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HOW MUCH PRECIPITATION GOES TO INFILTRATION DURING A STORM PERIOD?

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Based on a detailed investigation of factors influencing infiltration in a drainage basin, functional relationships amongst the abstractions during a storm period, storm characteristics and condition of the basin at the beginning of a storm are developed for a basin. Graphical multiple correlations are also obtained for estimating the abstractions. Basin characteristics like area, slope and soil characteristics are treated as time-invariant. When abstractions during a storm period due to other causes are negligible, the sum of the abstractions can be approximated to infiltration during the storm period. For 10 basins with 60 storms, graphical multiple correlations are prepared for estimating abstractions. These correlations are verified using a different set of 112 storms in addition to the 60 storms used in the calibration phase. The results obtained are discussed.

Infiltration is the process that provides water for all terrestrial plants and for much of animal life. It furnishes the yield in wells and the stream flow in periods of fair weather. In addition, it reduces floods and soil erosion. Determining infiltration, in cases where rainfall and runoff are known, enhances the understanding of the infiltration process. For studies related to water budget, ground water utilisation, runoff, agriculture etc., an estimate of infiltrating water during a storm period is required, given the rainfall and state of the basin at the start of precipitation.

Infiltration is a function of a number of variables, most of which are not easily susceptible to quantitative evaluation. A detailed study of the nature and extent of the influence of these factors has been reported by many investigators. Kulandaiswamy & Babu Rao (1969) presented a critical review of these investigations under various groups and classifications. From a study of various factors influencing infiltration, it can be illustrated that investigations based on natural structure of soil will be impossible. An intelligent application of the infiltration concept is essential to making a reasonably satisfactory estimate of runoff and accretion to ground water.

In this paper, graphical multiple correlations capable of estimating abstractions during a storm period, based on the detailed investigation of factors influencing infiltration in a drainage basin, are developed. Where abstractions due to other causes are negligible, the total abstractions can be approximated to infiltration during the storm period. The results obtained for 10 basins with 172 storm events are presented and discussed.

INFILTRATION DURING A STORM PERIOD

The amount of precipitation falling as snow or rain on a drainage basin is disposed of in one or more of the following ways:

i) Interception
ii) Evaporation
iii) Transpiration
iv) Infiltration
v) Precipitation directly on water course
vi) Surface runoff from the land.

Items (i) to (iv) constitute the losses (to surface runoff) and (v) and (vi) constitute what is termed the rainfall excess. That part of the precipitation which is not available for surface runoff is termed as precipitation losses or abstractions, and that which is available for surface runoff is called rainfall excess. Water that is retained in surface depressions will eventually come under infiltration and evaporation losses. Transpiration loss is evaporative in nature, and the quantity is drawn from the water that has infiltrated into the soil. Among the abstractions during precipitation, infiltration is the major component. Concerted efforts on infiltration studies began with the work of Horton in the early 1930's. On the basis of Horton's paper (1933) and Sherman's paper (1932) hydrologists began to think of the problem in terms of a two phase process, namely infiltration and runoff.

The factors that influence the abstractions in a basin are: the state of the basin at the time of precipitation, physical characteristics of the basin, and storm characteristics. These factors can be listed as follows (Chow 1962 & 1964):

1. State of the basin:
   a) Soil moisture
   b) Density of growth of vegetation
   c) Land use
   d) Temperature
   e) Wind
   f) Atmospheric pressure
   g) Humidity
   h) Solar radiation.
2. Basin characteristics:
   a) Area
   b) Shape
   c) Slope
   d) Soil type
   e) Geological conditions
   f) Land use
   g) Soil surface condition
   h) Stream density
   i) Size, shape, slope and roughness of the channel
   j) Storage capacity.
3. Storm characteristics:
   a) Type of precipitation
   b) Intensity
   c) Duration
   d) Time distribution
   e) Areal distribution.

The list is not exhaustive, nor are the factors enumerated independent. Many of them are in fact interdependent. The variables are too many and most of them are not susceptible to quantitative evaluation. Rainfall and runoff are historic events about which records are kept on the basis of actual field measurement.

Several analytical and experimental studies have been made by investigators on infiltration (Kulandaiswamy & Rao 1969). But an application of these investigations to the determination of infiltration during the period of precipitation in an actual drainage basin is very much complicated due to the basic nature of the above parameters and the complex nature of the actual drainage basin. A completely satisfactory solution has not been found so far. But it has helped to better quantitize the phenomenon of infiltration with mathematical equations. In the case of actual drainage basins, an intelligent use of the historic hydrologic events is warranted in developing a procedure for estimating the part of the precipitation that goes for infiltration during the storm period.

Considering the factors influencing the earlier listed abstractions, there are certain aspects that can be treated as time-invariant and there are others that change with time. When the study is restricted to a particular basin, the time-invariant factors like area, slope and soil characteristics need not be considered since they are constants. Among the time-dependent factors are the soil conditions, field moisture, rainfall characteristics, temperature, wind, atmospheric pressure and so on. In most design operations and flood forecasting problems, there is adequate justification for making a detailed analysis of the factors governing infiltration to ensure the development of relations which will be universally applicable to the basin under study. The independent variables in the required correlation must include one or more of the factors which represent total moisture deficiency of the basin, as well as the storm parameters. In the present state of the science it may be adequate if the conditions of soil moisture in the basin at the time of precipitation can be assessed. The soil moisture condition at the start of precipitation is referred to as "initial condition". Determination of initial condition is by no means an easy task. Antecedent precipitation index (I_{ap}), initial flow at the beginning of a storm (q_i), and a parameter based on soil moisture accounting, are some of the variables which could be thought of to represent the initial condition of the basin. The "antecedent precipitation index" (Linsley et al. 1949) is universally used in river forecasting and coaxial relations for basin recharge and runoff. It is certainly reasonable to assume that the soil moisture status at any instant will depend upon the preceding rainfall history. But the difficulty arises when one tries to express the effect of this preceding rainfall quantitatively. The number of days to be considered and the weight to be given to each day are, of necessity, fixed arbitrarily. The antecedent precipitation index, I_{ap} is expressed in terms of a series of the form:

$$I_{ap} = P_1/1 + P_2/2 + P_3/3 + \ldots + P_n/n \qquad \ldots \quad (1)$$

where P_n is the volume of rainfall during a 24 hour period recorded on the n^{th} day preceding the storm for which the runoff is being calculated. The value of "n" usually varies from 10 to 30. A refinement of antecedent precipitation index, for the effect of temperature, atmospheric pressure etc., is expected to yield more satisfactory results. This refinement requires considerable additional computational work and its value depends upon the scope of the study and the accuracy of the other types of data involved in the correlation. Taking into account the nature of the problem, acquisition of hydrologic information and the magnitude of the error likely to be introduced by not taking into account the effect of temperature, atmospheric pressure, humidity and solar radiation, the antecedent precipitation index, I_{ap} given in Eq. (1) is not modified. In the present investigation, antecedent precipitation index is considered adequate to represent the initial condition of the basin for the following reasons: (i) the errors in soil moisture accounting will be considerable, and it is very uncertain how accurately the soil moisture can be determined if this accounting happens to be over a long period, (ii) the initial flow at the beginning of a storm has been found to be very well correlated to antecedent precipitation index. Correlations have been made between antecedent precipitation index and total runoff from a storm and satisfactory results have been reported (Linsley et al. 1949). Attempts have also been made to develop graphical relationships between antecedent precipitation index and Φ-index for individual basins (Bhatnagar 1967, Linsley et al. 1949).

With regard to storm parameters; the volume of precipitation, R_v, the duration of precipitation, T, and the time to the centre of area of precipitation, T_g, are considered adequate to represent storm characteristics. The peak of the rainfall, r_p is not considered, as it was found in earlier studies (Kulandaiswamy & Rao 1969, 1971, 1973) that no significant correlation is seen between infiltration index and r_p. With regard to spatial variation in rainfall and watershed characteristics, it is worthwhile mentioning the work of Crawford & Linsley (1966). Since the data required in the method followed by these authors is prohibitively large and, in many cases, very difficult to obtain, its application is not feasible. In addition, the computational effort required to arrive at the infiltration parameters is rather tedious. Following the work of Crawford & Linsley on infiltration, Clark & Hebbert (1971) developed a simple procedure for estimating runoff volume, in which the concept of varying the area by assuming one particular spatial variation of infiltration capacity, is introduced. In this procedure, a multicorrelation relationship among parameters, taking into account area variability, volume of rainfall and antecedent precipitation index, is made. However, for area variation accounting, the methods so far developed are very approximate and they are far from providing a complete explanation of the complex hydrologic phenomenon. The development of this line of approach to area variability is very much in its infancy and it has a long way to go before it can be considered for broad practical application. In the present state of the science, this problem gets simplied substantially only if the hydrologic information can be accurately assessed in a basin.

Table 1.
Details of basins used in the determination of infiltration.

Basin No. (1)	Name of the basin (2)	Area (km^2) (3)	Number of storms analysed (4)	Source of data (5)
	Drainage Basins in U.S.A.			
1	Beech River Basin near Lexington, Teneessee	41.2	27	Tennessee Authority, Knoxville, Tennessee, U.S.A.
2	North Creek Basin near Jacksboro, Texas	56.2	12	From USGS through Colorado State University, Colorado, U.S.A.
3	West Fork, Deep River Watershed – W1, High Point, North Carolina	83.2	9	U.S.D.A.
4	Vero Beach Watershed-W1, Indian River Farms Drainage District, Indian River County, Florida	202.0	21	U.S.D.A.
5	Chestuee Creek Basin, Dentiville	296.00	50	Tennessee Valley Authority, Knoxville, Tennessee, U.S.A.
6	Mississippi Watershed-34, Oxford	304.0	7	U.S.D.A.

	Drainage Basins in India			
7	Pavanje River Basin, gauged at Kateel bridge site (gauging station 11)	69.4	11	The data for the Indian Basins No. 7, 8, 9 and 10 has been obtained from:
8	Gowri Hole basin, gauged at Kumaramangala (gauging Station 8)	116.7	20	i) the Chief Engineer and Administrator, M. H. P. Panambur, S. K.
9	Gurpur river basin, gauged at Polali (gauging station 10)	696.3	11	ii) The Chief Engineer, W. R. D. O., Bangalore.
10	Netravathi river basin, gauged at Panemangalore (gauging station 9)	3286.7	4	iii) The Superintending Engineer, West Coast Circle, Mangalore.
				iv) The District Statistical Officer, Mangalore.
				v) The Asst. Engineer, Major Irrigation Sub-Division, Mangalore.

MULTICORRELATIONS AMONG PARAMETERS REPRESENTING INFILTRATION, RAINFALL CHARACTERISTICS AND INITIAL CONDITION

Let F_v be the sum of the abstractions during a storm period. When evaporation and interception losses are negligible, the abstractions can be approximated to infiltration during the period of rainfall. The sum of the abstractions, F_v, and the variables of rainfall characteristics previously discussed in connection with the parameter I_{ap}, may be expressed in a functional form as follows:

$$f_1 (F_v, R_v, T, T_g, I_{ap}) = 0 \qquad \ldots \quad (2)$$

Through a process of dimensional analysis and treating R_v/T as average rainfall rate, r_a, the variables can be grouped as follows:

$$F_v/R_v \equiv f_2 (T_g/T, I_{ap}/r_a) \qquad \ldots \quad (3)$$

In Eq. 3, the parameter T_g/T represents the storm pattern, while I_{ap}/r_a gives a measure of the initial condition of the basin, and F_v/R_v represents the fraction of the precipitation going as abstraction.

In order to study the relationships among the parameters F_v/R_v, T_g/T and I_{ap}/r_a, and the multicorrelations pertaining to them, six American river basins and four Indian river basins, listed in Table 1, with 172 storms over these basins, were chosen. The details of the Indian basins used for study are illustrated in Fig. 1. In previous investigations (Kulandaiswamy & Rao 1969, 1971, 1973), the relationships of the form F_v/R_v vs. T_g/T and F_v/R_v vs. I_{ap}/r_a have been studied for 6 basins in the U.S.A. With the help of these studies, a single parameter representing both rainfall characteristics and initial condition was worked out for use in runoff predictions. However, a study of the multicorrelation relationship among these parameters has not been made previously. In the present study, a detailed investigation of the relationships F_v/R_v vs. T_g/T, F_v/R_v vs. I_{ap}/r_a and F_v/R_v vs. $I_{ap}/r_a \times T_g/T$ is made, using a large number of observed storms over the basins of different sizes listed in Table 1. The parameter F_v/R_v correlated fairly well with the parameters I_{ap}/r_a and T_g/T and very well with $I_{ap}/r_a \times T_g/T$ for all basins and hence their random variation is ignored. The plots for the Pavanje river basin are given in Fig. 2. From the plot of F_v/R_v vs. $I_{ap}/ra \times T_g/T$, multiple correlation relationships among the various non-dimensional parameters, representing abstractions, rainfall characteristics and initial condition of the basin, are prepared (Figs. 3 to 12).

It can be seen from the multicorrelation relationship among F_v/R_v, T_g/T and I_{ap}/r_a shown in Figs. 3 to 12 that, in all cases, F_v/R_v reduces from a value of unity to a constant for a basin, but this constant varies from basin to basin. The limits

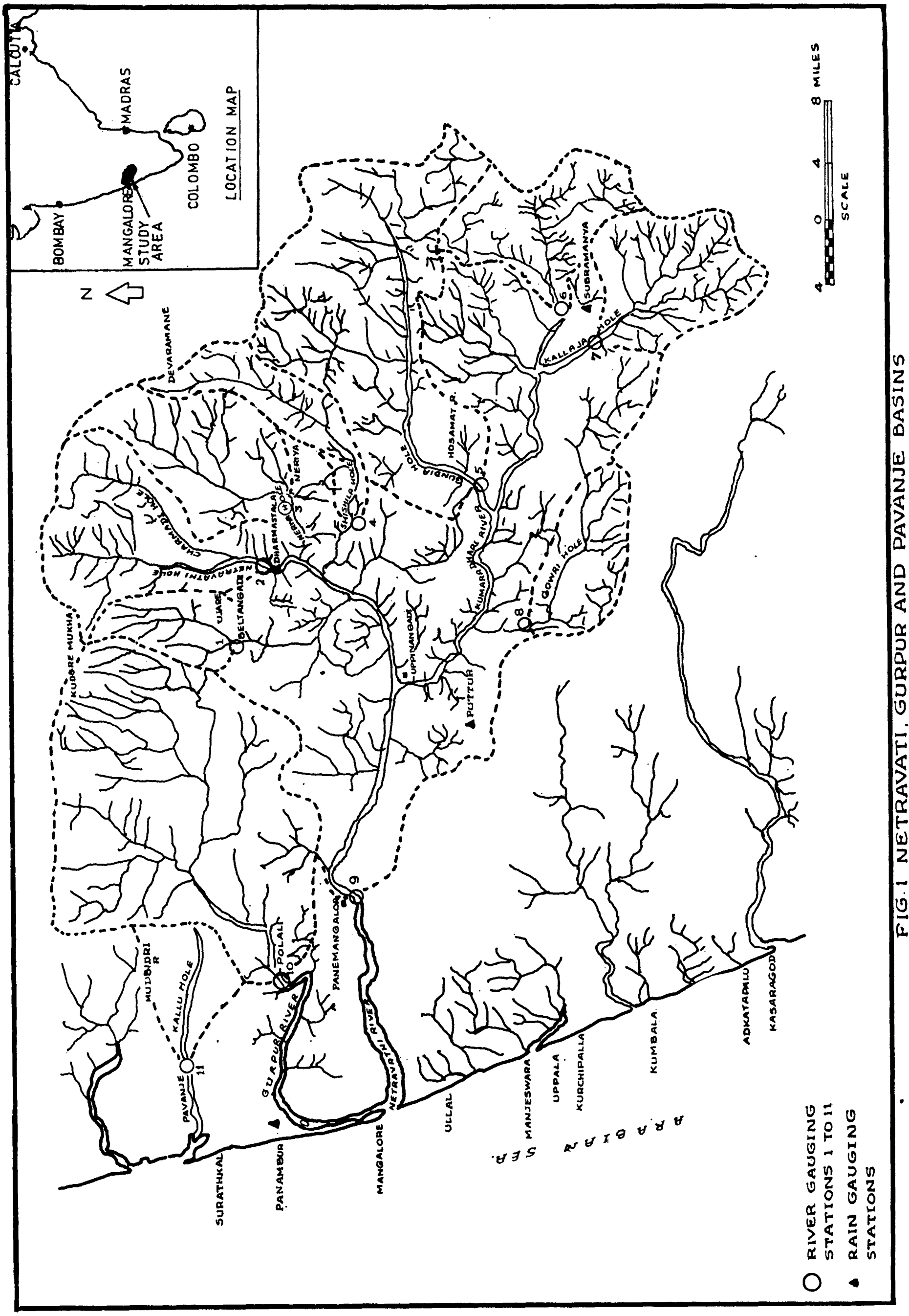

Fig. 1.

Netravati, Gurpur and Pavanje Basins.

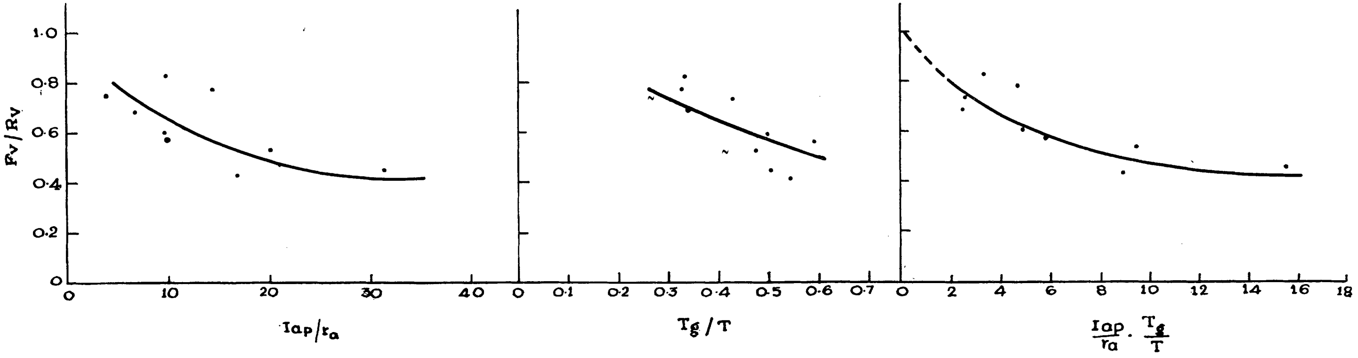

Fig. 2.

Pavanje River Basin; graph of F_V/R_V vs. $\frac{I_{ap}}{r_a}$, $\frac{T_g}{T}$ and $\frac{I_{ap}}{r_a}$, $\frac{T_g}{T}$

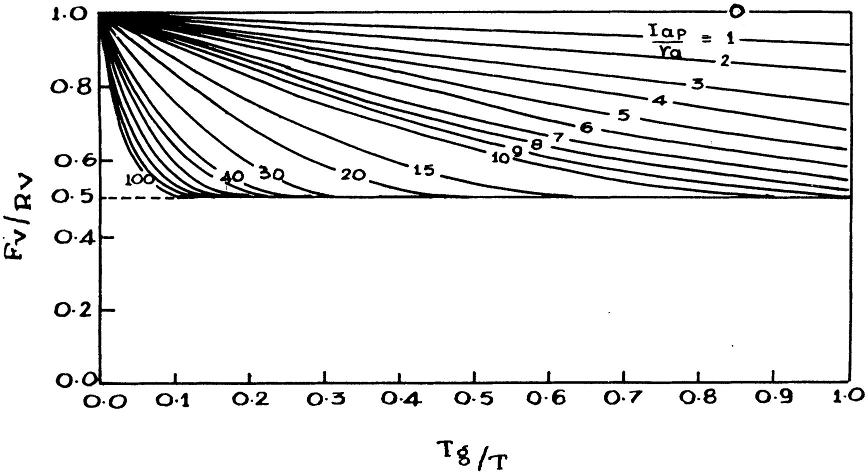

Fig. 3.
Beech River Basin; a multiple correlation between F_v/R_v and T_g/T and I_{ap}/r_a.

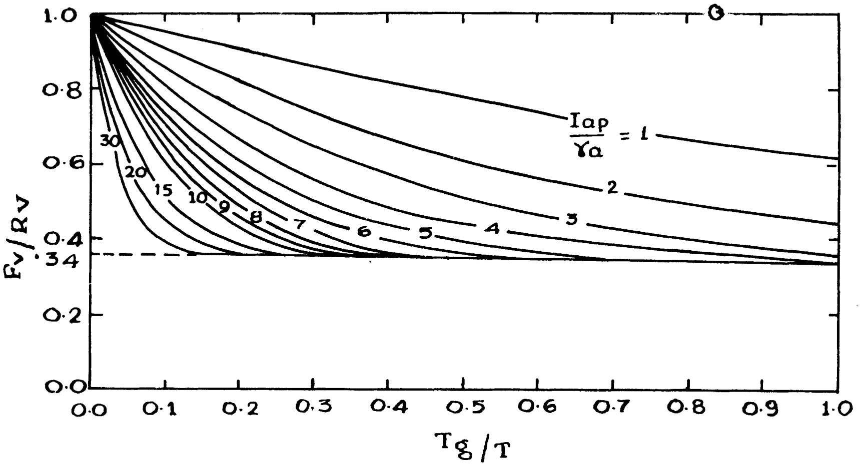

Fig. 4.
North Creek Basin; a multiple correlation between F_v/R_v and T_g/T and I_{ap}/r_a.

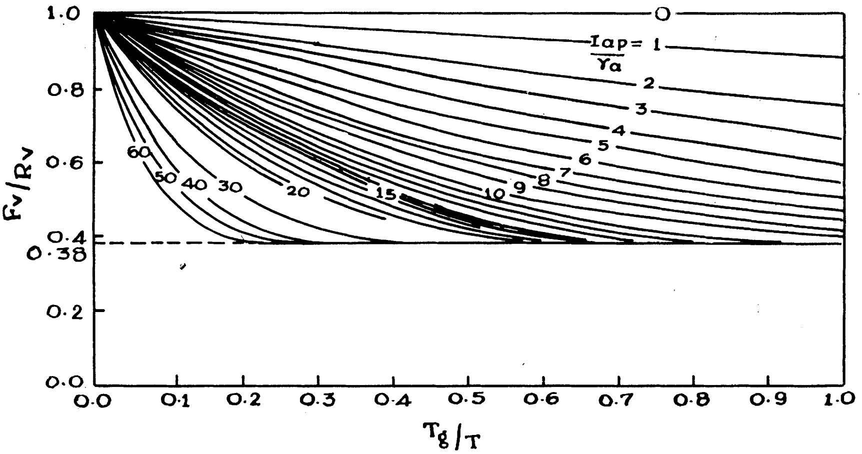

Fig. 5.
Vero Beach Watershed – W 1; a multiple correlation between F_V/R_V and T_g/T and I_{ap}/r_a.

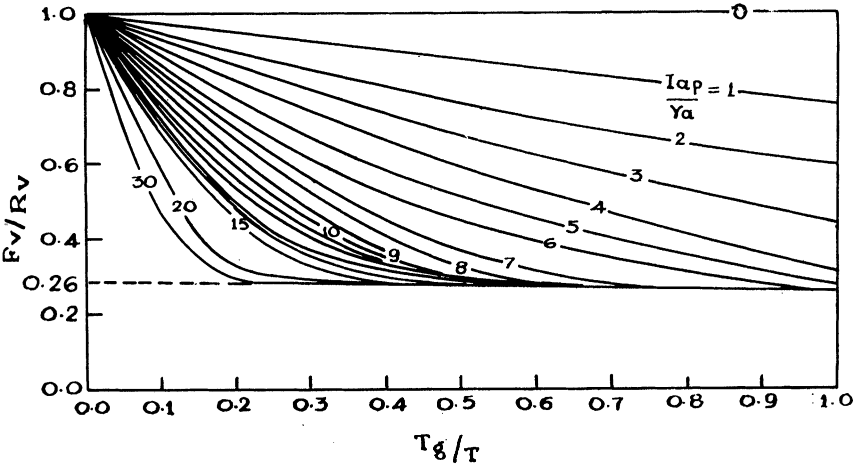

Fig. 6.
Deep River Watershed – W 1; a multiple correlation between F_V/R_V and T_g/T and I_{ap}/r_a.

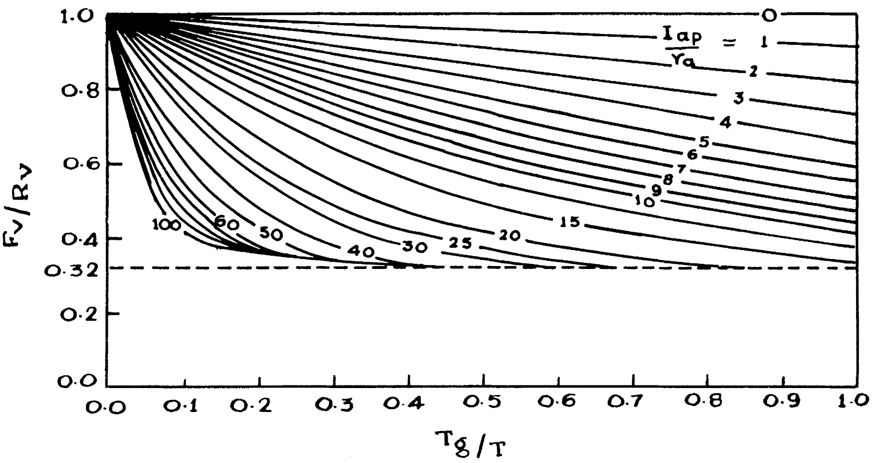

Fig. 7.
Chestuee Creek Basin; a multiple correlation between F_V/R_V and T_g/T and I_{ap}/r_a.

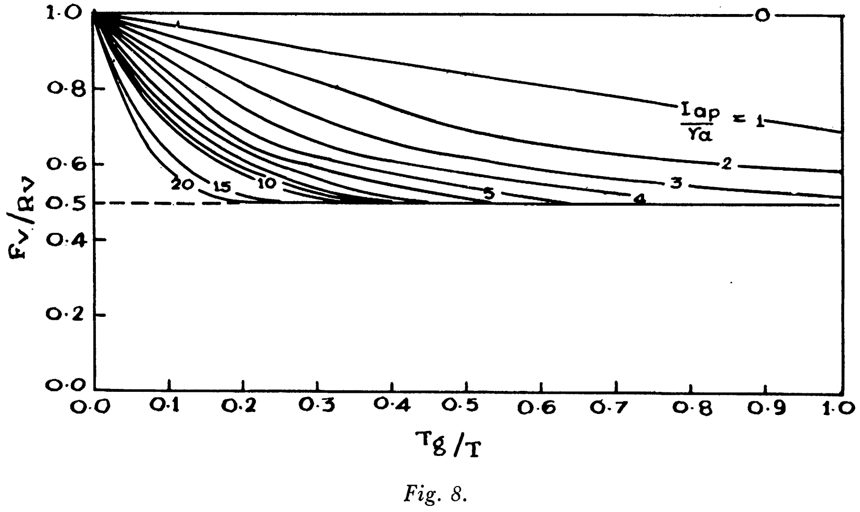

Fig. 8.
Mississippi Watershed – 34; a multiple correlation between F_V/R_V and T_g/T and I_{ap}/r_a.

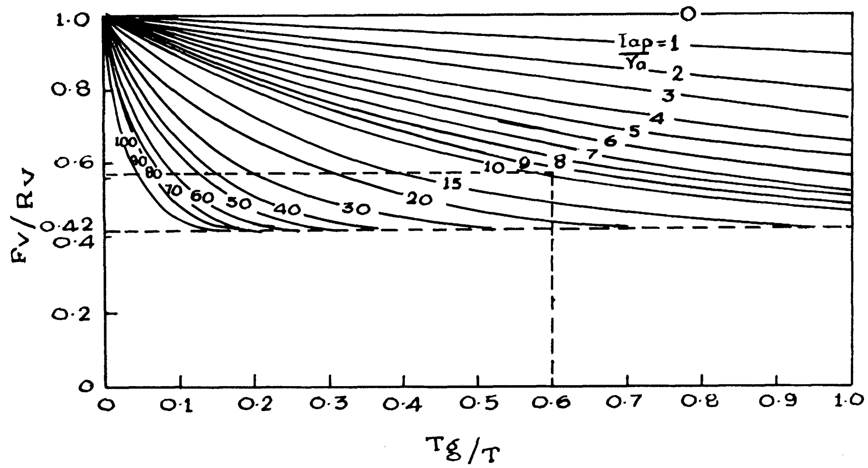

Fig. 9.

Pavanje River Basin; a multiple correlation between F_v/R_v and T_g/T and I_{ap}/r_a.

of the parameter, T_g/T, are from zero to one. The minimum value of I_{ap}/r_a is zero and for various values of I_{ap}/r_a, dimensionless curves for infiltration are worked out and the family of curves for each basin is indicated. It can be seen that for a given pattern of rainfall, there is a threshold value of F_v/R_v at a particular value of I_{ap}/r_a beyond which, whatever may be the value of I_{ap}/r_a, the value of F_v/R_v is a constant.

VERIFICATION OF MULTICORRELATION RELATIONSHIPS

For verification of the multicorrelation relationship prepared for 10 basins listed in Table 1, an entirely different set of 112 storm events, in addition to the 60 storm events used in the calibration phase, have been used. For each of the storms used in this verification, the abstractions are estimated as follows: For a given storm, the value of T is obtained from the hyetograph and the values of T_g, R_v and r_a are computed. Antecedent precipitation index, I_{ap} is determined using Eq. 1. From these values the non-dimensional parameters T_g/T and I_{ap}/r_a are computed. Using the values of T_g/T and I_{ap}/r_a, the value of F_v/R_v is obtained

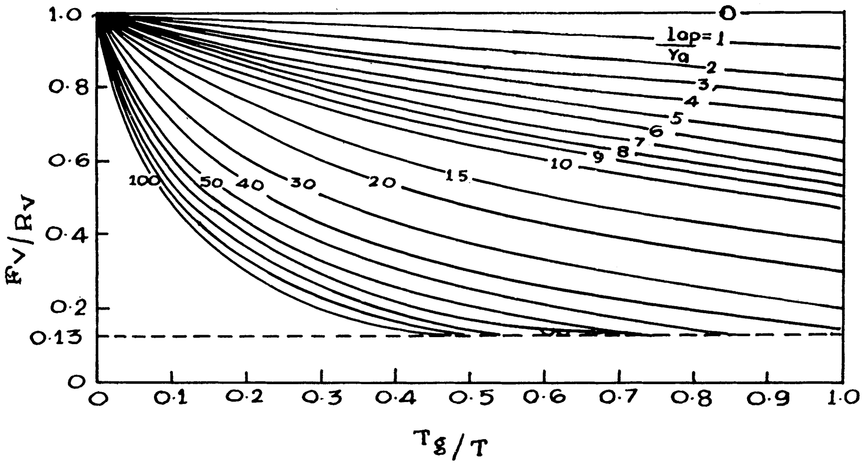

Fig. 10.

Gowri Hole Basin; a multiple correlation between F_v/R_v and T_g/T and I_{ap}/r_a.

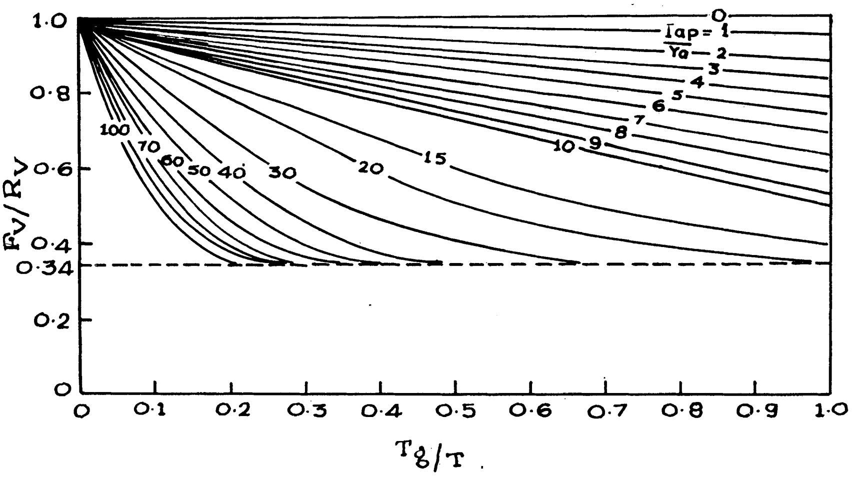

Fig. 11.

Gurpur River Basin; a multiple correlation between F_v/R_v and T_g/T and I_{ap}/r_a.

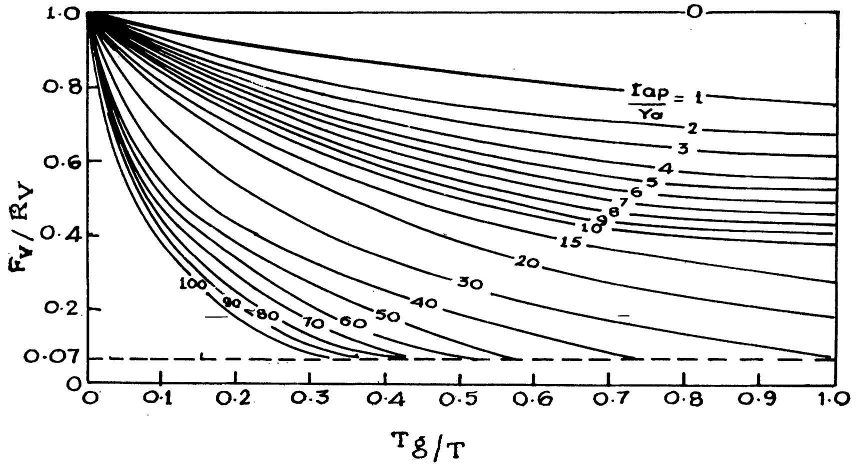

Fig. 12.

Netravati River Basin; a multiple correlation between F_v/R_v and T_g/T and I_{ap}/r_a.

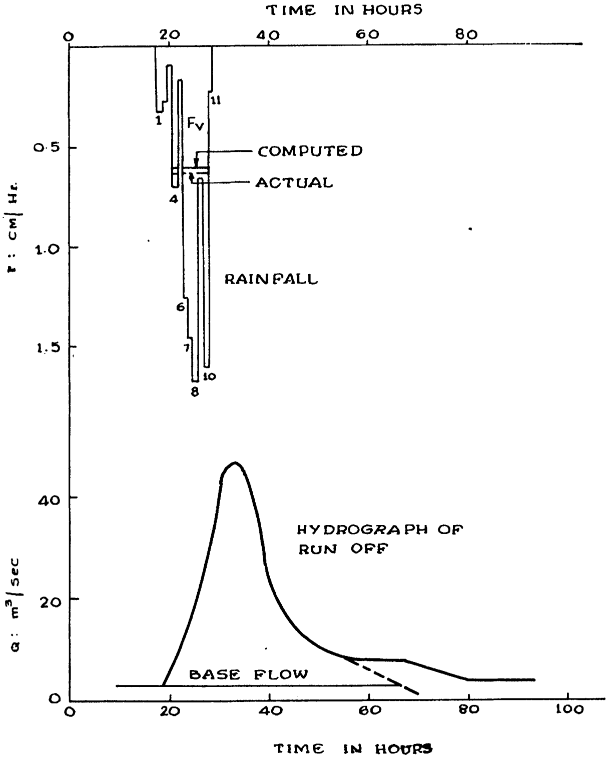

Fig. 13.

Pavanje Basin, Storm of July 14, 1971.

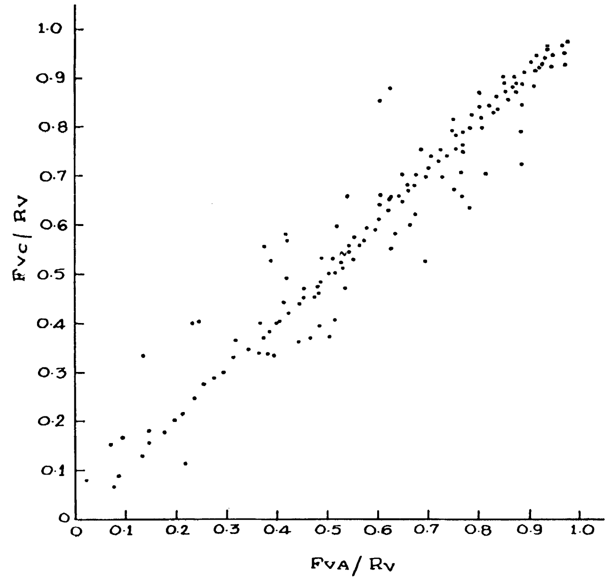

Fig. 14.

Graph of $\frac{F_{vc}}{R_v}\ V_s\ \frac{F_{vA}}{R_v}$.

from the multicorrelation relationship, as indicated in Fig. 9. The value of abstraction F_v is computed from F_v/R_v and R_v. When evaporation and interception losses are negligible, the abstractions can be approximated to infiltration. The part of the precipitation which goes to infiltration can be indicated for each storm as shown in Fig. 13 for the storm of July 14, 1971 over Pavanje basin. This is also explained by an example given in the Appendix.

Using the foregoing procedure, 172 storms in 10 basins mentioned above are analysed and the values of F_v are predicted. The predicted values of F_v (F_{vc}) and the actual values of F_v (F_{vA}) are expressed as fractions of R_v and a plot of F_{vc}/R_v vs. F_{vA}/R_v is shown in Fig. 14. It can be seen from this plot that the predicted values agree fairly well with the actual values for many storm events. The error in the computed value of abstractions (F_{vc}) is less than 5 percent for 82 percent of the storms, varies from 5 percent to 10 percent for 10 percent of the storms, from 10 percent to 15 percent for 5 percent of the storms, and 15 percent and above for 3 percent of the storms.

CONCLUSIONS

The following conclusions are drawn, based on these infiltration studies made over 10 drainage basins selected from the U.S.A. and India, using 172 storm events:

i) For all the basins studied, the multicorrelation curves drawn for estimating infiltration during precipitation were smooth and regular.

ii) For a given drainage basin where hydrologic data for a few representative past storm events are available, the multicorrelation curves for estimating infiltration during precipitation can be prepared.

iii) For a known initial condition, represented by I_{ap}/r_a, and rainfall pattern, represented by T_g/T (found to vary between 0.3 and 0.8), infiltration during the period of rainfall can be assessed using the multicorrelation curves for F_v/R_v.

iv) For a given storm pattern (T_g/T) after a certain higher value of I_{ap}/r_a, has been reached, the value of F_v/R_v is found to approach a constant, which means that the infiltration varies more or less linearly with the volume of rainfall when the basin is very wet.

v) In many design problems having to do with water use and ground water and river forecasting, the multicorrelations developed above can be used advantageously.

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NOTATIONS

The following are the symbols used in this paper:

Δt	Time interval (hr)
Φ	Φ-index (cm/hr)
F_v	Total abstractions during a storm period (cm)
F_{vA}	Total abstractions during a storm period (actual)
F_{vc}	Total abstractions during a storm period (predicted)
I_{ap}	Antecedent precipitation index (cm/day)
$p_n = 1, 2, \ldots$	Rainfall recorded on nth day preceding the storm (cm/day)
n	A variable
q_i	Initial flow at the gauging station (cm/hr)
r	Rainfall rate (cm/hr)
r_a	Average rainfall rate (cm/hr)
r_p	Maximum rainfall rate (cm/hr)
$r_1, r_2 \ldots$	Rainfall rate ordinates (cm/hr)
R_v	Total rainfall during a storm period (cm)
t_n	The time up to the beginning of nth Δt interval
T	Duration of rainfall (hr)
T_g	Time to the centre of area of precipitation (hr)

APPENDIX

Computation of abstractions during a storm of 14, July, 1971 over Pavanje river basin, by the proposed method. Illustrated in Fig. 13.

Data

i) Precipitation:

Time (hours):	0	1	2	3	4	5
Rainfall rate (cm/hr)	0.000	0.325	0.275	0.100	0.700	0.150
Time (hours):	6	7	8	9	10	11
Rainfall rate (cm/hr)	1.25	1.45	1.68	0.65	1.60	0.225

ii) Antecedent Precipitation:

Days before (n)	1	2	3	4	5	6	7	8	9	10
Rainfall (cm)	4.59	1.8	0.1	1.04	1.89	1.51	4.77	5.29	4.12	1.69

Computation of abstractions

Step 1: $$I_{ap} = \sum_{n=1}^{10} P_n/n = 7.54 \text{ cm/day}$$

$$R_v = 8.405 \text{ cm}$$

$$r_a = R_v/T = 8.405/11 = 0.764 \text{ cm/hr}$$

Step 2: $$T_g = \frac{\sum_{n=1}^{11} (r_n \cdot \triangle t)\,(t_n - \triangle t/2)}{R_v} = 6.55 \text{ hr}$$

Where r_n is the intensity of rainfall during the interval t_n and $t_n + \triangle t$.

Step 3: $$I_{ap}/r_a = 7.54/0.764 = 9.86$$

$$T_g/T = 6.55/11 = 0.595$$

Step 4: For $T_g/T = 0.595$ and $I_{ap}/r_a = 9.86$,

read $F_V/R_V = 0.578$ in Fig. 9

$F_V = 0.578 \times 8.405 = 4.865$ cm

The value of abstractions F_V computed from rainfall and runoff data is 4.819.

If the abstractions due to other causes are negligible, the total abstractions, F_V can be approximated to infiltration. This is indicated on the precipitation diagram in Fig. 13.

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