	87.1	96.3	99.4	95.5		94.7	99.8	93.3
2.0	88.7	96.9	99.4	93.5	88.0	96.8	99.7	96.6		95.5	99.9	94.6
2.1	89.3	97.2	99.6	94.4	88.7	97.2	99.9	97.4		96.0	99.9	95.5
2.2	89.9	97.5	99.8	95.1	89.5	97.4	99.9	97.8		96.4	100.0	96.0
2.3	90.6	97.8	100.0	95.6	90.3	97.7	100.0	98.2		96.9		96.4
2.4	91.3	98.1		96.0	91.0	98.0		98.3		97.4		96.7
2.5	91.9	98.4		96.3	91.8	98.3		98.5		97.8		96.9
2.6	92.5	98.7		96.6	92.6	98.6		98.6		98.3		97.1
2.7	93.1	99.0		96.9	93.4	98.8		98.7		98.8		97.4
2.8	93.7	99.2		97.1	94.3	99.1		98.8		99.1		97.5
2.9	94.3	99.4		97.3	95.1	99.3		98.9		99.3		97.7
3.0	94.9	99.5		97.5	95.9	99.5		99.0		99.5		97.9
3.1	95.5	99.7		97.9	96.8	99.6		99.2		99.7		98.1
3.2	96.1	99.8		98.2	97.3	99.8		99.4		99.8		98.4
3.3	96.6	100.0		98.5	97.6	100.0		99.5		100.0		98.6
3.4	97.0			98.7	97.9			99.6				98.8
3.5	97.5			98.9	98.3			99.6				99.0

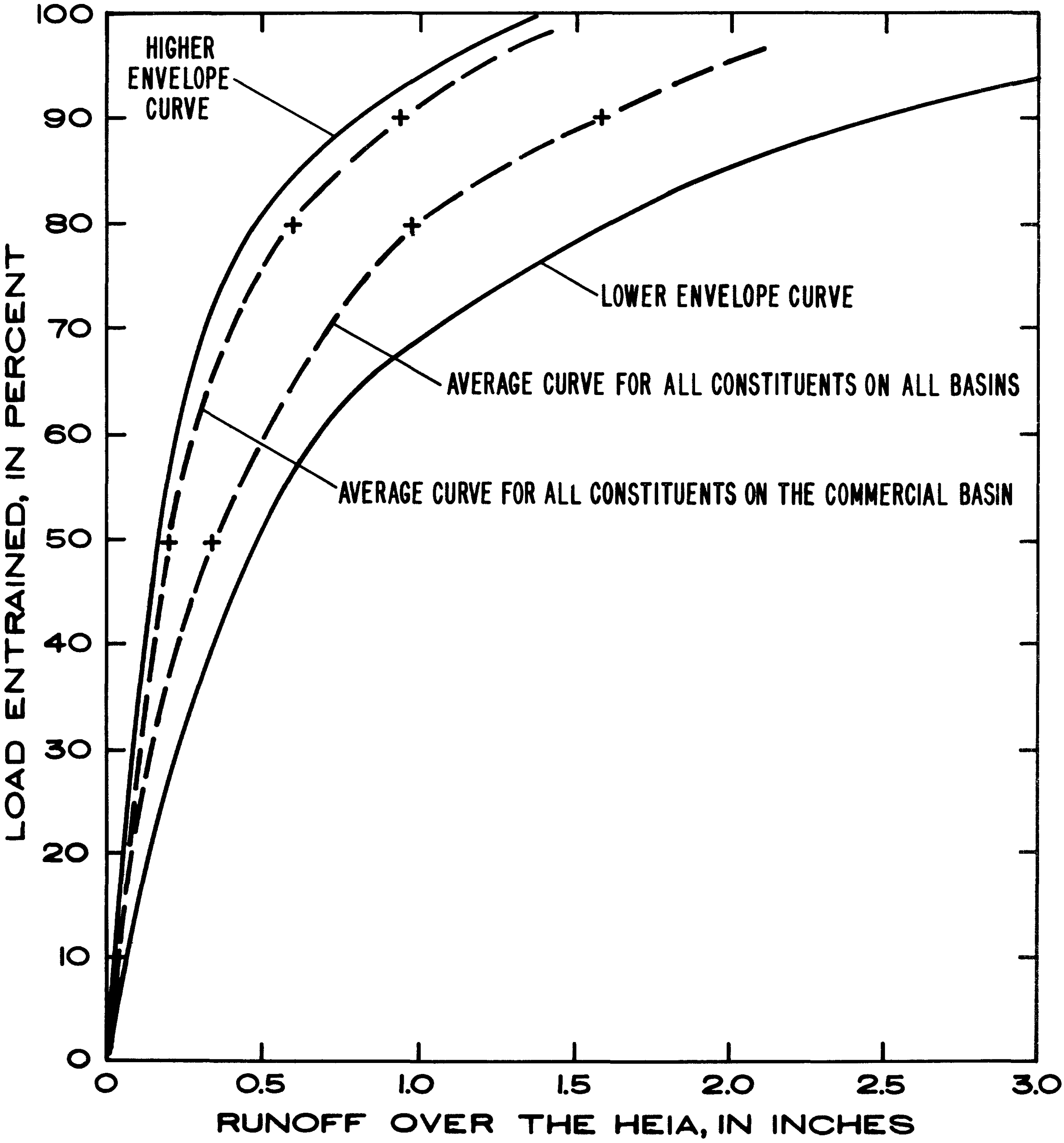

Figure 12.--Envelope and average curves for all percentage-entrainment curves calculated using the hydraulically effective impervious area as the source of runoff.

Analysis Using Estimated Contributing Area as Source of Runoff

The runoff was also calculated using the CA (contributing area) as the rce of runoff. The curves for the six constituents analyzed are shown in ures 13 through 15. The data used to plot the curves are given in tables 4 d 5. Total phosphorus and total lead show the largest range in basin curves, ith total phosphorus from the apartment basin and total lead from the esidential basin being the most severe outliers.

Envelope curves for all six constituents analyzed are plotted in figure 16. The runoff from the CA required to remove 90 percent of the constituent loads analyzed ranged from about 0.4 to 1.4 inches. The 80-percent range of runoff has values of about 0.3 to 0.9 inch, and the 50-percent range has values of about 0.2 to 0.4 inch.

Superimposed on the envelope curves is the average curve, defined by averaging runoff values for all curves (all constituents and all basins) at the 50, 80, and 90 percent levels. These values are 0.25, 0.65, and 0.95 inch of runoff, respectively. Also shown is the average curve for all constituents on the commercial basin.

STATISTICAL TESTING OF THE CONTRIBUTING-AREA ANALYSIS

Statistical testing, specifically ANOVA (analysis of variance) (Hicks, 1973), was used to determine if the factors "percentage entrainment," "basin," and "constituent" were statistically significant for the contributing-area analysis. Depth of runoff from the estimated contributing area was used as the response variable (table 6). The factor "percentage entrainment" was operated at three levels--50 percent, 80 percent, and 90 percent; factor "basin" was operated at four levels; and factor "constituent" at six levels.

The purpose of the ANOVA is to evaluate the hypothesis that the means of all levels (states at which an experiment is run) within a factor are equal. The design of the experiment was 3x4x6 factorial arrangement with one observation per cell. Additionally, Duncan's Multiple Range Test (Helwig and Council, 1979), hereafter called the range test, was used to determine those means different from other means. Both the ANOVA and the range test were run at a significance probability of 0.05.

On the full data set the results of the ANOVA indicated that all three factors were significant. The range test showed that an exclusive difference existed for the means of the factor "percentage entrainment"; any one level was different from any other one. For the factor "basin," the means showed some overlap; the levels of apartment and highway were similar, but differed from commercial and residential, which were also similar. The factor "constituent" had large overlaps in its levels, without definitive groupings.

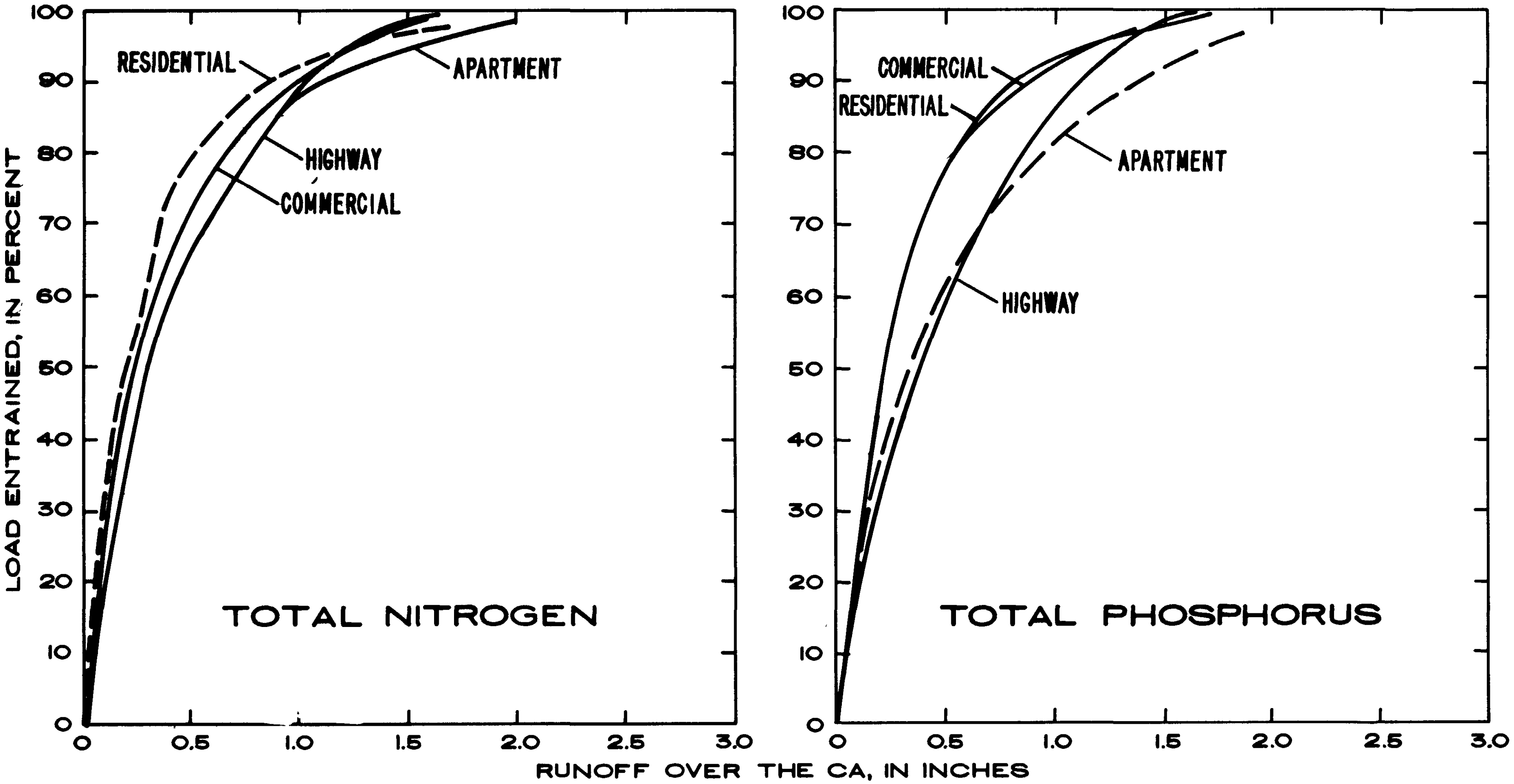

Figure 13.--Percentage-entrainment curves for total nitrogen and total phosphorus when the contributing area is considered as the source of runoff.

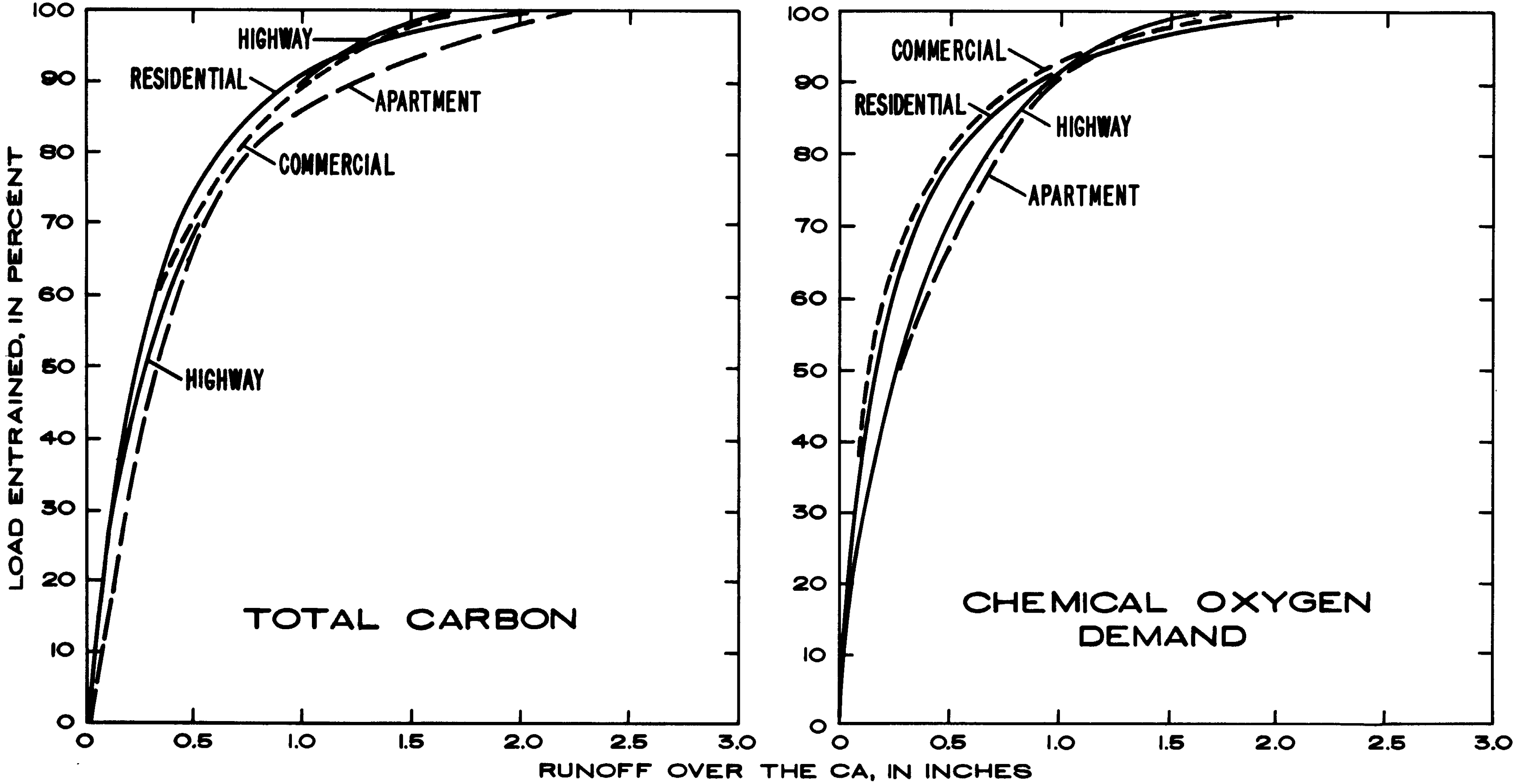

Figure 14.--Percentage-entrainment curves for total carbon and chemical oxygen demand when the contributing area is considered as the source of runoff.

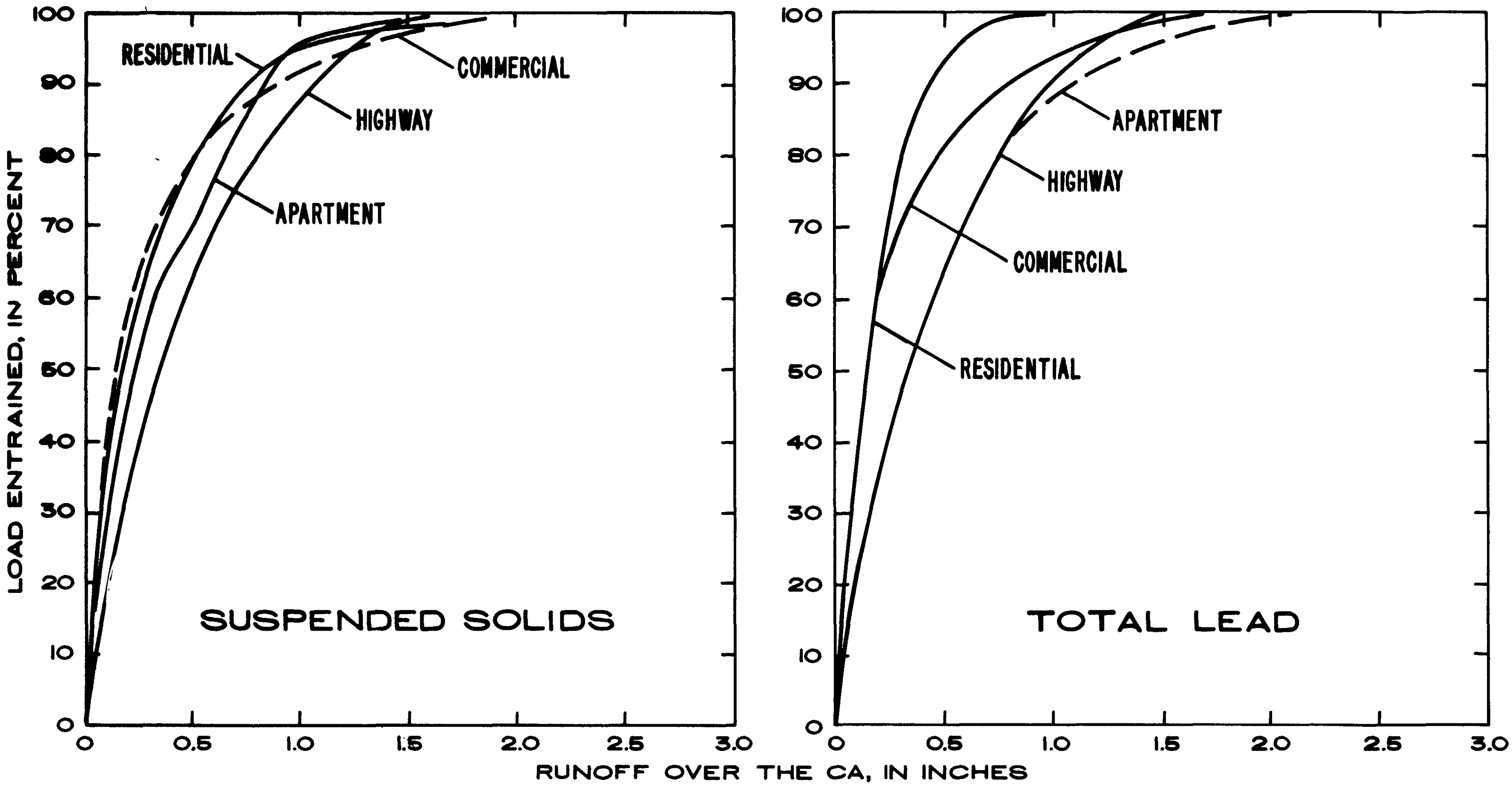

Figure 15.--Percentage-entrainment curves for suspended solids and total lead when the contributing area is considered as the source of runoff.

Table 4.--Percent entrainment of total nitrogen, total phosphorus, and total carbon from the contributing area

[CA, contributing area]

Runoff from the CA, in inches	Percent entrainment of total nitrogen				Percent entrainment of total phosphorus				Percent entrainment of total carbon			
	Residential	Highway	Commercial	Apartment	Residential	Highway	Commercial	Apartment	Residential	Highway	Commercial	Apartment
0.1	32.6	24.2	28.2	20.8	28.0	17.9	30.9	18.3	28.1	27.4	28.8	17.0
.2	50.7	40.6	45.5	39.0	45.9	31.0	50.6	35.1	45.9	42.9	45.7	33.1
.3	63.4	52.4	57.5	50.7	58.8	41.4	63.4	46.0	58.6	53.7	56.8	46.4
.4	74.0	60.6	66.0	58.9	70.1	50.2	71.8	53.6	69.4	62.0	63.9	58.8
.5	78.9	67.2	72.5	65.4	76.7	57.7	77.8	59.3	75.2	68.9	70.3	68.7
.6	83.1	72.6	77.4	71.0	82.4	64.3	82.0	64.3	80.3	74.5	75.2	74.9
.7	86.4	77.8	81.7	76.6	86.4	70.9	85.4	69.6	83.7	79.7	79.6	79.1
.8	89.4	82.4	85.4	81.5	89.9	76.4	88.3	74.5	86.9	84.0	83.3	82.6
.9	91.4	86.5	88.6	85.2	92.2	81.4	90.6	78.5	89.4	87.6	86.4	84.8
1.0	92.6	90.3	91.5	87.7	93.6	86.1	92.8	81.3	91.3	90.9	89.4	86.2
1.1	93.8	93.1	93.7	89.7	95.0	89.7	94.5	83.6	93.3	93.2	92.2	87.8
1.2	94.7	95.7	95.5	91.5	95.9	93.3	96.0	85.7	94.6	95.4	94.5	89.4
1.3	95.4	97.8	97.0	93.1	96.4	96.2	97.2	87.8	95.2	97.2	96.3	90.8
1.4	96.0	98.5	97.8	94.3	96.9	97.5	97.8	89.5	95.8	98.0	97.2	91.9
1.5	96.6	99.1	98.6	95.4	97.4	98.5	98.5	91.4	96.5	98.8	98.0	93.1
1.6	97.2	99.8	99.1	96.3	97.9	99.6	98.9	93.1	97.1	99.7	98.6	94.4
1.7	97.9	100.0	99.5	97.2	98.3	100.0	99.3	94.9	97.8	100.0	99.1	95.8
1.8	98.5		99.7	97.8	98.8		99.5	96.0	98.4		99.4	96.7
1.9	99.1		99.9	98.4	99.3		99.7	97.1	99.1		99.8	97.6
2.0	99.7		99.9	99.1	99.8		99.8	98.3	99.7		100.0	98.6
2.1	100.0		100.0	99.7	100.0		99.9	99.4	100.0			99.5
2.2				100.0			100.0	100.0				100.0
2.3												
2.4												
2.5												

Table 5.--Percent entrainment of chemical oxygen demand, suspended solids, and total lead from the contributing area

[CA, contributing area]

Runoff from the CA, in inches	Percent entrainment of chemical oxygen demand				Percent entrainment of suspended solids				Percent entrainment of total lead			
	Residential	Highway	Commercial	Apartment	Residential	Highway	Commercial	Apartment	Residential	Highway	Commercial	Apartment
0.1	34.2	24.8	37.8	21.8	33.2	17.7	38.0	23.8	35.7	20.1	37.2	20.5
.2	51.4	40.7	57.0	40.2	53.6	32.4	57.5	45.1	59.9	34.2	59.0	38.2
.3	62.8	52.3	68.2	51.8	66.0	45.4	68.0	57.9	77.2	45.8	70.5	48.6
.4	72.4	61.2	75.3	59.7	75.1	54.8	75.0	64.8	88.3	55.1	77.1	55.8
.5	77.6	68.6	80.0	65.6	80.8	62.3	79.5	70.0	92.8	63.3	81.6	62.2
.6	82.3	74.7	83.4	71.3	84.8	68.9	82.8	75.5	96.3	70.5	85.3	68.8
.7	85.1	80.2	86.4	77.8	88.5	74.9	85.4	82.4	98.2	76.7	88.2	75.5
.8	87.7	84.6	88.8	83.7	91.8	79.8	87.9	88.4	99.7	81.8	90.7	81.4
.9	89.8	88.2	90.7	88.4	94.4	84.3	89.9	93.0	100.0	86.2	92.7	85.9
1.0	91.4	91.5	92.2	91.3	95.6	88.6	91.7	95.7		90.3	94.0	88.7
1.1	93.1	93.8	93.7	93.1	96.8	91.8	93.0	97.0		93.1	95.1	90.7
1.2	94.2	96.0	95.2	94.3	97.5	95.0	94.6	97.7		95.7	96.3	92.3
1.3	94.9	97.7	96.4	95.3	97.8	97.2	96.0	98.2		97.7	97.5	93.6
1.4	95.6	98.4	97.0	95.9	98.1	98.2	96.9	98.4		98.5	98.3	94.6
1.5	96.3	99.0	97.8	96.6	98.4	98.9	97.9	98.8		99.1	99.1	95.7
1.6	97.0	99.7	98.4	97.3	98.7	99.7	98.3	99.0		99.8	99.4	96.7
1.7	97.7	100.0	98.8	97.9	99.0	100.0	98.7	99.3		100.0	99.6	97.8
1.8	98.3		99.1	98.4	99.3		99.3	99.5			99.7	98.5
1.9	99.0		99.4	98.8	99.6		99.7	99.6			99.9	99.0
2.0	99.7		99.6	99.3	99.9		99.8	96.8			99.9	99.4
2.1	100.0		99.8	99.7	100.0		99.9	99.9			100.0	99.8
2.2			100.0	100.0			100.0	100.0				100.0
2.3												
2.4												
2.5												

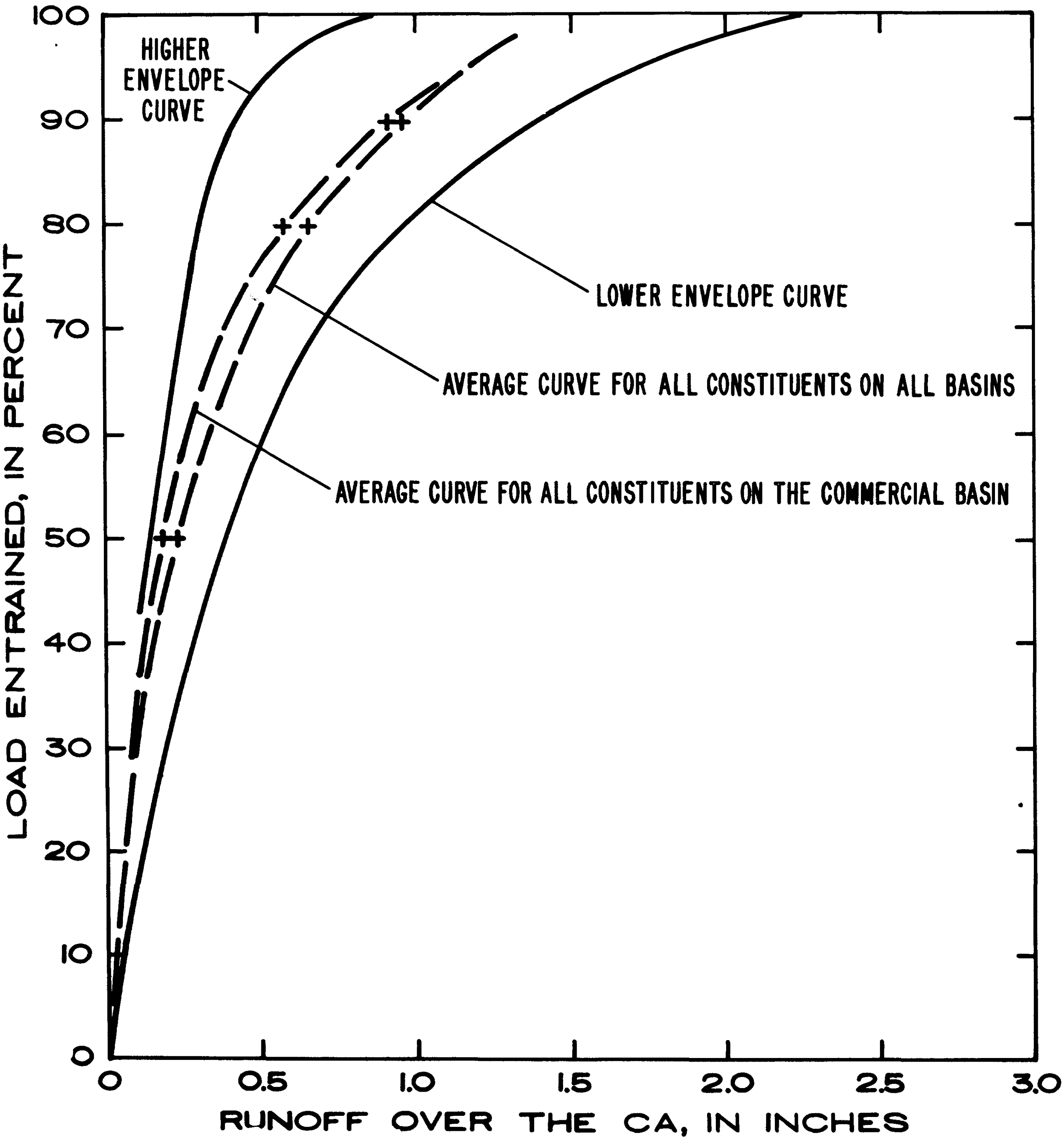

Figure 16.--Envelope and average curves for all percentage-entrainment curves calculated using the contributing area as the source of runoff.

Table 6.--Depth of runoff, in inches, from the contributing area for six constituents from four basins

Constituent	Basin	Percent entrainment 50	80	90
Total nitrogen	Residential	0.20	0.52	0.85
Do.	Highway	.28	.75	1.00
Do.	Commercial	.24	.66	.95
Do.	Apartment	.30	.77	1.12
Total phosphorus	Residential	.24	.55	.80
Do.	Highway	.39	.87	1.10
Do.	Commercial	.20	.55	.88
Do.	Apartment	.35	.95	1.42
Total carbon	Residential	.23	.59	.93
Do.	Highway	.27	.71	.97
Do.	Commercial	.24	.71	1.02
Do.	Apartment	.33	.73	1.24
Chemical oxygen demand	Residential	.19	.55	.91
Do.	Highway	.28	.70	.95
Do.	Commercial	.16	.50	.87
Do.	Apartment	.28	.74	.95
Suspended solids	Residential	.18	.49	.75
Do.	Highway	.35	.80	1.05
Do.	Commercial	.15	.51	.91
Do.	Apartment	.23	.67	.83
Total lead	Residential	.15	.32	.43
Do.	Highway	.35	.77	.99
Do.	Commercial	.15	.46	.77
Do.	Apartment	.32	.78	1.06

The means of runoff from the contributing area as a function of percentage entrainment (averaged across constituents and basins) are given in table 7. These means form the basic points of the one, generalized percentage-entrainment curve derived from the data.

Table 7.--Means of runoff, in inches, from contributing area, all constituents, all basins

Percent entrainment	Mean
50	0.25
80	.65
90	.95

Now that the means of "percentage entrainment" was shown to be exclusively different, the data set was broken into three separate sets, one for each level of percentage entrainment, and ANOVA performed on each set. This setup provided three separate experiments of 4x6 factorial arrangements. For the 50-percent entrainment, "basin" was found to be significant and "constituent" was not. The range test for "constituent" showed a large overlap of levels having similar means, and for "basins," highway and apartment were similar, but different from residential and commercial, which were similar.

Testing for the 80-percent entrainment showed the same results as for the 50-percent entrainment. At the 90-percent entrainment, results were similar to the two previous testings. The only difference was in the range test for "basin"; differentiation was not as concise, with highway and commercial not significantly different from each other.

The means of runoff from the estimated contributing area (averaged across constituent) as a function of percentage entrainment and basin are shown in table 8.

Table 8.--Means of runoff, in inches, from contributing area, all constituents

Percent entrainment	Basins	Means
50	Residential/commercial	0.198/0.190
	Highway/apartment	.320/.302
80	Residential/commercial	.503/.565
	Highway/apartment	.767/.773
90	Residential/commercial	.778/.900
	Commercial/highway	.900/1.01
	Highway/apartment	1.01/1.10

ANALYSIS WITH RESPECT TO SOURCE AREA

The ANOVA procedures quantify the similarities and differences among the curves, and indicate what factors are responsible in forming the curves. The factor "constituent" is not statistically significant in determining the percentage entrainment, but the factor "basin" is significant. Therefore, the analysis of the data will proceed by pooling curves of differing constituents, but paying close attention to basin hydraulics.

Average entrainment curves for the six constituents analyzed have been plotted for each basin in figures 17 and 18. On each figure are superimposed three entrainment curves, one curve for each of the three source areas of the basin. The three source areas are: (1) HEIA (hydraulically effective impervious area), (2) CA (contributing area), and (3) DA (drainage area).

For the commercial basin (fig. 17), the three curves for the HEIA, CA, and DA lie nearly on top of each other because more than 97 percent of the basin is impervious and hydraulically effective.

For the highway basin (fig. 17), the positions of the HEIA and CA curves are similar, but the position of the DA curve differs considerably from the first two. The locations of the curves are related to the relative sizes of the source areas--the CA is not much larger than the HEIA, but the DA is much larger than either. For the highway basin, 90 percent of the load is entrained within less than 0.3 inch of runoff if the DA is considered as the source area.

The three curves for the residential basin (fig. 18) are rather evenly spaced, inferring that the CA is considerably larger than the HEIA but much smaller than the DA. For this basin also, the DA curve lies far to the left on the plot, and 90 percent of the load is entrained within less than 0.2 inch of runoff from the DA.

The three curves for the apartment basin (fig. 18) are also evenly spaced. But for this basin, the DA curve is much closer to the CA curve than for the highway and residential basins because the DA is not much larger than the CA. For the apartment basin, 90 percent of the load is entrained within about 0.8 inch of runoff from the DA.

In the section on statistical testing of the CA curves, it was shown for the factor "basin" that the apartment basin and highway basin were statistically similar, and that the commercial basin and residential basin were similar, but that the two groups were not similar to each other. These conclusions can be seen by comparing the CA-runoff curves for each of the four basins, figures 17 and 18.

Both the residential and commercial basins have rather compact shapes with storm-sewer systems which are also compact and efficient. In contrast, the highway and apartment basins have elongated sewerage configurations. Therefore, for the latter two basins, constituent loads occurring early in the storm runoff would be washed from areas near the outlet of the basin. As the storm event continues, loads from the early part of the storm at more distant points

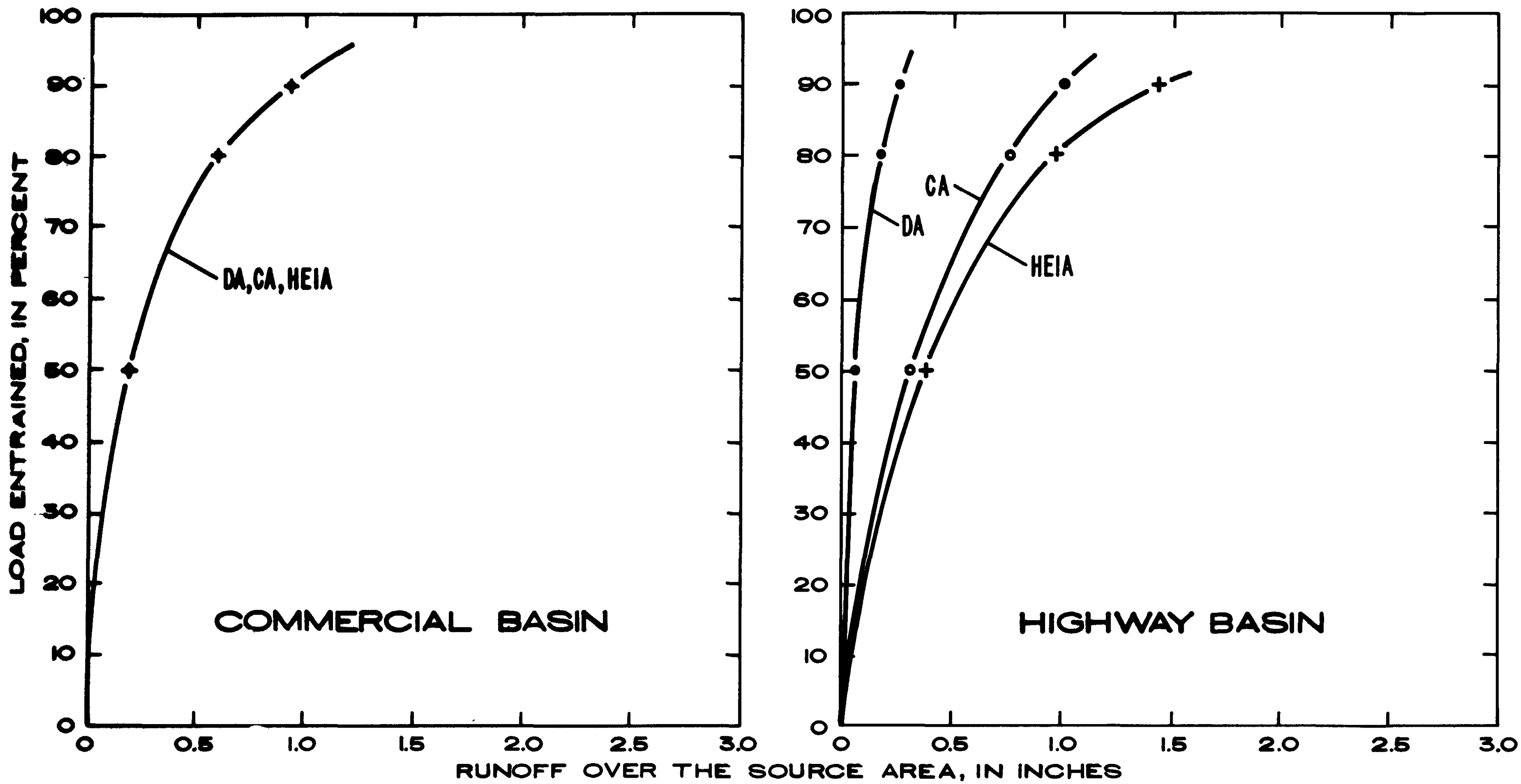

Figure 17.--Average percentage-entrainment curves for the commercial and highway basins when the drainage area (DA), contributing area (CA), and hydraulically effective impervious area (HEIA) are considered as the source of runoff.

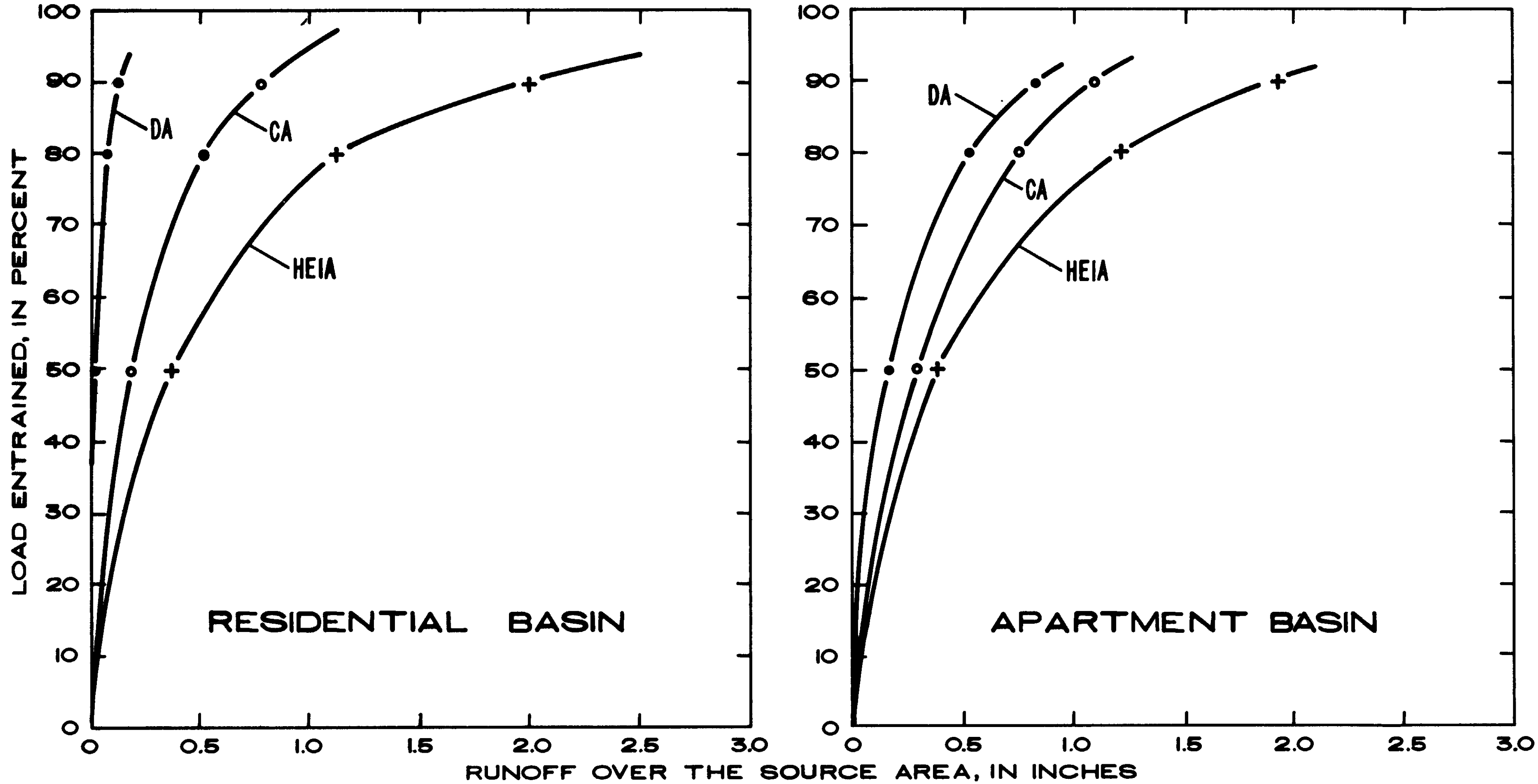

Figure 18.--Average percentage-entrainment curves for the residential and apartment basins when the drainage area (DA), contributing area (CA), and hydraulically effective impervious area (HEIA) are considered as the source of runoff.

arrive at the basin outlet, and are combined with loads from areas near the basin outlet which were washed by rains during a later time of the storm. This process, basically due to the time of travel within the storm sewer, causes the percentage-entrainment curve for the highway and apartment basins to rise less rapidly than curves generated on compact basins. The net effect is a curve that is statistically different from those curves generated from more compact sewerage systems.

SUMMARY AND CONCLUSIONS

To provide a better understanding of stormwater runoff processes, data from two studies in south Florida were analyzed to determine the volumes of runoff that entrain various percentages of different constituent loads. Runoff and runoff-quality data were available from four homogenously developed basins having land uses of residential, highway, commercial, and apartment. The product of concentration, instantaneous discharge, and the necessary conversion factor provided the instantaneous load. The accumulative load and total load for each event having water-quality data were calculated by summing the instantaneous loads for small time periods.

A computational procedure was set up that: (1) developed the accumulative loadograph, (2) interpolated values of the accumulative loadograph for specified depths of runoff, and (3) calculated the percentage of constituent load entrained in the specified depths of runoff. The curve developed by the calculation, the percentage of constituent load entrained as a function of runoff, is called the percentage-entrainment curve. Constituents analyzed in this manner are total nitrogen, total phosphorus, total carbon, chemical oxygen demand, suspended solids, and total lead.

Percentage-entrainment curves were developed for three different types of source areas, the HEIA (hydraulically effective impervious area), the CA (contributing area), and the DA (drainage area). The contributing area for each storm event was calculated by multiplying the slope of the runoff-rainfall curve at the rainfall depth for the event by the drainage area.

In evaluating the runoff-rainfall curves, three different forms were found: (1) a one-curve relation, (2) a two-curve, intercepted relation, and (3) a two-curve, disjointed relation. The three forms are caused by the hydraulics of the overland flows coming from different physical areas within the basin--the HEIA, the noneffective impervious area, and the pervious area.

The percentage-entrainment curves based on the hypothesis of the HEIA as the source area of runoff show a wide spread from basin to basin. For example, at 1 inch of runoff from the HEIA, the percentage of total phosphorus ranges from a little less than 70 percent to slightly more than 90 percent. Under this hypothesis, it is common for the commercial-basin curve to lie to the upper left, and either the apartment-basin or residential-basin curve to lie to the lower right when curves for a particular constituent for each of the four basins are superimposed.

The percentage-entrainment curves based on the hypothesis of the CA being the source area of runoff show much less spread than the curves based on the HEIA concepts. The curves for total phosphorus and total lead show the larger ranges. The runoff from the CA required to entrain 90 percent of all constituents loads analyzed ranges from about 0.4 inch to 1.4 inches. The 80-percent range is about 0.3 to 0.9 inch of runoff, and the 50-percent range is about 0.2 to 0.4 inch. This closeness of fit was taken to be an indirect confirmation that the estimated contributing area was a better estimator than the HEIA of the source area of runoff from the four basins.

An analysis of variance procedure was used on runoff depth from the contributing area to determine which factors were important in shaping the curves. The factor "constituent" was found not to be significant, but the factors "percentage entrainment" and "basin" were found to be significant. These results infer that the basin washoff process entrains the six analyzed constituents in a very similar manner, and that chemical differences play a small part in the runoff process, at least at the scale analyzed; and additionally, that the sewerage design may play an important role in forming the percentage-entrainment curve. Compact sewerage systems produce percentage-entrainment curves that are steep relative to the curves produced by elongated sewerage designs. The fundamental difference is thought to be the time of travel by the stormwater within the sewer system.

With the factor "constituent" indicated to be unimportant, the percentage-entrainment curves for each basin were averaged, and then analyzed with respect to the three possible source areas of runoff--the HEIA, the CA, and the DA. For the commercial area, the three curves overlie each other because the basin is nearly all HEIA. For the highway and residential basins, the curves computed using the drainage area as the source of runoff lie far to the left of the curves portraying runoff from the HEIA and the CA. For the apartment basin, the three curves were more evenly and closely spaced than the curves for the highway and residential basins.

One general percentage-entrainment curve based on runoff from the contributing area was formed by averaging across both constituents and basins. Its coordinates are: 0.25 inch of runoff for 50-percent entrainment, 0.65 inch of runoff for 80-percent entrainment, and 0.95 inch of runoff for 90-percent entrainment. The general percentage-entrainment curve based on runoff from the HEIA has runoff values of 0.35, 0.95, and 1.6 inches, respectively.

REFERENCES

Betson, R. P., 1964, What is watershed runoff?: Journal of Geophysical Research, v. 69, no. 8, p. 1541-1552.

Dawdy, D. R., Schaake, J. C., Jr., and Alley, W. M., 1978, User's guide for distributed routing rainfall-runoff model; U.S. Geological Survey Water-Resources Investigations 78-90, 146 p.

Engman, E. T. and Rogowski, A. S., 1974, A partial area model for storm flow synthesis: Water Resources Research, v. 10, no. 3, p. 464-472.

Hardee, Jack, Miller, R. A., and Mattraw, H. C., Jr., 1978, Stormwater runoff data for a highway area, Broward County, Florida: U.S. Geological Survey Open-File Report 78-612, 166 p.

-----, 1979, Stormwater-runoff data for a multifamily residential area, Dade County, Florida: U.S. Geological Survey Open-File Report 79-1295, 68 p.

Helwig, J. T., and Council, K. A., eds., 1979, SAS User's Guide, 1979 ed.: SAS Institute Inc., Raleigh, N.C., 494 p.

Hewlett, J. D., and Hibbert, A. R., 1967, Factors affecting the response of small watersheds to precipitation in humid areas, in Forest hydrology edited by Sopper and Lull: Oxford, Pergamon Press.

Hicks, C. R., 1973, Fundamental concepts in the design of experiments: New York, Holt, Rinehart and Winston, 349 p.

Mattraw, H. C., Jr., Hardee, Jack, and Miller, R. A., 1978, Urban stormwater runoff data for a residential area, Pompano Beach, Florida: U.S. Geological Survey Open-File Report 78-324, 108 p.

Mattraw, H. C., Jr., and Miller, R. A., 1981, Stormwater quality processes for three land-use areas in Broward County, Florida: U.S. Geological Survey Water-Resources Investigations 81-23, 56 p.

Miller, R. A., 1978, The hydraulically effective impervious area of an urban basin, Broward County, Florida, in International symposium on urban stormwater management: University of Kentucky, Lexington, Kentucky, 1978, p. 259-261.

----- 1979, Characteristics of four urbanized basins in south Florida: U.S. Geological Survey Open-File Report 79-694, 45 p.

----- 1984, Rainfall-runoff mechanics for developed urban basins, south Florida, in 1984 International symposium on urban hydrology, hydraulics, and sediment control: University of Kentucky, Lexington, Kentucky, 1984, p. 135-141.

Miller, R. A., and Mattraw, H. C., Jr., 1982, Stormwater runoff quality from three land-use areas in south Florida: Water Resources Bulletin, v. 18, no. 3, p. 513-519.

Miller, R. A., and Mattraw, H. C., Jr., and Hardee, Jack, 1979, Stormwater runoff data for a commercial area, Broward County, Florida: U.S. Geological Survey Open-File Report 79-982, 127 p.

Terstriep, M. L., and Stall, J. L., 1974, The Illinois urban drainage area simulator, ILLUDAS: Bulletin 58, Illinois State Water Survey, 90 p.

GLOSSARY

Breakpoint rain.--The depth of rainfall at which runoff is contributed from the basin area beyond the hydraulically effective impervious area.

Constituent.--An elemental chemical component, usually an ion or atom.

Constituent load.--The mass of the constituent contained within the runoff, such as the total amount for a storm.

Contributing area (CA).--The part of the basin which contributes surface runoff at some time during a storm.

Entrainment.--The carrying along (to entrain) of any particular constituent load within the stormwater runoff.

Envelope curves.--Two curves on a plot of data, one representing the maximum of all data on the plot and the other representing the minimum of all data on the plot.

Hydraulically effective impervious area (HEIA).--The impervious areas adjoining the sewer inlets which contribute runoff to the sewer system as soon as initial abstractions (surface wetting, ponding, and other conditions) are met.

Noneffective impervious area.--Impervious area other than the HEIA. Runoff from these areas must pass over pervious area.

Percentage-entrainment curve.--A curve which results when percentage of accumulated constituent load is plotted against basin runoff.

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