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ESTIMATING WATER LOSS AND DIRECT RUNOFF FROM STORM RAINFALL BY THE USE OF THE INFILTROMETER

By

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Prepared in cooperation with the
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ABSTRACT

This study explored the feasibility of using infiltrometer data to estimate water losses in ungaged drainage basins during storms and to determine the direct runoff from design-storm rainfall. The infiltrometer was used in 14 selected drainage basins in California where short-term records of precipitation and streamflow were available. The data were used to obtain an infiltration-index value, which then was related to the minimum infiltration rate obtained from records of rainfall and runoff. The minimum infiltration rate was used with a regional relation between the storm-recurrence interval and the ratio of storm-infiltration rate to minimum-infiltration rate to provide a means for estimating the infiltration rate used with design storms of any specified recurrence interval. To obtain the last-mentioned relation--that between storm-recurrence interval and infiltration ratio--one must have the results of a regional flood-frequency and unit-hydrograph study.

This study was somewhat inconclusive because a poor relation was obtained between infiltration-index values and minimum infiltration rates. However, additional testing of the infiltrometer technique is recommended because a practicable method would be a boon to the study of storm runoff in desert basins. Future workers should consider using a stratified sampling design that would include bottom-land and hillside areas.

INTRODUCTION

A prerequisite in the design of storm-drainage facilities is the determination of flood-frequency relations that involve peak discharges, or flood volumes, or both. Because it is not economically feasible to sample all sites along all of the streams in a region, generalized flood-frequency relations commonly are derived from available long-term streamflow records. An example of such an analysis is found in a flood-frequency report for California streams by Young and Cruff (1967). Invariably, such analyses are handicapped by a dearth of long-term streamflow records for small streams--those with drainage areas smaller than about 10 square miles--and workers should be cautioned about extrapolating generalized flood-frequency relations for use with small drainage basins. The seriousness of the lack of flood-frequency data for the smaller drainage basins is apparent when it is realized that nearly $1 billion is spent annually in the United States for the construction and repair of highway culvert structures.

In recent years, the increasing awareness of the need for streamflow records for small drainage basins has resulted in a corresponding increase in the number of small streams being gaged. However, a long streamflow record is desirable for deriving flood-frequency relations by statistical analysis. In the absence of such data, hydrologists use long-term precipitation records to estimate the stream discharges needed for flood-frequency studies. One of the procedures used for that purpose is the unit hydrograph. Preliminary to applying the unit-hydrograph technique, regional precipitation-frequency data are used to derive the design storms for selected recurrence intervals of 2, 5, 10, 25, 50, and 100 years.

For each of these design storms it is necessary to abstract increments of storm rainfall that are stored or detained for a period of time on or below the land surface. Those increments of water, hereafter referred to as water loss, do not appear as storm runoff (direct runoff) because they are lost through evaporation or transpiration, or because they enter stream channels after direct runoff has ceased. The rate of water loss commonly is expressed as the ϕ-index. Also, the ϕ-index may be considered an average for the basin, and may be expressed as a constant rate of recharge that will occur in a drainage basin during a storm. Thus, the ϕ-index is a constant quantity of water that must be withheld from each time increment of precipitation to obtain the observed runoff. After subtracting water losses from the design storms, a unit hydrograph is applied to the remaining precipitation (precipitation excess) to obtain the required runoff hydrographs.

The method described above is commonly used by hydrologists, but a critical element in the method is the determination of water losses for ungaged drainage basins. Water losses result principally from the infiltration of precipitation; but because of differences in topographic slopes, soil characteristics, vegetation, and other factors, infiltration rates may vary widely both areally and with time. In the absence of long-term streamflow records, no satisfactory technique is presently available for quantitatively determining water losses. This study was an attempt to develop a technique that would permit quantitative estimates of water losses in ungaged basins.

Purpose and Scope

This study, exploratory in nature, tested the feasibility of using infiltrometer data to estimate water losses in small drainage basins during storms in order to establish a basis for the determination of direct runoff from design-storm rainfall. Two derived relations were basic to the method that was tested. The first relation was an infiltration-index value obtained from a comparison of infiltrometer observations and the minimum infiltration rate obtained from records of rainfall and runoff that are available for the 14 basins. The second relation was a storm-infiltration rate, expressed as a ratio of the minimum infiltration rate, to the storm-recurrence interval. To apply the two derived relations, infiltrometer tests were made in several ungaged drainage basins. The infiltration index obtained from those observations was used with the infiltration-index value to obtain the minimum infiltration rate for the ungaged drainage basins. The minimum infiltration rate was used with the storm-infiltration rate to obtain the infiltration rates or water losses during design storms of selected recurrence intervals.

The infiltration-index value was obtained by making infiltrometer tests at four randomly selected sites in each of 14 small drainage basins in coastal and desert environments in California (fig. 1). Each of the basins had short-term records of streamflow and precipitation records obtained from continuous recording gages. The results of a recent regional unit-hydrograph study for the San Francisco Bay region provided a basis for derivation of the storm-infiltration rate; however, only three of the 14 test basins sampled by the infiltrometer were located in that region. Limited funds precluded collection of infiltrometer data in other parts of the San Francisco Bay region when the desirability of additional information for this region was realized.

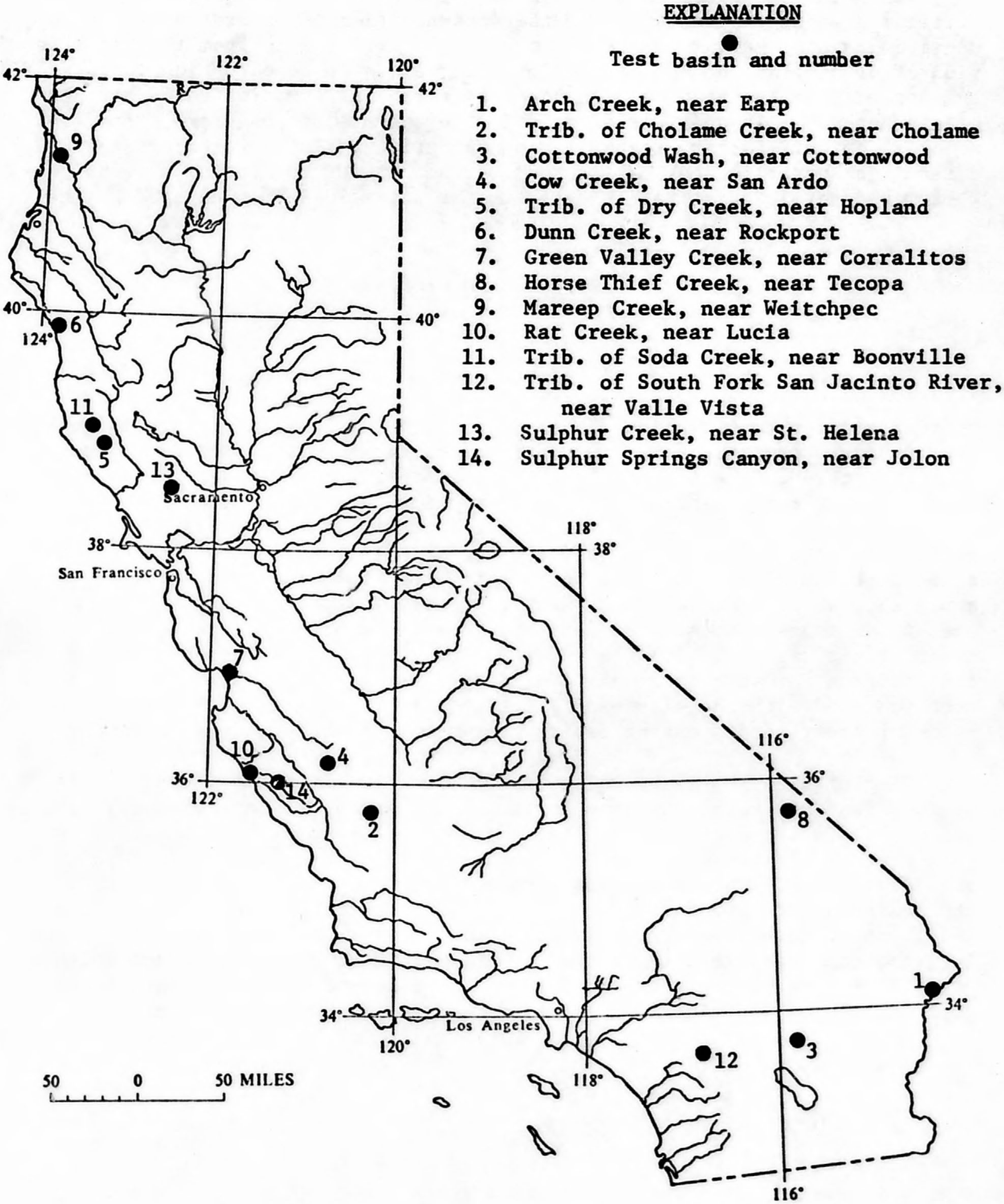

FIGURE 1.--Index map of California showing location of test basins.

Acknowledgments

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Technical guidance was provided by S. E. Rantz, research hydrologist, who offered valuable suggestions and criticism during the study.

INFILTRATION-MEASURING SYSTEMS

A number of infiltration-measuring instruments have been developed by hydrologists investigating erosional effects, water-intake rates on range land, and surface runoff associated with storm rainfall. However, infiltration data obtained from these instruments provide only an index of natural infiltration resulting from rainfall, and results are not transferable among them. The most widely used infiltrometers are of three general types: sprinkler, ring, and rainfall simulator.

The best known examples of the sprinkler infiltrometer are the North Fork infiltrometer (Rowe, 1940) and the Rocky Mountain infiltrometer (Dortignac, 1951). Both spray water on a small test area--2 to 4 square feet--at a rate that exceeds the infiltration capacity of the test plot. The excess water, analagous to surface runoff, is collected and measured, and the difference between the rates of water application and runoff is the infiltration rate. The sprayed area is larger than the test plot--the sprayed area surrounding the test plot acts as a buffer zone to inhibit lateral subsurface flow from the test plot. Sprinkler-type infiltrometers have the advantage of not disturbing the soil, but have the disadvantage of not being hand portable.

Ring infiltrometers (Johnson, 1963) include the single-ring and double-ring types. Ring dimensions are not standardized and the rings may range from 1 to 2 feet in diameter. When a double-ring infiltrometer is used, the smaller ring is placed concentrically within the larger ring. The ring infiltrometer is used by pressing the ring or rings into the earth to a depth of about 3 inches. Water is added to fill the ring or rings to a depth of between 6 and 10 inches. Additional water is supplied as infiltration progresses, to maintain a constant depth of water within the ring or rings. When the double-ring infiltrometer is used, only the water added to the inner ring is measured--the purpose of the outer ring is to furnish a water-supplied buffer zone to inhibit the lateral subsurface flow of water from the inner ring. The measured rate at which water is added to the inner ring is the infiltration rate. Ring infiltrometers have the advantage of being hand portable, but have the disadvantage of disturbing the soil.

The rainfall-simulator infiltrometer (McQueen, 1963) delivers simulated rainfall to a small (30 sq in) test plot. Its essential elements are a rainulator which forms the drops, and a Marriotte vessel which maintains a constant pressure head on the rainulator and permits water to be delivered at a preselected rate between 1 and 15 inches per hour. As with the sprinkler infiltrometer, water is applied at a rate in excess of the infiltration capacity of the soil. The excess water is drawn off, and the difference between the rate of water application and the rate at which excess water (runoff) is withdrawn, is the infiltration rate.

The rainfall-simulator infiltrometer was selected for use in this study because it is hand portable and does not disturb the soil. The instrument is subject to some of the shortcomings common to all infiltrometers in that it indicates an infiltration rate greater than that which naturally occurs during storms. The principal reasons for infiltrometers giving exaggerated values of infiltration capacity during a test run are: (1) air entrapped in the soil can escape laterally, thereby removing an impediment to infiltration that is always present during a storm; and (2) the infiltrated water can escape laterally beyond the boundary of the test plot. However, the infiltrometer rate is an index of the natural infiltration rate, and an index rate serves the purpose of this study.

COLLECTION OF INFILTROMETER DATA

At each of the 56 randomly selected test sites, the initial tests were made on comparatively dry soil. The analyses showed that the moisture content averaged less than 5 percent. In order to determine which infiltration index produced a better correlation with the ϕ-index, the tests were repeated 2 or 3 days later at the same sites with the soil-moisture content at field capacity. Following the initial tests on dry soil, the test plots were covered with plastic sheets and mulch to reduce evaporation. For each test site, average infiltration curves, similar to those shown in figure 2, were derived from the test data. The infiltration index for each site was computed as the rate of change of infiltrated water after a steady minimum rate was attained during a 1-hour test period. The mean of the four test rates for each drainage basin was termed the "infiltration index." Table 1 gives infiltration-index values for dry soil conditions (I_1) and wet (field capacity) soil conditions (I_2).

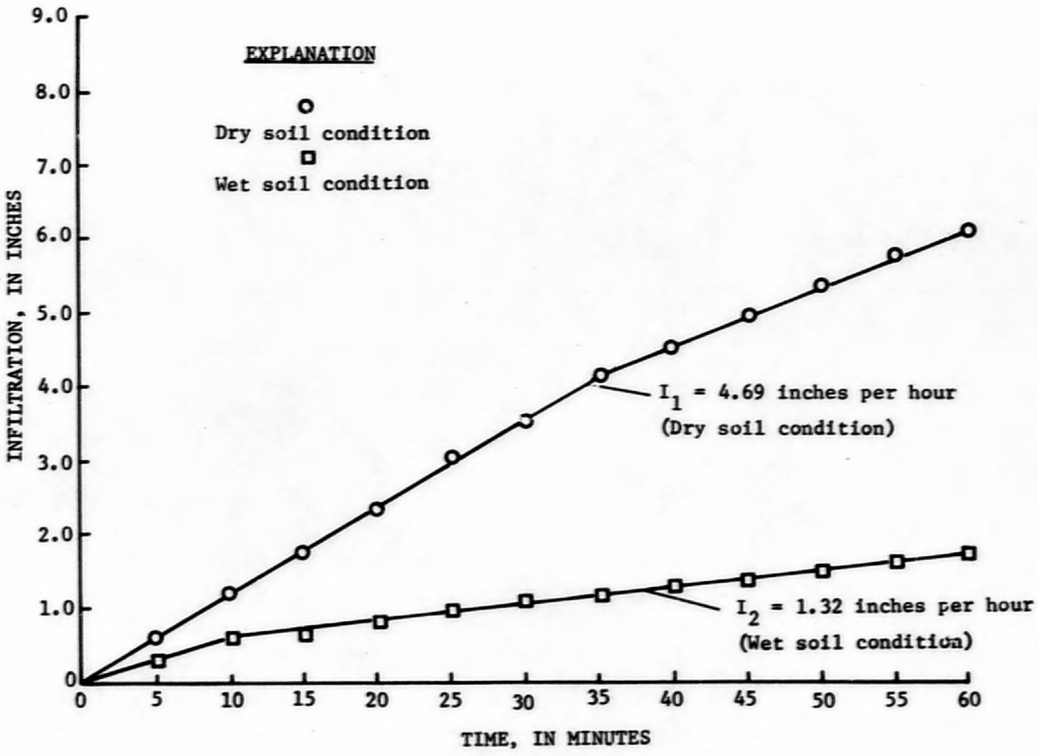

FIGURE 2.--Infiltration test, sample no. 2, Rat Creek, near Lucia.

TABLE 1.--*Infiltration-index data for 14 small drainage basins*
[Location of drainage basins shown on figure 1]

No.	Drainage basin	Drainage area (sq mi)	Infiltration index (I) in inches per hour	
			I_1 (Soil initially dry)	I_2 (Soil initially wet)
1	Arch Creek, near Earp	1.52	0.62	0.62
2	Tributary of Cholame Creek, near Cholame	9.26	3.56	.74
3	Cottonwood Wash, near Cottonwood	.71	2.45	2.70
4	Cow Creek, near San Ardo	4.80	3.61	1.66
5	Tributary of Dry Creek, near Hopland	1.27	1.50	.78
6	Dunn Creek, near Rockport	1.88	.80	.82
7	Green Valley Creek, near Corralitos	7.05	.99	.48
8	Horse Thief Creek, near Tecopa	3.06	4.70	2.02
9	Mareep Creek, near Weitchpec	3.56	.56	1.33
10	Rat Creek, near Lucia	.82	3.46	2.04
11	Tributary of Soda Creek, near Boonville	1.53	1.93	1.64
12	Tributary of South Fork San Jacinto River, near Valle Vista	2.20	2.58	1.07
13	Sulphur Creek, near St. Helena	4.50	2.72	2.10
14	Sulphur Springs Canyon, near Jolon	5.16	.91	.56

In 10 of the 14 drainage basins the initial infiltration test, made on dry soil, gave higher infiltration values (as expected) than subsequent tests made on the same plots with wet soil conditions. In two basins (1 and 6, table 1) the infiltration rates were virtually equal for dry and for wet soil conditions; and in two other basins (3 and 9, table 1) the tests for wet soil conditions showed greater infiltration rates than those obtained for dry soil conditions. The reason for these inconsistencies is not known. Two (1 and 3, table 1) of the four basins that had infiltration rates for wet conditions equal or greater than the rates for dry conditions are in desert areas of southeastern California. The other two basins (6 and 9, table 1) are in the north-coastal region of the State.

COMPUTATION OF THE ϕ-INDEX AND THE STORM INDEX

The ϕ-index, like other infiltration indices, is computed from records of rainfall and streamflow. As mentioned earlier (p. 2), the ϕ-index is the constant recharge that will occur during a storm period and is the quantity of water that must be withheld from each time increment of precipitation to obtain the observed direct runoff. Direct runoff consists mostly of surface runoff; however, a small part may include water that infiltrates the banks and bottoms of stream channels and rain that falls directly on stream surfaces. The relation of the ϕ-index to precipitation is shown schematically on the hyetograph shown in figure 3. For short, high-intensity storms, the ϕ-index represents mostly surface retention. For long storms, the ϕ-index approaches the average infiltration of the basin. The significance of the ϕ-index may be obscured by complexities of contributing drainage areas and the distribution of rainfall intensities. Variations of the ϕ-index with rainfall intensities are shown in a handbook by the American Society of Civil Engineers (1949, p. 45-47).

ϕ-index values were computed for 55 storms in 14 basins where infiltrometer tests had been run. The results of these computations are given in table 2.

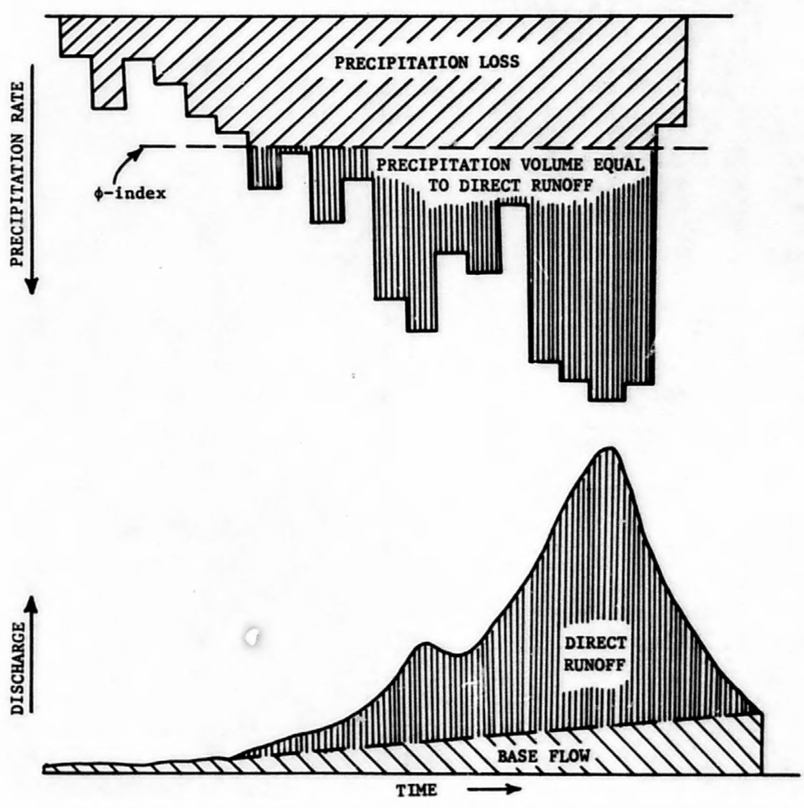

FIGURE 3.--Hyetograph and resulting hydrograph showing significance of the ϕ-index.

TABLE 2.--*Storm-index and ϕ-index data for 14 small drainage basins*
[Location of drainage basins shown in figure 1]

No.	Drainage basin	Date of storm	Storm index (inches)	ϕ-index (inches per hour)	Minimum ϕ-index (ϕ_{min}) (inches per hour)
1	Arch Creek, near Earp	Sept. 17, 1963	2.70	0.094	0.07
		Mar. 11, 1965	1.80	.079	
2	Tributary of Cholame Creek,	Feb. 9, 1962	3.17	.211	.09
	near Cholame	Oct. 15, 1963	1.41	.094	
3	Cottonwood Wash, near	Oct. 3, 1966	3.55	.124	.08
	Cottonwood	July 15, 1967	.94	.088	
4	Cow Creek, near San Ardo	Feb. 9, 1962	4.82	.277	.06
		Feb. 10, 1962	4.67	.073	
		Feb. 14, 1962	5.20	.088	
		Jan. 31, 1963	4.71	.055	
		Feb. 12, 1963	2.88	.066	
		Mar. 27, 1963	1.64	.046	
5	Tributary of Dry Creek,	Jan. 9, 1968	4.63	.223	.08
	near Hopland	Jan. 13, 1968	5.68	.094	
		Jan. 28, 1968	8.00	.094	
		Mar. 12, 1968	4.19	.100	
		Mar. 16, 1968	3.85	.061	
		Dec. 15, 1968	7.74	.076	
6	Dunn Creek, near Rockport	Nov. 9, 1962	8.37	.175	.11
		Dec. 2, 1962	8.94	.130	
		Apr. 5, 1963	12.25	.142	
		Nov. 13, 1963	8.38	.169	
7	Green Valley Creek, near	Dec. 21, 1964	9.43	.097	.10
	Corralitos	Jan. 21, 1967	8.90	.130	
8	Horse Thief Creek, near	Dec. 29, 1965	5.69	.157	.14
	Tecopa	Dec. 6, 1966	4.77	.289	
		Nov. 6, 1967	2.18	.163	
9	Mareep Creek, near Weitchpec	Jan. 13, 1967	10.72	.100	.09
		Jan. 27, 1967	9.42	.085	
		Jan. 11, 1969	12.59	.187	
10	Rat Creek, near Lucia	Feb. 9, 1962	13.55	.223	.15
		Feb. 13, 1962	11.02	.253	
		Oct. 13, 1962	5.39	.289	
		Jan. 30, 1963	21.56	.151	
		Mar. 27, 1963	4.37	.271	
11	Tributary of Soda Creek,	Nov. 9, 1964	4.89	.139	.07
	near Boonville	Apr. 15, 1965	3.24	.043	
		Jan. 20, 1967	8.80	.079	
		Jan. 29, 1968	4.97	.070	
		Feb. 19, 1968	5.52	.124	
12	Tributary of South Fork San	Apr. 1, 1964	2.87	.094	.10
	Jacinto River, near	Apr. 4, 1965	2.78	.082	
	Valle Vista	Apr. 9, 1965	3.64	.109	
		Nov. 22, 1965	10.10	.295	
		Dec. 29, 1965	.26	.145	
		Feb. 6, 1966	1.87	.172	
		Dec. 5, 1966	9.87	.130	
13	Sulphur Creek, near	Feb. 1, 1966	2.62	.115	.06
	St. Helena	Feb. 19, 1966	2.00	.097	
		Feb. 25, 1966	1.90	.070	
		Mar. 30, 1966	3.48	.124	
		Nov. 19, 1966	9.11	.226	
		Mar. 15, 1967	5.62	.064	
14	Sulphur Springs Canyon,	Jan. 24, 1968	8.56	.101	.08
	near Jolon	Feb. 23, 1969	5.17	.086	

The storm index (S.I.), shown in table 2 is an arbitrarily weighted precipitation accumulation beginning with antecedent rainfall. This storm index (S.I.) is defined by equation 1.

$$S.I. = 2P_A+P_0+1.0P_{-1}+0.9P_{-2}+0.8P_{-3}+\cdots+0.1P_{-10} \quad (1)$$

where

$S.I.$ = storm index, in inches;

P_A = precipitation, in inches, occurring between the time that storm runoff begins and the time that peak discharge occurs;

P_0 = precipitation, in inches, occurring on the same day as the peak discharge, but prior to the time storm runoff begins; and

$P_{-1}, P_{-2} \ldots P_{-10}$ = precipitation, in inches, for the day denoted by the subscript, for the 10 days preceding the day that storm runoff begins.

ANALYSIS OF DATA

The data analysis involved the derivation of four types of relations. The first two relations provided an estimate of the minimum ϕ-index value for an ungaged drainage basin and included the following:

1. For each of the 14 basins, the relation between the ϕ-index and storm index (S.I.) for individual storms was determined to obtain minimum ϕ-index (ϕ_{min}) values.

2. A regional relation between the infiltration index (I) and ϕ_{min} for each basin was determined and used to obtain ϕ_{min} for ungaged basins whose infiltration index had been estimated from infiltrometer tests.

The other two types of relations provided an estimate of the ratio of the ϕ-index for flood-producing storms of various recurrence intervals (ϕ_{RI}) to the minimum ϕ-index for an ungaged basin. The data required for this part of the analysis were available at only three of the 14 basins sampled. The analysis included the following:

1. For each of the three basins, the relation between the ϕ-index for flood-producing storms and the corresponding recurrence interval of the storms were determined.

2. The average relation between the ratio ϕ_{RI}/ϕ_{min} and recurrence interval of storms was determined and multiplied by ϕ_{min} for the ungaged basin to obtain values for ϕ_{RI}.

Relation of ϕ-Index to Storm Index

The relation between the ϕ-index and the storm index for each of the 14 basins was determined by plotting corresponding ϕ-index and storm-index values. It was hypothesized that the ϕ-index (or precipitation loss) would vary inversely with the storm index. Basically, with small storms or at the beginning of large storms, the ϕ-index value will be relatively high because the infiltration capacity will be greater when the soil is dry than when it is wet (Horton, 1933). For large storms (high storm-index values) the average condition of the soil may approach saturation and severely limit the infiltration capacity. The relation between ϕ-index and storm-index values was derived to obtain a minimum ϕ-index value for each basin. A typical graphical solution of the relation between the ϕ-index and the storm index is illustrated in figure 4, which shows the relation of ϕ-index to storm index for Rat Creek, near Lucia. Data for the 14 basins are given in table 2.

As shown in figure 4, the selection of a minimum ϕ-index value is quite subjective, it being that value where the slope of the relation apparently approaches the horizontal. It is not unlikely that even lower ϕ-index values would be experienced in 100-year storms. In the section that follows minimum ϕ-index values are related to infiltration-index values for the 14 basins.

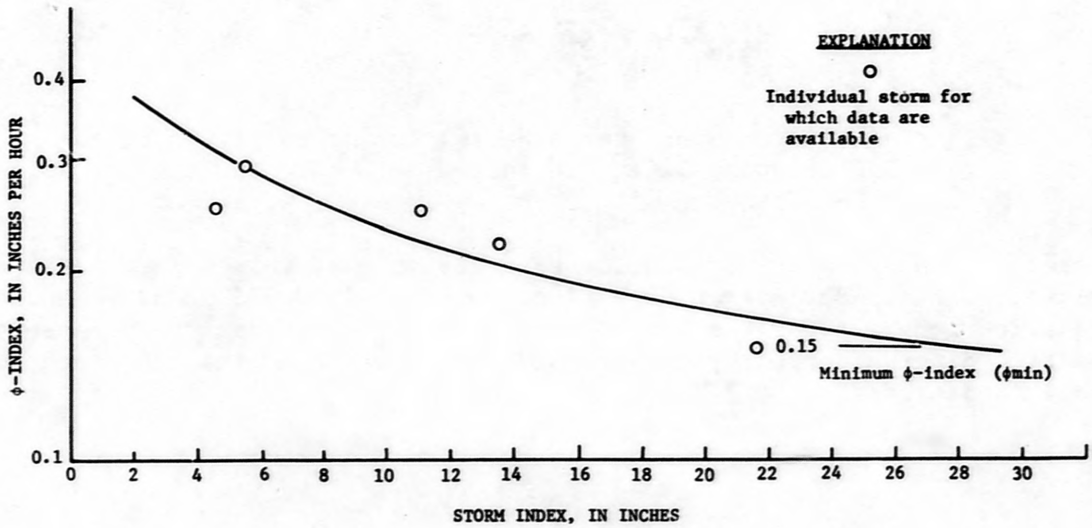

FIGURE 4.--Relation of ϕ-index to storm index for Rat Creek, near Lucia.

Relation of Minimum ϕ-Index to Infiltration Index

The relation between the minimum ϕ-index (table 2) and infiltration index (table 1) is shown in figure 5. The equation, derived by the least-squares method, for the test with soil initially dry is:

$$\phi_{min} = 0.076+0.007I_1 \tag{2}$$

where ϕ_{min} = minimum ϕ-index for a basin, in inches per hour; and
I_1 = infiltration index, in inches per hour, for the dry soil condition.

The relation, though poor, is considered acceptable at this stage of the experiment; the standard error of estimate of ϕ_{min} is 0.025 inch per hour. The equation for ϕ_{min} for the wet soil condition was not derived because of the scatter diagram formed by data points was inferior to that obtained for dry soil conditions.

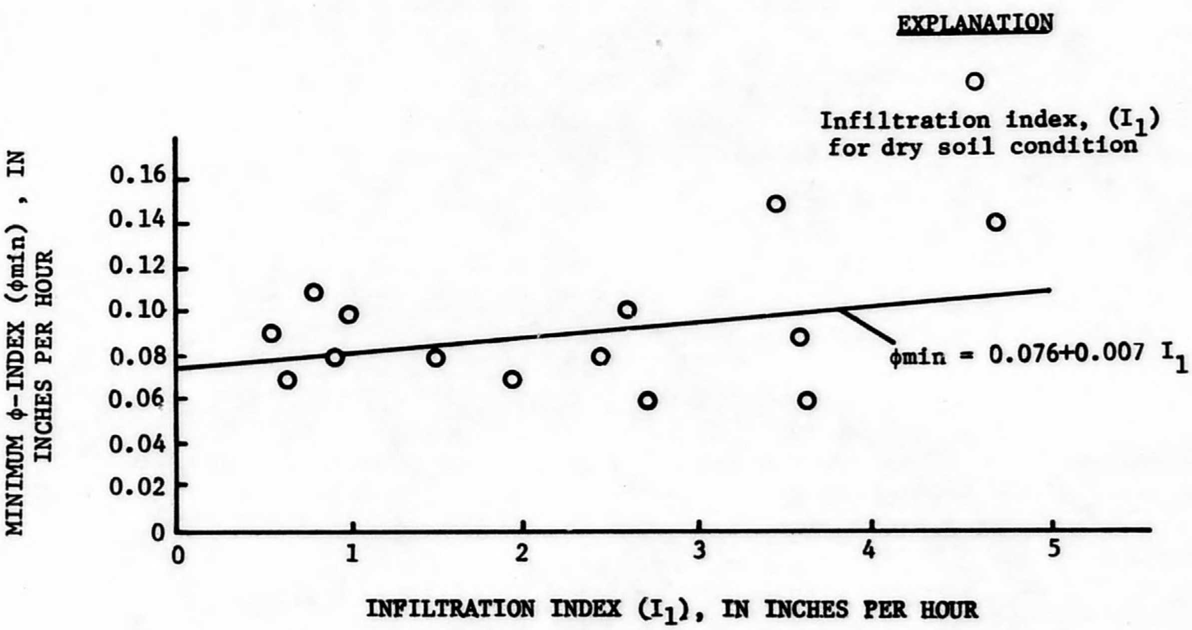

FIGURE 5.—Relation of minimum ϕ-index to infiltration index.

Relation of ϕ-Index to Recurrence Interval

Development of the relation of the ϕ-index to recurrence interval requires conversion of values of ϕ_{min} for a basin to appropriate values of the ϕ-index for use with design storms of various recurrence intervals. Data from a group of long-term gaging stations, with records that have been studied to provide regional flood-frequency and regional unit-hydrograph relations, are needed in this study. The resulting information will include ϕ-index values for each study basin, such that their use with design storms in the unit-hydrograph method results in computed peak discharges that agree with those obtained by statistical flood-frequency analyses.

Preliminary flood-frequency and unit-hydrograph studies for the San Francisco Bay region have been made by S. E. Rantz (1971), but only three of the 14 drainage basins sampled by the infiltrometer lie in that region. The ϕ-index values for the three basins for storms of selected recurrence interval, as obtained from the unit-hydrograph study are listed in table 3. The relation of the ϕ-index to recurrence interval is shown in figure 6.

TABLE 3.--*Summary of ϕ-index data for three basins in the San Francisco Bay region*

Recurrence interval (years)	Tributary of Dry Creek, near Hopland		Green Valley Creek, near Corralitos		Sulphur Creek, near St. Helena	
	ϕ-index (inches per hour)	Ratio [1] ϕ_{RI}/ϕ_{min}	ϕ-index (inches per hour)	Ratio [1] ϕ_{RI}/ϕ_{min}	ϕ-index (inches per hour)	Ratio [1] ϕ_{RI}/ϕ_{min}
2	0.497	4.97	0.348	4.97	0.376	4.64
5	.393	3.93	.258	3.68	.300	3.70
10	.308	3.08	.205	2.93	.239	2.95
25	.219	2.19	.140	2.00	.166	2.05
50	.144	1.44	.093	1.33	.111	1.37
[1] 75	.100	1.00	.070	1.00	.081	1.00
100	.078	.78	.054	.77	.065	.80

[1] Comparison of ϕ-index values obtained from the unit-hydrograph study and ϕ_{min} values obtained from figure 5, indicates that the ϕ_{min} values most closely correspond to the ϕ-index values for a 75-year storm (ϕ_{75}). Therefore, the ratio ϕ_{RI}/ϕ_{75} is considered equivalent to the ratio ϕ_{RI}/ϕ_{min} for these basins.

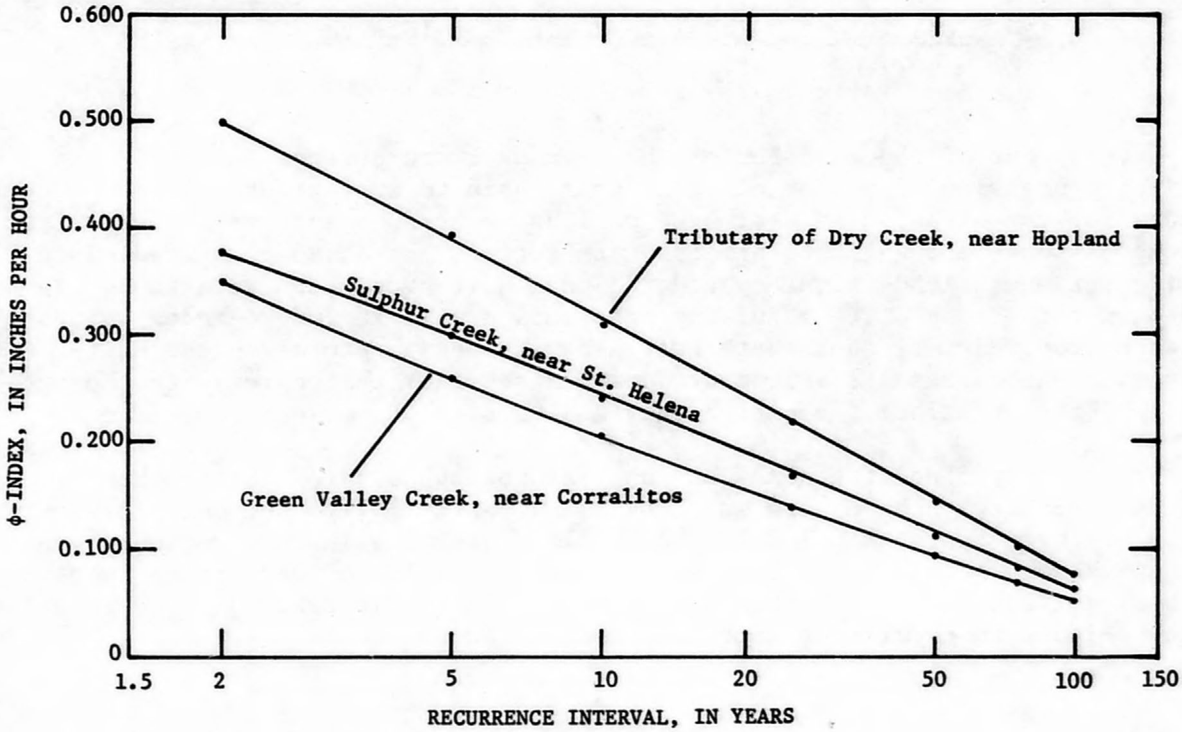

FIGURE 6.--Relation of ϕ-index to recurrence interval of flood-producing storms for three basins in the San Francisco Bay region.

Relation of ϕ-Index Ratio to Recurrence Interval

The study described in the preceding section provided information on individual relations of ϕ-index to corresponding recurrence interval for each of three basins in the San Francisco Bay region. A composite regional relation between recurrence interval and the ratio of the ϕ-index for a given recurrence interval to ϕ_{min}, where ϕ_{min} is obtained from the relation in figure 5, actually is reached. The footnote to table 3 indicated that the ϕ_{min} was equivalent to ϕ_{75} for the three basins in the San Francisco Bay region. Accordingly, ratios of ϕ_{RI} to ϕ_{min}, as shown in table 3, were computed by dividing all ϕ-index values by the appropriate value of ϕ_{75}. The ϕ-index ratios so obtained then were plotted against their corresponding recurrence intervals to obtain a locus of average values (fig. 7).

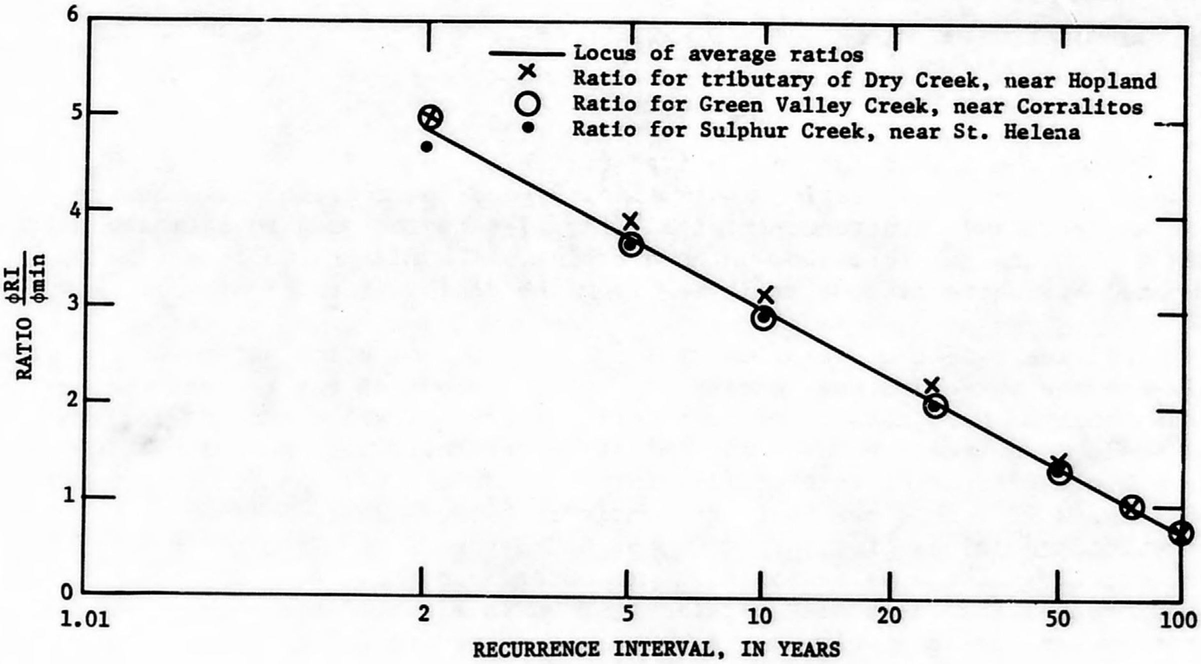

FIGURE 7.--Relation of the ratio ϕ_{RI}/ϕ_{min} to recurrence interval of flood-producing storms in the San Francisco Bay region.

The equivalence of ϕ_{min}, derived from short streamflow records, to ϕ_{75}, seem to indicate the occurrence of a flood of magnitude nearly equivalent to that of the 75-year flood during the short period of record. However, that is not the case--75-year floods have not occurred in the three stream basins during the period of record. In California, floods of major significance actually result from a complex sequence of short storms. The unit-hydrograph technique is used in a probability study of flood peaks under the assumption that a flood is caused by a simple, relatively short, design storm whose direct runoff is superposed upon a design base flow. Because an unrealistic storm must be used to compute a flood hydrograph and peak discharge whose magnitude matches that of a historic flood, the resulting ϕ-index may be unrealistic in magnitude. Thus, the average ϕ-index values are in every sense index figures that permit simulation of "real" flood peaks from unreal storms.

COMPUTATION OF WATER LOSS, DIRECT RUNOFF, AND PEAK DISCHARGE

Two of the four relations derived during this study--the relation between ϕ_{min} and infiltration index (fig. 5) and the relation between the ϕ-index ratio and recurrence interval (fig. 7)--may be used to estimate water losses from design storms for ungaged basins. The direct runoff may be computed by subtracting water losses from the design storm.

To illustrate the use of figures 5 and 7 for computing water losses, we will use the three drainage basins in the San Francisco Bay region. Let us assume that we have no streamflow records or precipitation records for any of the basins, but that we have made infiltrometer tests in each basin. Table 1 shows the infiltration indexes (I_1) for test basins 5, 7, and 13 to be 1.50, 0.99, and 2.72 inches per hour, respectively. From figure 5, the corresponding values of ϕ_{min} are 0.086, 0.083, and 0.095 inch per hour, respectively. These values of ϕ_{min} are entered in table 4. Next, the coordinates of the composite relation shown in figure 7 are entered in the first two columns of table 4. To compute the required water losses for the various recurrence intervals (ϕ_{RI}), the values of ϕ_{min} are multiplied by each of the ratios in column 2 of table 4. The values of the ϕ-index, so computed, are given in the last three columns of table 4. Comparison of those ϕ-index values with the ϕ-index values in table 3, which were obtained from the unit-hydrograph study, shows that while large percentage differences occur between the two sets of ϕ-index values, the differences are small enough to be measured in hundredths of an inch per hour. Consequently, there will generally be no great difference in computed values of direct runoff and peak discharge if computations are first made by using the set of water losses from table 3, and then recomputed using the set of water losses from table 4.

TABLE 4.--*Computation of water losses using infiltrometer data and the φ-index ratio*

Recurrence interval (years)	Ratio Φ_{RI}/Φ_{min} (from fig. 7)	Tributary of Dry Creek, near Hopland	Green Valley Creek, near Corralitos	Sulphur Creek, near St. Helena
		Φ_{min} = 0.086 in/hr (from fig. 5)	Φ_{min} = 0.083 in/hr (from fig. 5)	Φ_{min} = 0.095 in/hr (from fig. 5)
		Φ-index (inches/hour)	Φ-index (inches/hour)	Φ-index (inches/hour)
2	4.86	0.418	0.403	0.462
5	3.75	.322	.311	.356
10	3.02	.260	.251	.287
25	2.10	.181	.174	.200
50	1.43	.123	.119	.136
75	1.00	086	.083	.095
100	.78	.067	.065	.074

A detailed discussion of the method of computing peak discharge is beyond the scope of this report, but the four basic elements in the procedure are enumerated below:

1. Derive regional synthetic unit hydrograph for the ungaged drainage basin, based on regional equations for computing basin lag.

2. Derive storm sequences of various recurrence intervals for use with the ungaged basin having various values of lag.

3. Derive rates of water losses from design storms for the ungaged basin. (This report has demonstrated a method using the infiltrometer.)

4. Determine the base flow for recurrence intervals of various storms.

With the above four elements established, design hydrographs for various recurrence intervals can be computed. By subtracting water losses (item 3) from the design-storm sequence (item 2), the volume of precipitation excess, or direct runoff may be obtained. Now, the unit hydrograph (item 1) may be applied to the increments of precipitation excess to obtain the design hydrograph of surface runoff. Finally, the base flow (item 4) may be added to the hydrograph of surface runoff to obtain the design hydrograph of total runoff. The peak discharge of the design hydrograph is the peak value sought. The entire procedure is based on the assumption that the frequencies of peak discharge and peak precipitation are identical.

During this study, an attempt also was made to obtain direct runoff by using the concept of "curve numbers" (U.S. Soil Conservation Service, 1968), in place of the ϕ-index. The Soil Conservation Service (SCS) relates direct runoff to storm precipitation by means of a family of curves, each of which bears a number. Each curve number is based on soil type, vegetation type, and an antecedent moisture condition. For any given basin, the soil type is constant; the vegetation type may vary from year to year in an agricultural area but is otherwise constant; the antecedent moisture condition may vary from storm to storm. In this study, it was found that the wide variation of the curve numbers for the storms in any basin had no relation to the storm index. In other words, with storm precipitation and direct runoff being known for the 55 storms at the 14 test basins, the SCS curves could be used to obtain the curve number for each of the storms. However, when the curve numbers were related to the storm index for each basin--analogous to relating ϕ-index to the storm index (fig. 4)--no relation was found. Hence, the SCS approach was abandoned. The validity of the SCS approach is vague because it does not take storm duration into consideration. For example, the SCS curves for a given set of conditions indicate a definite quantity of direct runoff for 2 inches of storm precipitation, with no differentiation being made on the basis of whether the 2 inches fell in 1 hour or in 6 hours. Differences in storm duration should cause significant differences in direct runoff.

SUMMARY AND CONCLUSIONS

This study tested the feasibility of using infiltrometer data to estimate water losses in ungaged drainage basins during storms and to determine the direct runoff from design-storm rainfall. Two derived relations are basic to the method that was tested. The first relates an infiltration-index value (I) obtained from infiltrometer observations to a minimum infiltration rate (ϕ_{min}) obtained from records of rainfall and runoff. The second relates a storm-infiltration rate (ϕ_{RI}), expressed as a ratio to the minimum ϕ-index (ϕ_{min}), to the storm-recurrence interval. To apply the two derived relations, infiltrometer tests were made in ungaged drainage basins, and the infiltration index obtained from those tests was used with the infiltration-index values (I) to obtain the minimum infiltration rate (ϕ_{min}) for the basin. The minimum infiltration rate (ϕ_{min}) was then used with the storm-infiltration rate (ϕ_{RI}) to obtain infiltration rates (water losses) that corresponded to design storms of selected recurrence intervals.

The results obtained in a study of storm runoff in the San Francisco Bay region indicated that the storm-infiltration rate (ϕ_{RI})--a regional relation involving ϕ-index ratios--can be satisfactorily derived. An objective of this study was to determine whether the first relation--a determination of ϕ_{min} from infiltrometer data--could be satisfactorily derived. The relation, as obtained in this study, is shown in figure 5, but the correlation between infiltrometer index and ϕ_{min} is discouraging. Infiltrometer readings may be a poor index of water losses that occur during storms for many reasons. If the soil mantle is thin, or if a relatively impermeable soil horizon is close to land surface, infiltration may not govern the rate of water loss after a prolonged period of rainfall. With respect to infiltration capacity, the heterogeneity of the surface soil may be even more important, and the number of sampling sites used in the infiltrometer tests may have been inadequate. Instead of using four randomly selected sampling sites, perhaps a stratified sampling design should have been adopted, using not only more sites, but sampling both bottom land and hillside areas. Data obtained from the different sampling sites might be weighted in accordance with the percentage of area occupied by each type of terrain. Additional testing of the infiltrometer technique is recommended because a practicable infiltrometer method would be a particular boon to the study of storm runoff in desert areas.

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