The First Flush of Runoff and Its Effects On Control Structure Design

Prepared by

Environmental and Conservation Services Department
Environmental Resources Management Division
City of Austin, Texas

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EXECUTIVE SUMMARY

This report provides information on first flush of stormwater runoff. Storm-event data collected between 1984 and 1988 from seven single-land-use watersheds were analyzed.

The study found that although the first flush concentration is significantly higher, in many cases the first ½-inch of runoff does not carry most of the storm load. For example, the average maximum runoff amount per storm for a 90 percent impervious cover area is about 2.25 inches. During storm events of about this amount of runoff, the pollutant load removed by the first ½-inch of runoff averages about only 40 percent of the total storm load. This finding is contrary to the common assumption that, during a storm event the first ½-inch of runoff washes off 90% of pollutants accumulated on the impervious cover.

Percentage data of storm runoffs and loads corresponding to all runoff intervals were developed on an annual basis. If a water quality control basin is designed to treat the first ½-inch of runoff, part of the storm runoff may not be treated. On the annual basis, the untreated runoff volume increases from 0 to 47 percent of the total storm runoff when impervious cover increases. On the other hand, the amount of pollutant load carried by the untreated runoff increases at a lower pace, averaging from 0 to 28 percent of the total annual load with increasing impervious cover.

INTRODUCTION

The City of Austin's (COA) Stormwater Monitoring Program[1] (SWMP) monitors storm runoff quality and quantity for various land uses and control structures. Based on four years of SWMP data, the City has prepared two studies. One study[2] provides information concerning stormwater runoff pollutant loading characteristics. The average annual runoff loading rate and runoff event mean concentration (EMC) data for various monitoring sites were developed and 14 related to impervious cover and types of land use. The other study[3] presents results concerning the treatment efficiency of several stormwater control structures. Our present report evaluates the effects of the first flush on runoff loading rates and on the treatment efficiency of control structures. The first flush generally refers to the wash-off of pollutants in the first ½-inch or less of runoff.

Data in this study were collected from 7 monitoring sites as listed in Table 1. These sites are all small single-land-use suburban watersheds, including: Bear Creek (BC), primarily an undeveloped area; Rollingwood (RO), Maple Run (MI), Hart Lane (HL), and Highwood Apartment Complex (HI) which are newer, better maintained subdivisions; Barton Creek Square Mall (BCSM), a shopping mall and its parking lot; and Brodie Oaks Plaza (BI), a shopping center/office development. Both BCSM and BI sites are maintained by street sweeping programs. During the period of 1984-1988, 16 to 30 storm events were monitored for each site. The runoff depth for each storm ranged from 0.001 to 3.9 inches. Detailed information of rainfall, runoff, and runoff pollutant load and concentration for each storm was presented in the COA SWMP data books[4].

RAINFALL AND RUNOFF ANALYSIS

Rainfall and runoff data analyses were presented in a previous study[5]. The 1976-1985 daily rainfall data from Shoal Creek, a centrally located watershed, were chosen to represent the rainfall conditions for the Austin area. Daily rainfall depth data were divided into 12 range groups as shown in Table 2. The average annual rainfall depth corresponding to each group was estimated. For example, the average annual rainfall depth for the 0.41 to 0.50 inch group and the 0.51 to 0.75 inch group are 3.0 and 6.9 inches, respectively. The volumes of runoff generated from these rainfall amounts depend on the values of runoff coefficients. Table 3 presents runoff coefficients for various watershed imperviousness. These coefficients represent 10-year average values which were developed from a simulation study[5].

FIRST FLUSH CONCENTRATIONS

The runoff data for each site and for each monitored storm were divided into many intervals, such as 0 to 0.1 inch, 0.11 to 0.2 inch, and so on. The average concentration and incremental load corresponding to each runoff interval were computed. In this report the first flush concentration (FCONC) is defined as the mean concentration of a pollutant in the first 0 to 0.1 inch runoff of a storm event. In general, this concentration is significantly higher than those of other runoff intervals, and in turn, significantly higher than the storm event mean concentration (EMC). The mean concentrations for successive runoff intervals follow a decreasing trend. For most pollutant parameters, the decrease of the mean concentration values follows an exponential function instead of a linear relationship. In other words, the concentration approaches a constant value at the higher ranges of runoff. An example of the exponential function is presented in Figure 1. Table 4 presents the EMC and FCONC values for various watershed imperviousness. Except for the nutrient parameters, the FCONC values generally increase when impervious cover is increased. The FCONC data were further related to the number of dry days before a runoff event. The regressions of the FCONC on the number of dry days are generally not significant. Therefore, it is assumed that the FCONC's are relatively independent of the conditions preceding rainfall. The effect of street sweeping on the FCONC was not studied for BI and BCSM, however.

STORM LOAD OF THE FIRST HALF-INCH OF RUNOFF

It is commonly assumed that during a rainfall storm event, the first ½-inch of runoff will wash off most of the pollutants on impervious cover. The Hydroscience study[6] presented information on the characteristics of pollutant removal from street surfaces. The study referred to the assumption that ½-inch of runoff from a storm event is sufficient to remove 90 percent of road surface particles. The present report provides no experimental evidence to confirm or reverse this assumption. However, the data of this report indicate that for the larger storm events, the pollutant load removed by the first ½-inch of runoff does not necessarily constitute the majority of the total storm load. Based on the runoff data of the monitored storms, the average maximum storm runoff amount for each site was determined. The cumulative storm loads corresponding to this maximum amount and the first ½-inch of runoff for each of the larger storms were computed. The cumulative storm load data were averaged over a number of larger storms, i.e., storm events which produced the maximum runoff (0.75, 1.25, and 2.25 inches corresponding to different watershed imperviousness). In Table 5, the storm load averages for the first ½-inch of runoff are expressed as percentage values of the storm load averages for the maximum amount of runoff. For sites with less than 30 percent of impervious cover, the first ½-inch of runoff carries all or most storm load because most of the storms produce ½-inch or less amount of runoff. For sites with higher impervious cover, the average maximum runoff amount is significantly higher than a ½-inch. As shown in Table 5, the average maximum runoff amounts per storm for 50 and 90 percent impervious covers are 1.25 inches and 2.25 inches, respectively. In both cases, the pollutant loads removed by the first ½-inch of runoff average about 52 and 39 percent of the total storm load averages. In these cases, if the maximum storm load average (carried by the average of maximum runoff) can represent the average of pollutant mass accumulated on the watershed surface, then the first ½-inch of runoff can remove only one-half or less of the accumulated pollutants.

ANNUAL STORM LOAD DISTRIBUTION

This section discusses the percentage distributions of annual storm loads corresponding to different levels of storm runoff volume. As described before, for each site, the storm runoff volume data were divided into many intervals. The average of pollutant concentrations for a specific runoff interval was computed as the arithmetic mean of the concentration values for that interval. The computations for all runoff intervals were based on the same set of storm events. The annual runoff volume for a specific runoff interval was estimated using rainfall and runoff coefficient data (as provided in Tables 2-3). The annual storm load for the same runoff interval is the product of the annual runoff volume and the average of pollutant concentration. The annual load is the sum of the annual storm loads for all runoff intervals. Therefore, the annual storm load for any runoff interval is a fraction of the annual load and can be expressed in a percent of the annual load. The distribution of percentage of the annual storm load for each monitoring site and for each pollutant was developed. The percentage data of all sites were further related to the impervious cover levels of the corresponding sites. The resulting relationships are presented in Table 6. As an example, the annual load average of BOD for an area with 30 percent impervious cover is 12 pounds per acre. The annual storm load average for the 0.0 to 0.10 inch storm runoff interval is 45 percent of the annual load average. The annual storm load averages for 0.11 to 0.30, 0.31 to 0.50, and 0.51 to 0.75 storm runoff intervals are 32, 16, and 7 percent of the annual load average, respectively.

Figures 2-15 were developed using data of Table 6. In each of these figures, a set of curves was drawn to represent load versus runoff relationships for a specific pollutant parameter. Using these curves, the annual storm load, expressed as a percentage of the total annual load, can be estimated for a group of storm events of specific sizes. From Figure 3, for example, for sites of 10, 30, 50, and 90 percent impervious covers, the annual storm loads of COD for storms of equal or less than ½-inch of runoff are 100, 97, 83, and 75 percent of the total annual COD load, respectively. For the same token, from Figure 9, for sites of 10, 30, 50, and 90 percent impervious covers, the annual storm loads of TSS for storms of equal or less than 3/4-inch of runoff are 100, 100, 93, and 83 percent of the total annual TSS load, respectively.

LOAD UNTREATED BY CAPTURING THE FIRST HALF-INCH OF RUNOFF

The COA Environmental Criteria Manual[7] specifies that whenever a water quality control sedimentation/filtration basin is required, the basin should store and treat the first ½-inch of runoff, and this volume of runoff should be isolated from the balance of larger storms. In this design, however part of the runoff from a development site may not be treated by the sedimentation/filtration basin. This report provides data concerning the pollutant load carried by the untreated runoff.

As shown in Table 7, on an annual basis the by-pass or untreated runoff volume increases from 0 to 47 percent of the total storm runoff when impervious cover increases. On the other hand, the amount of pollutant load carried by the untreated runoff increases at a lower pace averaging from 0 to 28 percent of the total annual load with increasing impervious cover. If a sedimentation/ filtration basin were designed to treat the first ½-inch of runoff from a 90 percent impervious cover development, the untreated annual COD and TSS load will be approximately 21 and 23 percent of the total annual load, respectively. In this case, the treatment efficiencies for COD and TSS should be reduced accordingly. Suppose the treatment efficiency for COD and TSS were 67 and 87 percent, the reductions of efficiency due to the untreated runoff should be about 16 and 20 percent, respectively.

CONCLUSIONS

Based on the discussion and the data presented, the following conclusions are drawn:

1. In general, the first flush concentration is significantly higher than the average concentrations of the succeeding runoff intervals during a storm. The decrease in concentration values follows an exponential function instead of a linear relationship.

2. The common assumption that the first ½-inch of runoff during a rainfall storm washes off 90 percent of pollutants on impervious cover may be arbitrary. This study found that for developments with higher impervious cover the first ½-inch of runoff cannot remove most of the storm load during larger storms. For a development with a 90 percent impervious cover the first ½-inch of runoff of a larger storm can remove about 40 percent of the total storm load on the average.

3. Percentage data of storm loads corresponding to all storm runoff intervals were developed on an annual basis. If a water quality control basin was designed to treat the first ½-inch of runoff from a development, the by-pass or untreated annual load can be substantial. The untreated annual load increases when impervious cover is increased, averaging to approximately 0 to 27 percent of the total annual load depending on the degree of impervious cover.

REFERENCES

1. City of Austin. *City of Austin Stormwater Monitoring Program Description*. Environmental and Conservation Services Department, March 1986.
2. City of Austin. *Stormwater Pollutant Loading Characteristics for Various Land Uses in the Austin Area*. Environmental and Conservation Services Department, Technical Report, March 1990.
3. City of Austin. *Removal Efficiencies of Stormwater Control Structures*. Environmental and Conservation Services Department, Draft Report, April 1990.
4. City of Austin. *City of Austin Stormwater Monitoring Program Five Year Data Summary: 1984-1988*. Draft Report, Environmental and Conservation Services Department, February 1990.
5. City of Austin. *Stormwater Quality Modeling for Austin Creeks*. Environmental and Conservation Services Department, Technical Report, April 1990.
6. Hydroscience. *Water Quality Management Planning Methodology for Urban and Industrial Stormwater Needs*. Prepared for the Texas Water Quality Board, December 1976.
7. City of Austin. <u>Environmental Criteria Manual</u>. June 1988.

TABLE 1. WATERSHED CHARACTERISTICS

Watershed Monitored	D.A. (acres)	Imp. Cover (%)	SCS Soil Group	No. of Events Monitored	Range of Runoff Monitored (inch)
Bear Creek (BC)	301	3	C	21	0.001-0.10
Rollingwood (RO)	63	21	C	16	0.01-0.28
Maple Run (MI)	28	36	C	26	*
Hart Lane (HL)	371	39	C	21	0.07-0.89
Highwood (HI)	3	50	C	29	0.15-1.40
Barton Creek Square Mall (BCSM)	47	86	C	30	0.24-2.80
Brodie Oaks (BI)	31	95	C	16	0.43-3.90

* Maple Run runoff discharges were not measured; however, the instantaneous concentration for each runoff event were obtained.

TABLE 2. ANALYSIS OF DAILY RAINFALL DATA FOR AUSTIN AREA*

Range of Rainfall (inch)	Frequency of Occurrence (%)	No. of Days of Rainfall (per year)	Rainfall Depth (inch)	Cumulative Depth (inch)
0.05-0.10	14	9	0.7	0.7
0.11-0.20	15	10	1.4	2.1
0.21-0.30	18	13	3.3	5.1
0.31-0.40	10	7	2.3	7.4
0.41-0.50	10	7	3.0	10.4
0.51-0.75	15	11	6.9	17.2
0.76-1.00	5	3	2.3	19.6
1.01-1.25	3	2	2.1	21.7
1.26-1.50	2	1	1.3	23.0
1.51-2.00	3	2	3.1	26.2
2.01-2.50	2	1	2.1	28.4
>2.51	3	2	5.2	33.7

* 1976-1985 Shoal Creek (above 12th Street) daily rainfall data were analyzed.
A daily rainfall depth of less than 0.05 was considered as no rainfall.

TABLE 3. ANNUAL STORMWATER RUNOFF COEFFICIENT AVERAGE FOR VARIOUS WATERSHED IMPERVIOUSNESS (IN NON- RECHARGE ZONE)

Impervious Cover (%)	5	10	20	30	40	50	60	70	80	90
Runoff Coefficient (%)	7	10	14	18	22	30	41	52	65	81

TABLE 4. FIRST FLUSH CONCENTRATION AS A FUNCTION OF PERCENT OF IMPERVIOUS COVER

Pollutant	5		30		50		70		90	
	EMC*	FCONC*	EMC	FCONC	EMC	FCONC	EMC	FCONC	EMC	FCONC
BOD	9	9	9	10	9	14	9	16	9	19
COD	26	26	42	52	42	65	42	66	42	69
TOC	7	7	11	13	11	14	11	18	11	24
NO_2+NO_3	0.15	0.15	1.10	0.71	0.35	0.52	0.35	0.55	0.35	0.67
TKN	0.52	0.52	1.10	0.91	1.10	1.1	1.10	1.24	1.10	1.40
NH_3	0.09	0.09	0.20	0.24	0.02	0.38	0.20	0.30	0.20	0.24
PO_4	0.04	0.04	0.18	0.22	0.18	0.20	0.18	0.20	0.18	0.20
TSS	80	80	170	170	170	212	170	220	80	123
Cu	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
Fe	0.36	0.36	0.36	0.68	0.36	0.48	0.36	0.54	0.36	0.58
Pb	0.004	0.004	0.02	0.045	0.02	0.03	0.02	0.04	0.03	0.06
Zn	0.008	0.008	0.04	0.06	0.04	0.09	0.04	0.12	0.05	0.17
F. Coli.	9	9	26	39	26	28	26	28	26	31
F. Strep.	9	9	26	39	26	27	26	27	26	30

* EMC and FCONC are event mean concentration and first flush concentration, respectively. First flush concentration is defined as the mean concentration of a pollutant in the first 0-0.1 inch of runoff. The unit of fecal coliform and fecal streptococci concentrations is 1,000 colonies per 100 milliliter. The unit of other parameters is milligrams per liter.

TABLE 5. HALF-INCH RUNOFF STORM LOAD EXPRESSED IN PERCENT OF MAXIMUM RUNOFF STORM LOAD

½-Inch Runoff Storm Load
— In Percent of Average Maximum Storm Load —

Imp. Cover (%)	30	50	90
Ave. Max. Runoff (inch)	0.75	1.25	2.25
BOD	68 (%)	53 (%)	33 (%)
COD	77	57	48
TOC	74	62	45
NO_2+NO_3	62	56	40
TKN	72	46	35
NH_3	71	58	30
PO_4	68	45	37
TSS	81	61	41
Cu	67	42	31
Fe	70	43	36
Pb	75	59	44
Zn	76	57	44
F. Coli.	80	44	36
F. Strep.	79	42	42
Average	73	52	39

TABLE 6. ANNUAL STORM LOAD DISTRIBUTION FOR VARIOUS IMPERVIOUS COVER LEVELS

Annual Storm Loads For Various Runoff Depth Intervals
— Expressed in Percent of Average Annual Load —

Pollutant	Percent Imp. Cover	Average Annual Load (lbs./acre)	Runoff Depth Intervals in Inches							
			0.00-0.10	0.11-0.30	0.31-0.50	0.51-0.75	0.76-1.00	1.01-1.50	1.51-2.00	2.01-3.00
BOD	10	6.3	65	35						
	30	12.0	45	32	16	7				
	50	20.1	31	42	13	4	10			
	70	34.7	13	37	30	6	8	6		
	90	53.9	16	22	32	7	5	8	4	6
COD	10	18.3	72	28						
	30	56.1	60	26	11	3				
	50	93.7	37	36	13	5	9			
	70	161.9	19	33	28	6	7	7		
	90	251.6	28	19	32	7	5	4	1	4
TOC	10	4.9	67	33						
	30	14.9	49	28	17	6				
	50	24.6	33	38	12	5	12			
	70	42.4	22	35	25	7	7	4		
	90	66.0	30	19	29	8	5	5	1	3
NO_2 + NO_3	10	0.11	59	41						
	30	1.47	30	45	15	10				
	50	0.78	22	53	12	4	9			
	70	1.35	13	39	28	5	7	8		
	90	2.10	23	17	33	7	5	5	3	7
TKN	10	0.37	63	37						
	30	1.51	33	37	21	9				
	50	2.52	25	32	27	9	7			
	70	4.36	13	27	39	8	6	7		
	90	6.77	22	18	32	8	5	5	3	7
NH_3	10	0.06	62	38						
	30	0.27	42	32	22	4				
	50	0.45	26	40	22	4	8			
	70	0.77	10	29	37	8	8	8		
	90	1.20	11	20	30	9	6	9	7	8
PO_4	10	0.03	61	39						
	30	0.24	35	26	30	9				
	50	0.40	24	39	18	8	11			
	70	0.69	13	33	31	7	8	8		
	90	1.08	22	21	30	7	5	6	3	6

TABLE 6 – Continued

Annual Storm Loads For Various Runoff Depth Intervals
— Expressed in Percent of Average Annual Load —

Pollutant	Percent Imp. Cover	Average Annual Load (lbs./acre)	Runoff Depth Intervals in Inches 0.00-0.10	0.11-0.30	0.31-0.50	0.51-0.75	0.76-1.00	1.01-1.50	1.51-2.00	2.01-3.00
	10	56	65	35						
	30	227	49	30	19	2				
TSS	50	379	40	35	12	5	8			
	70	655	19	34	29	5	6	7		
	90	746	22	21	34	5	4	4	3	7
	10	.007	64	36						
	30	.013	46	32	15	7				
Cu	50	.022	21	39	20	6	14			
	70	.039	12	31	33	6	8	10		
	90	.060	17	22	37	8	7	8	1	2
	10	.254	67	33						
	30	.480	58	32	9	1				
Fe	50	.803	23	41	17	5	14			
	70	1.388	12	32	30	5	9	12		
	90	2.162	20	17	29	5	5	7	5	12
	10	.003	47	53						
	30	.027	42	50	7	1				
Pb	50	.045	40	39	15	4	2			
	70	.077	19	37	27	5	6	6		
	90	.180	27	23	31	6	7	3	1	2
	10	.028	71	29						
	30	.053	61	27	10	2				
Zn	50	.089	40	36	11	4	9			
	70	.154	20	29	25	4	9	13		
	90	.300	27	15	28	5	6	8	3	8
	10	288	70	30						
F.	30	1574	66	22	5	7				
Coli.*	50	2632	16	47	20	7	10			
	70	4547	15	32	30	7	9	7		
	90	7083	15	17	30	9	11	7	3	8
	10	288	60	40						
F.	30	1211	46	23	22	9				
Strep.*	50	2025	16	50	16	5	13			
	70	3498	9	35	31	7	8	10		
	90	5449	15	16	32	12	4	6	4	9

* The unit of annual load average for fecal coliform and fecal streptococci is millions of colonies per acre.

TABLE 7. AVERAGE AMOUNTS OF ANNUAL UNTREATED RUNOFF AND RUNOFF LOAD EXPRESSED IN PERCENT OF ANNUAL RUNOFF VOLUME AND RUNOFF LOAD AVERAGES

Impervious Cover (%)	10	30	50	70	90
Runoff Coefficient (%)*	10	18	30	52	81
Untreated Runoff (%)	0	9	22	37	47
BOD (%)	0	7	14	20	30
COD	0	3	14	20	21
TOC	0	6	17	18	22
NO_2+NO_3	0	10	13	20	27
TKN	0	9	16	21	28
NH_3	0	4	12	24	39
PO_4	0	9	19	23	27
TSS	0	2	13	18	23
Cu	0	7	20	24	26
Fe	0	1	19	26	34
Pb	0	1	6	17	19
Zn	0	2	13	26	30
F. Coli.	0	7	17	23	38
F. Strep.	0	9	18	25	35
Average	0	6	15	22	28

* Runoff coefficient was computed as the annual runoff volume average divided by the annual rainfall volume average. Using 1976-1985 Shoal Creek daily rainfall data the average annual rainfall amount for the Austin area was estimated to be 33.7 inches.

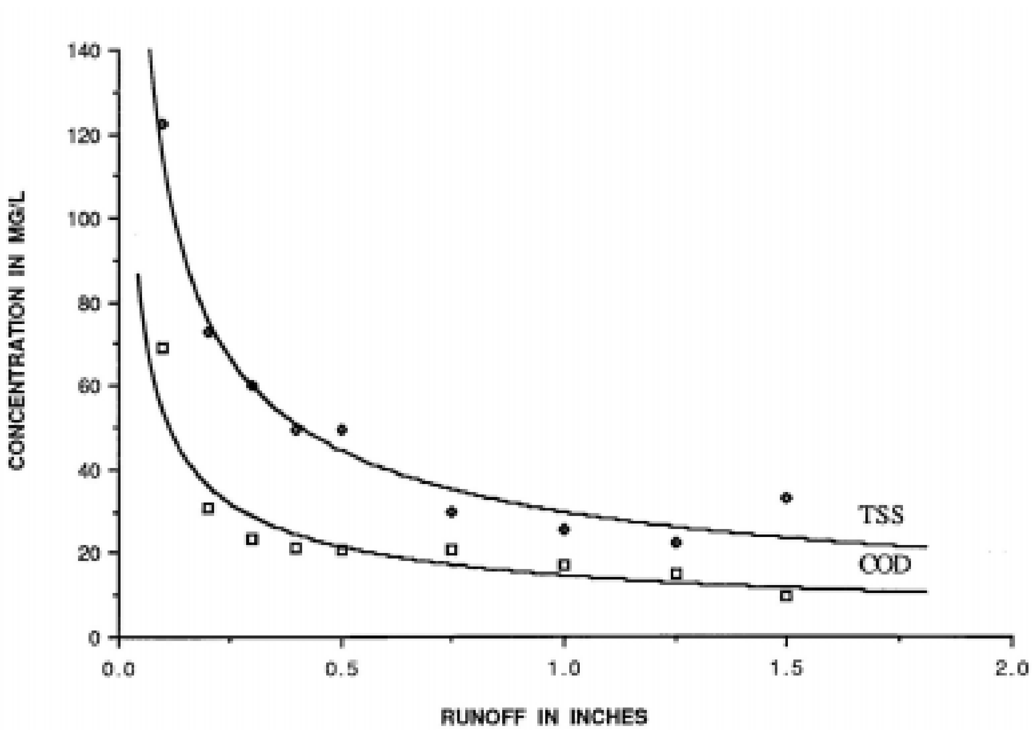

FIGURE 1. AVERAGE VALUES OF CONCENTRATION DURING RUNOFF EVENTS OF LARGER STORMS AT BCSM SITE

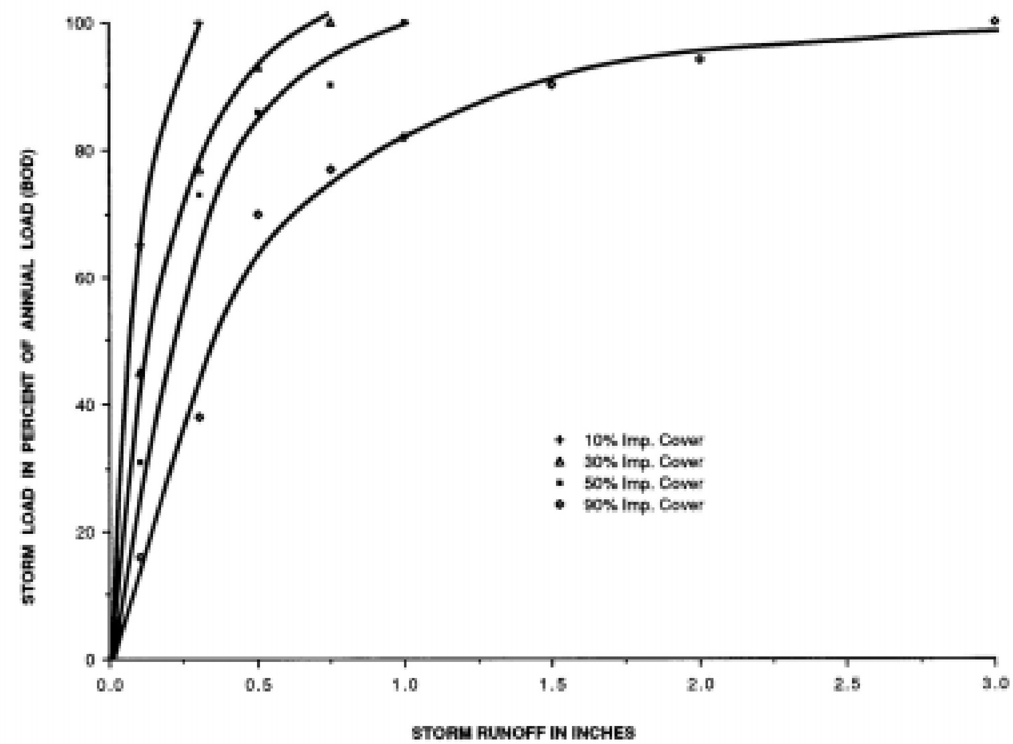

FIGURE 2. ANNUAL STORM LOAD DISTRIBUTION FOR VARIOUS IMPERVIOUS COVER LEVELS - BOD

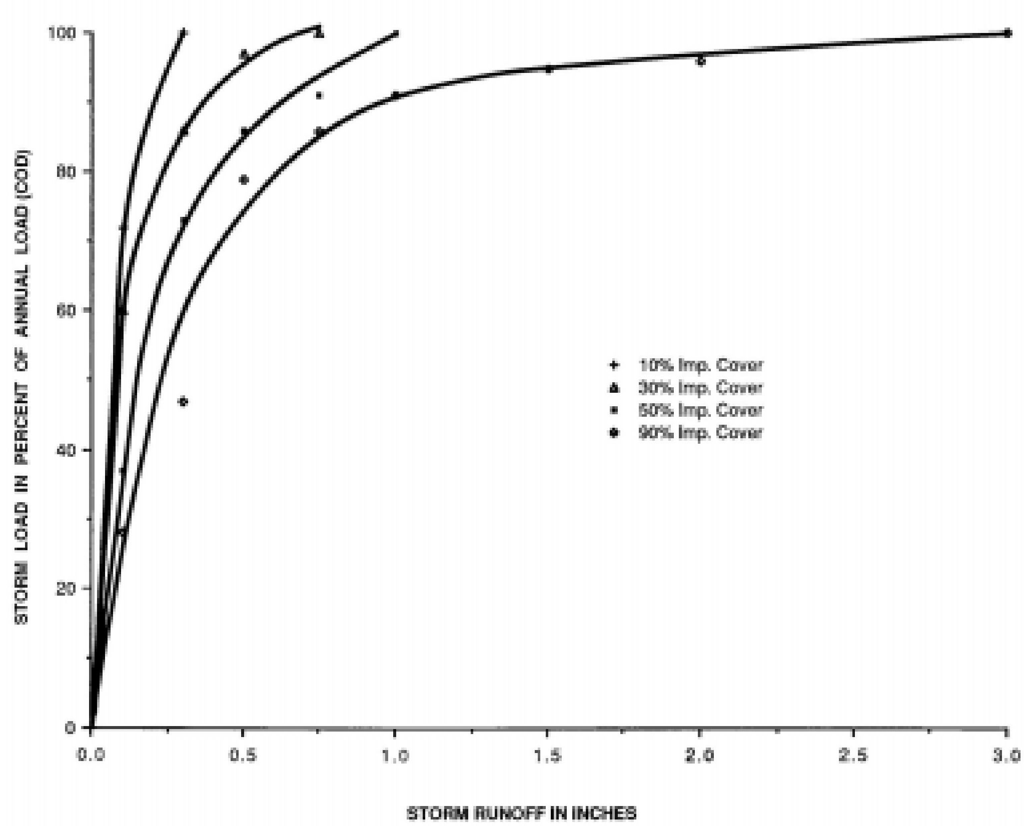

FIGURE 3. ANNUAL STORM LOAD DISTRIBUTION FOR VARIOUS IMPERVIOUS COVER LEVELS - COD

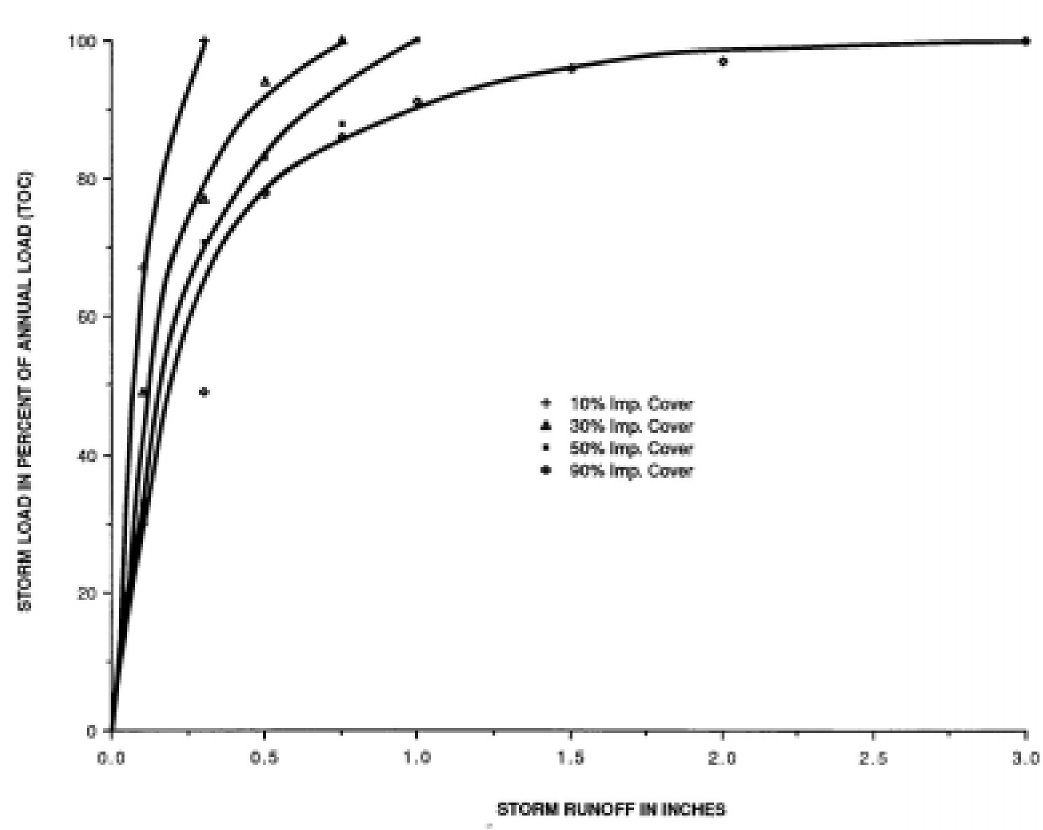

FIGURE 4. ANNUAL STORM LOAD DISTRIBUTION FOR VARIOUS IMPERVIOUS COVER LEVELS - TOC

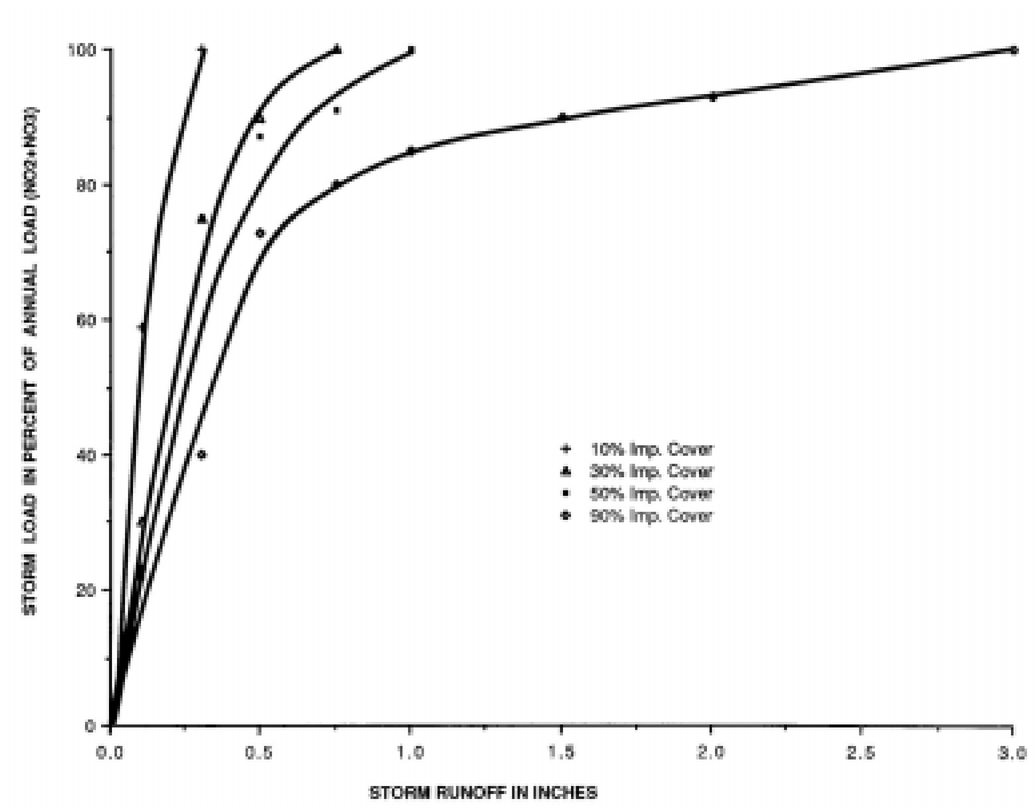

FIGURE 5. ANNUAL STORM LOAD DISTRIBUTION FOR VARIOUS IMPERVIOUS COVER LEVELS – NO_2+NO_3

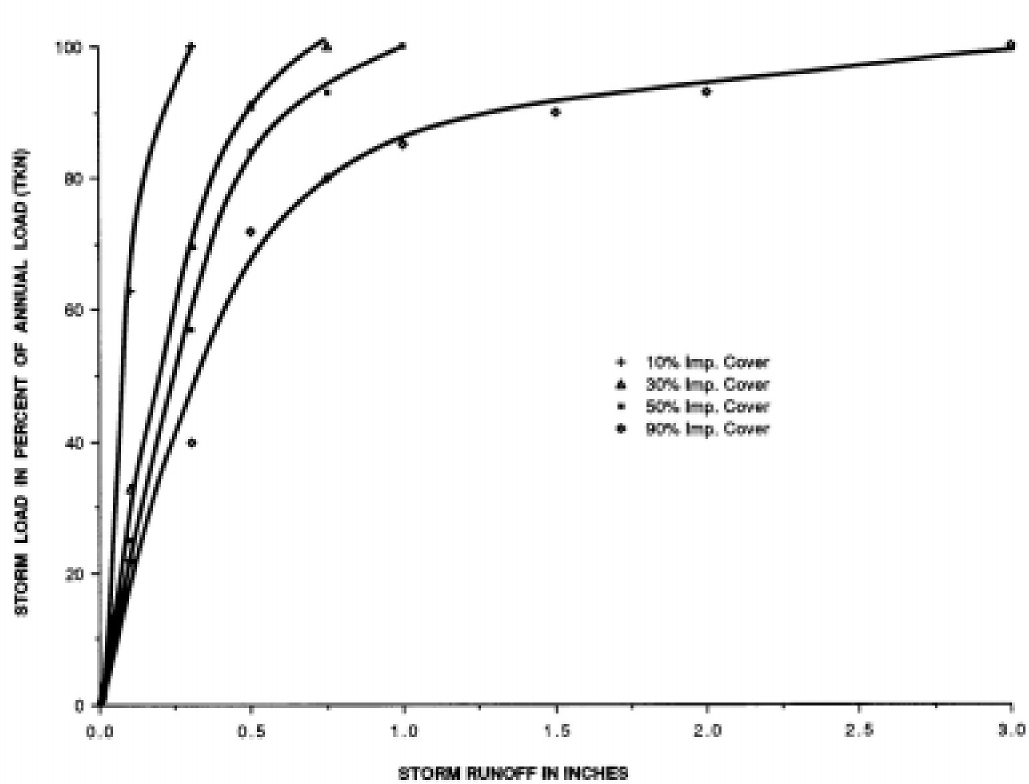

FIGURE 6. ANNUAL STORM LOAD DISTRIBUTION FOR VARIOUS IMPERVIOUS COVER LEVELS – TKN

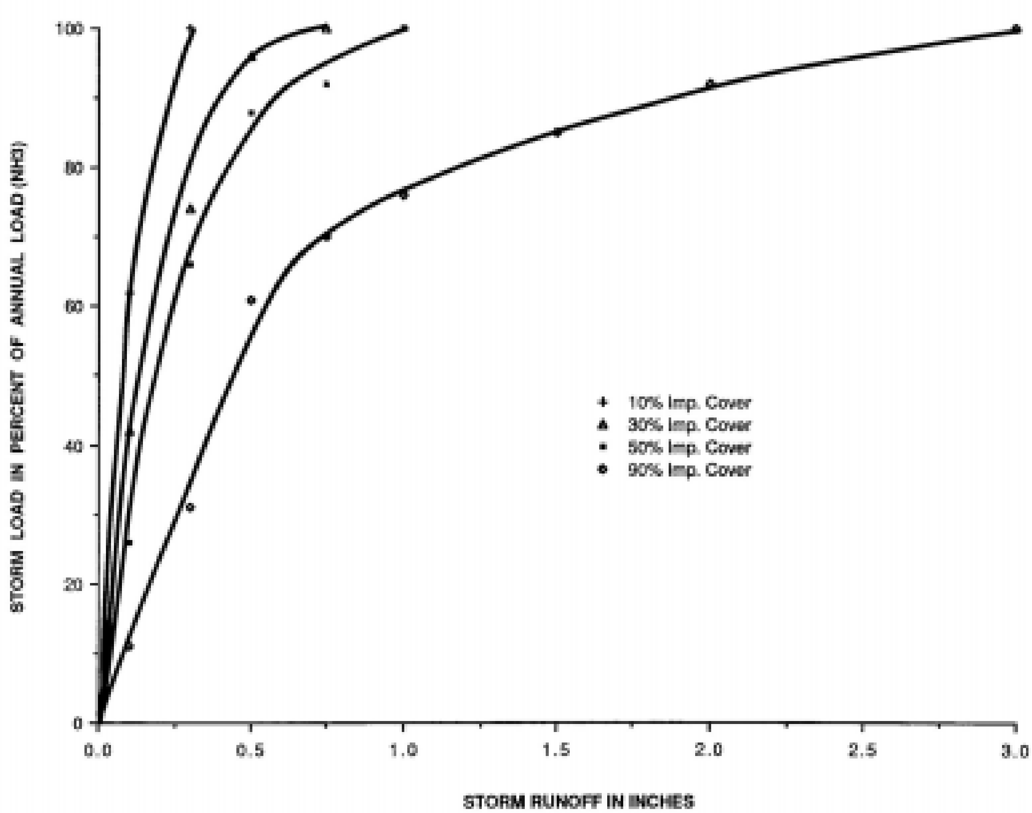

FIGURE 7. ANNUAL STORM LOAD DISTRIBUTION FOR VARIOUS IMPERVIOUS COVER LEVELS – NH_3

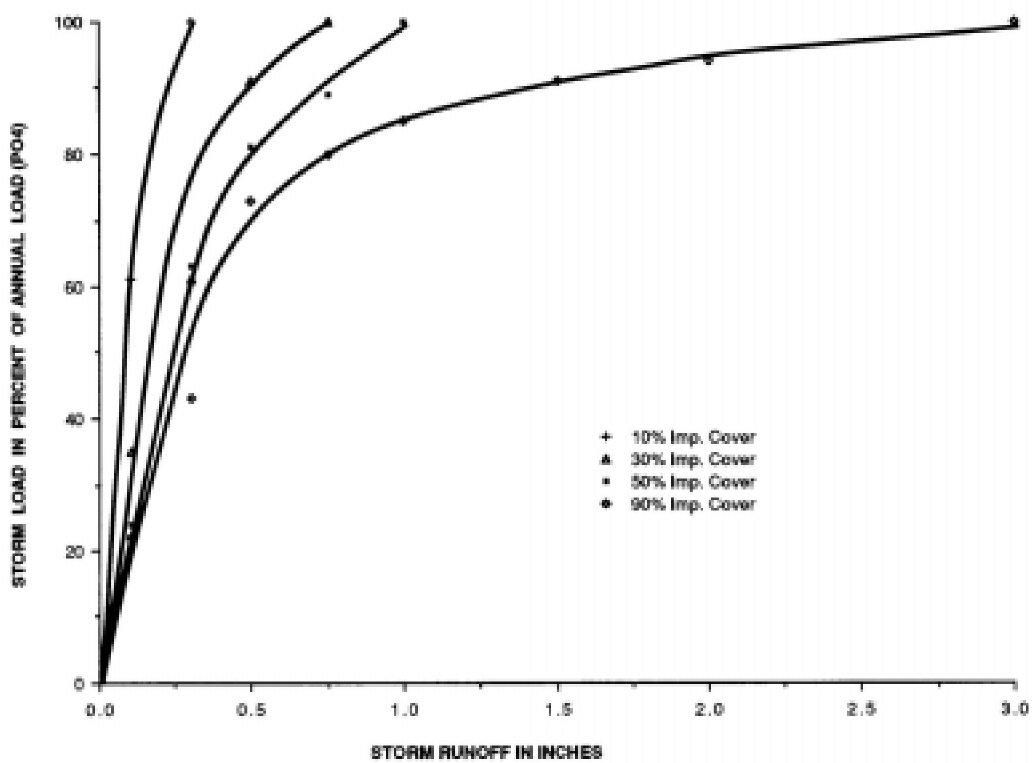

FIGURE 8. ANNUAL STORM LOAD DISTRIBUTION FOR VARIOUS IMPERVIOUS COVER LEVELS – PO_4

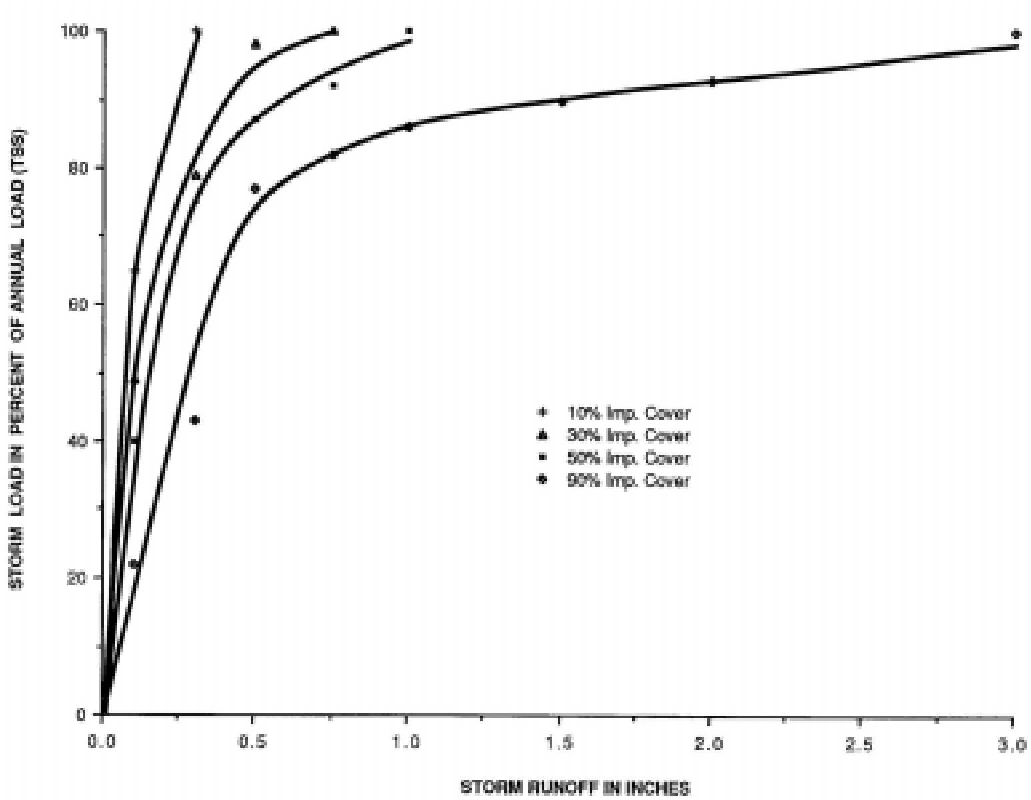

FIGURE 9. ANNUAL STORM LOAD DISTRIBUTION FOR VARIOUS IMPERVIOUS COVER LEVELS - TSS

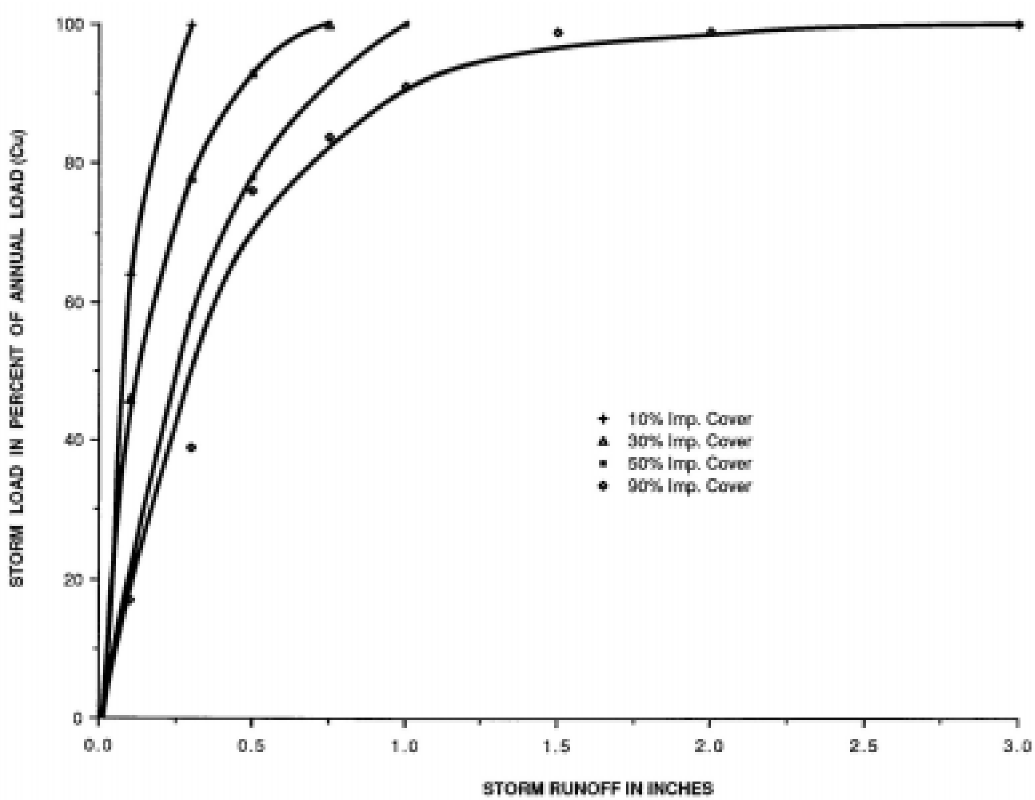

FIGURE 10. ANNUAL STORM LOAD DISTRIBUTION FOR VARIOUS IMPERVIOUS COVER LEVELS – Cu

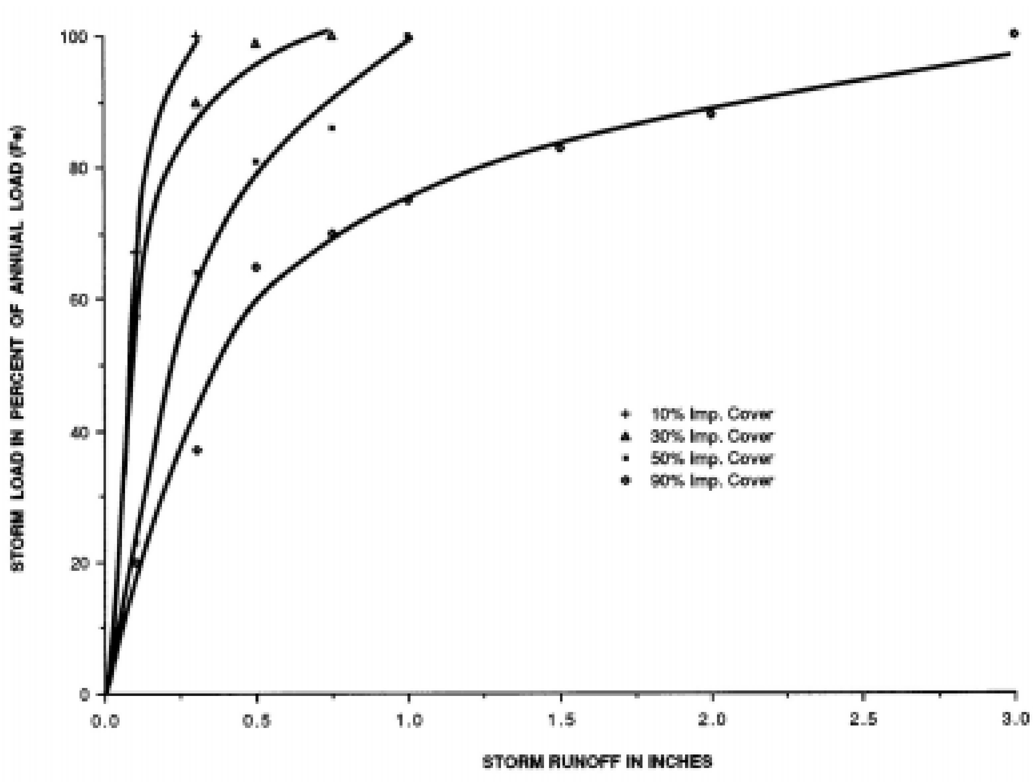

FIGURE 11. ANNUAL STORM LOAD DISTRIBUTION FOR VARIOUS IMPERVIOUS COVER LEVELS – Fe

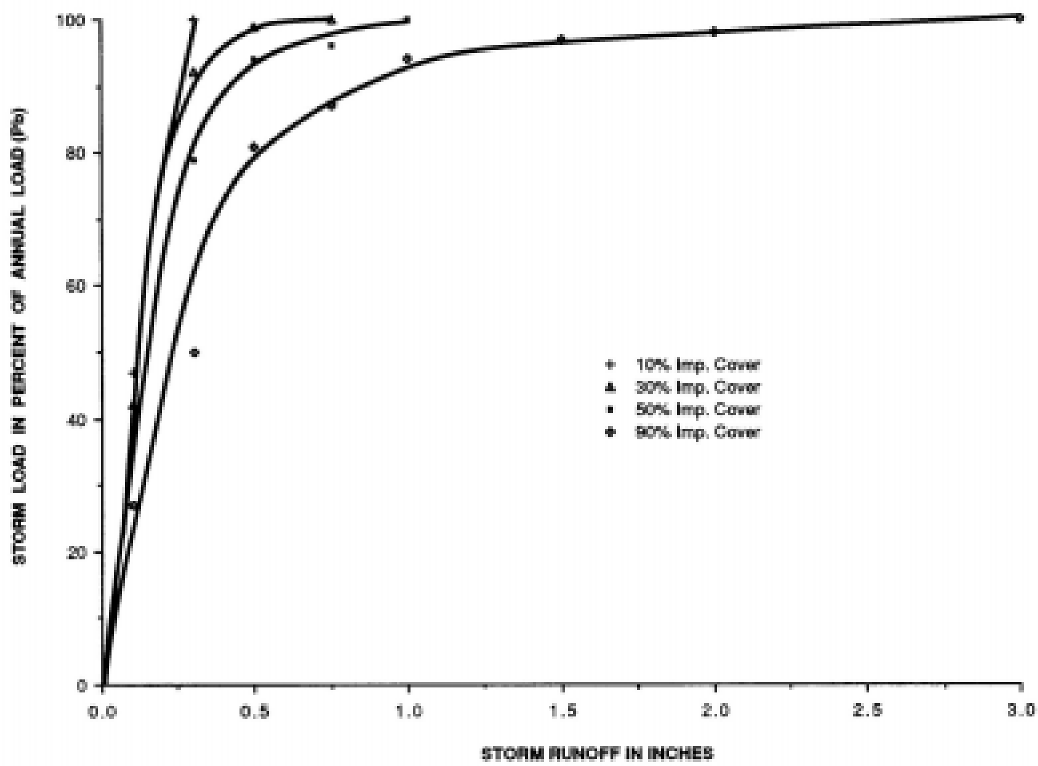

FIGURE 12. ANNUAL STORM LOAD DISTRIBUTION FOR VARIOUS IMPERVIOUS COVER LEVELS – Pb

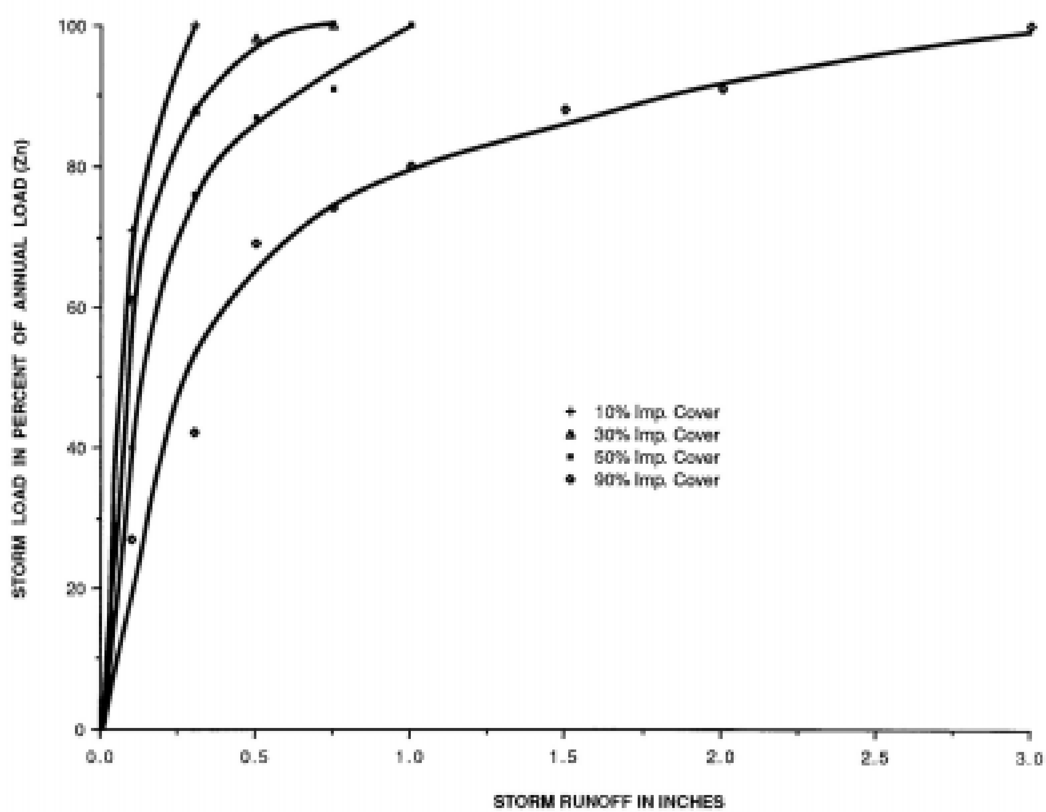

FIGURE 13. ANNUAL STORM LOAD DISTRIBUTION FOR VARIOUS IMPERVIOUS COVER LEVELS – Zn

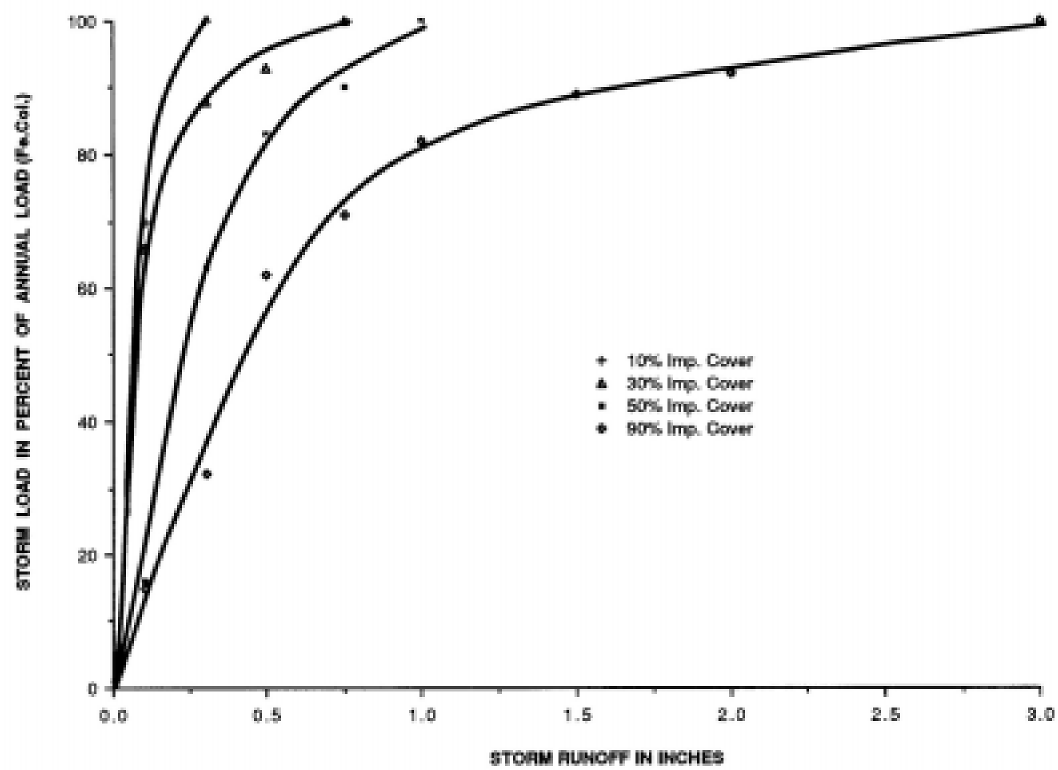

FIGURE 14. ANNUAL STORM LOAD DISTRIBUTION FOR VARIOUS IMPERVIOUS COVER LEVELS – F. COLI.

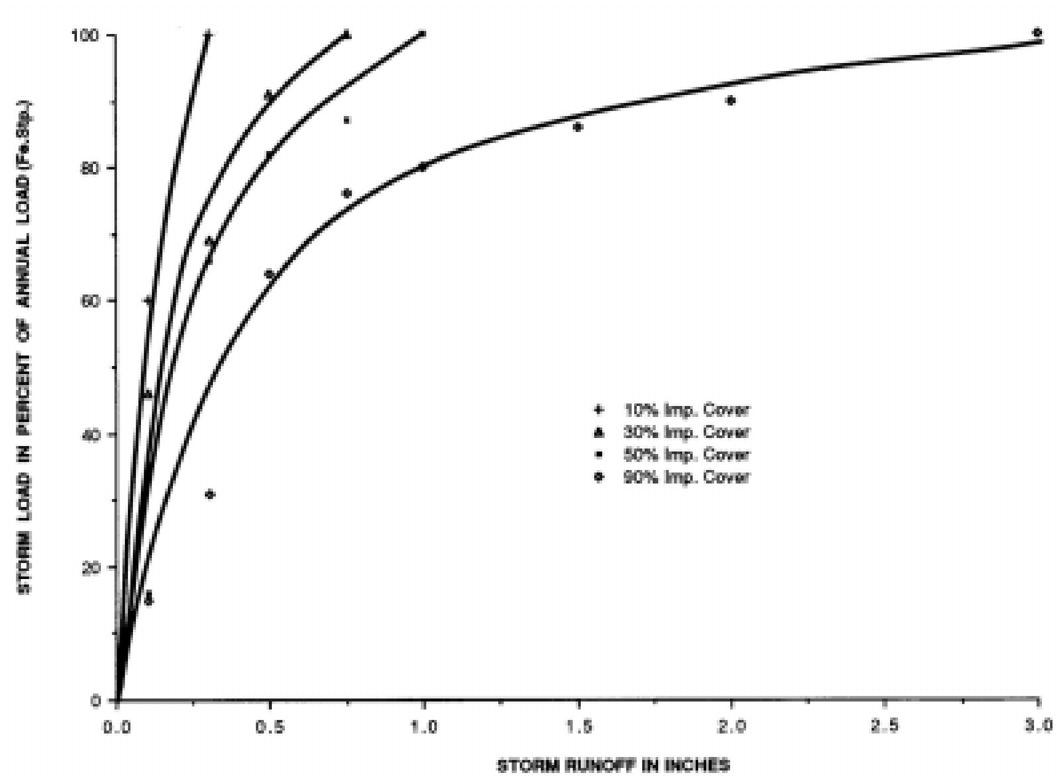

FIGURE 15. ANNUAL STORM LOAD DISTRIBUTION FOR VARIOUS IMPERVIOUS COVER LEVELS – F. STREP.