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REGIONAL MODEL FOR ANNUAL RUNOFF ESTIMATION

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PREFACE

The volumetric runoff refers to the volume of water available from a stream at a specified point over a specified period of time. Frequently the point of determination is the watershed outlet and the period of time a day or longer. For planners and water resources managers, the emphasis is on the volume of flow rather than the instantaneous discharge. Because of the complex nature of a natural basin, the direct physical or analytical approach to the determination of runoff is not feasible, and therefore empirical relations have to be developed through statistical analysis of measurable factors which are directly related to runoff phenomena. The parameters to be used depend upon the required accuracy, available data, and climatic conditions and to some extent, upon personal preference.

In India, generally longer series of hydrological data for several basins are not available, while for several other basins even shorter series data is not available. In most cases, project implementation require decision be taken with available data for the purpose of runoff computation. The problem of insufficient data necessitates development of regional models with fewer input parameters for estimating surface runoff. Keeping the above points in view, constrained linear and non-linear models with one parameter have been developed with sufficiently longer data series pertaining to the Saurashtra area of Gujarat. In addition a two-parameter linear model has also been developed for the region.

The report has been prepared by Mr. Rajan Vatsa, Scientist-B of the Surface Water Analysis and Modeling Division under the guidance of Mr. R. Mehrotra, Sceintist E and Head of the Division. I hope the report would of immense use to field engineers, water resources managers and planners of semi-arid regions.

K. S. Ramashastri
Director

ABSTRACT

Successful planning and implementation of water resources projects require reliable data on volumetric runoff. Given the financial constraints it is not feasible to have discharge stations in all the river basins of interest. Therefore regional rainfall runoff models are preferred. The utility of such models can be improved if rainfall – runoff models for different regions are developed with data specific to the regions. An attempt has been made in the present study to develop a seasonal rainfall – runoff model for the Saurashtra region and also parts of Narmada river basin. A constrained simple bivariate linear regression model, a constrained bivariate non-linear model and a multivariate linear regression model with hydro-meteorological data pertaining to 12 sub-basins of Saurashtra region have been developed. The efficiency of the models have been evaluated as 61%, 66% and 65% respectively. Considering the efficiency of the models discussed above, the bivariate non-linear model has a distinct advantage over the multivariate model as it requires only the rainfall data but has an efficiency comparable to that of the multivariate model that requires pan-evaporation data in addition to rainfall data.

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1.0 INTRODUCTION

The volumetric runoff refers to the volume of water available from a stream at a specified point over a specified period of time. Frequently the point of determination is the watershed outlet and the period of time a day or longer. The emphasis is on the volume of flow rather than the instantaneous discharge. Thus, water yield reflects a volumetric relationship between rainfall and runoff. Because of the complex nature of a natural basin, the direct physical or analytical approach to the determination of runoff is not feasible, and therefore empirical relations have to be developed through statistical analysis of measurable factors which are directly related to runoff phenomena. The parameters to be used depend upon the required accuracy, available data, and climatic conditions and to some extent, upon personal preference.

Determination of runoff from a basin is required for solution of a number of water resource problems such as:

(1) design of storage facilities,
(2) determination of minimum amount of water available for agricultural, industrial, or municipal use,
(3) estimation of future dependable water supply for power generation under varying patterns of rainfall,
(4) adjustment of long records of runoff for varying rainfall regimes for study of time trends in water yield,
(5) planning irrigation operation, and
(6) design of irrigation projects.

Many factors affect water yield depending upon its period of determination, some of which are interdependent. These factors can be classified as (1) meteorologic factors, (2) watershed factors, and (3) hydrogeologic factors. Space time distribution of precipitation amount, intensity and duration, and space-time distribution of temperature, humidity, sunshine and wind velocity are some of the most important meteorological factors. Some important watershed factors include surface vegetation, soil moisture, soil characteristics, surface topography and drainage density. Important hydrologeologic factors are hydraulic conductivity, location of water table, porosity, aquifer characteristics and geology of porous media.

In India, generally longer series of hydrological data for several basins are not available, while for several other basins even shorter series data is not available. In most cases, project implementation require decision be taken with available data for the purpose of runoff computation. The problem of insufficient data necessitates development of regional models with few input parameters for estimating surface runoff. Keeping the above points in view, constrained linear and non-linear models with one hydro-meteorological parameter have been developed with sufficiently longer data series pertaining to the Saurashtra area of Gujarat. In addition a two-parameter multiple-linear model has also been developed for the region. Different techniques have been adopted for the optimization of model parameters.

2.0 REVIEW

As noted previous section, volumetric runoff refers to the volume of water available from a stream at a specified point over a specified period of time. Thus, a volumetric relationship between rainfall and runoff may be expressed mathematically as:

$$V = \int_0^t Q(t)dt \tag{1}$$

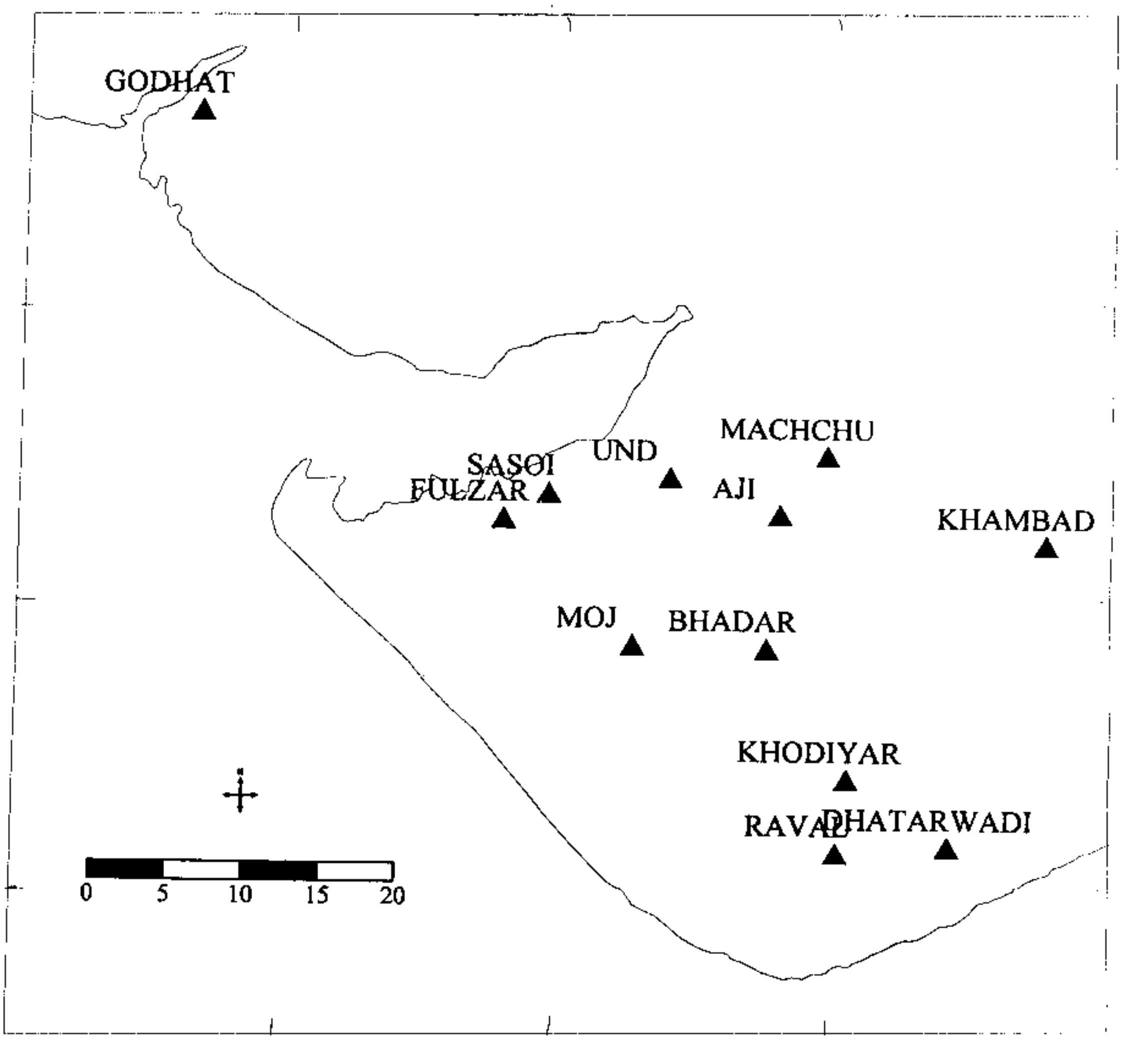
Where the time period is from 0 to t, Q is discharge and V water yield. The discharge Q is composed of surface runoff Q_S, interflow Q_I and base flow Q_G,

$$Q(t) = Q_S(t) + Q_I(t) + Q_G(t) \tag{2}$$

For determining the runoff from a basin, several models have been developed. Most of these models can be classified as (1) empirical, (2) conceptual, and (3) continuous-time simulation, as shown in Fig. 1. The models in the last category simulate the entire hydrologic cycle such as the Stanford watershed model (Crawford & Linsley, 1966) These models are greatly influenced by the selection of period for which the water yield is to be determined. Normally for larger time periods, the model is simpler. The time period of interest is equal to storm duration (storm-scale), a month or longer.

It may be more convenient to group water yield models according to their time basis as (1) Storm-scale volumetric rainfall-runoff models, (2) monthly volumetric rainfall-runoff models, and (3) seasonal/annual volumetric rainfall-runoff models.

Figure 1. Index map of the study area



The governing equation in all of these models is constituted by the volume balance for a given time period,

$$\Delta S = V_P - E - V_S - V_I - V_G \quad (3)$$

where, V_P represents precipitation, E actual evapotranspiration, V_S surface runoff, V_I interflow, V_G groundwater runoff, and ΔS change in storage.

2.1 Storm-scale volumetric rainfall - runoff models

A number of models have been developed to estimate direct runoff from storm rainfall (Kohler, 1963a, 1963b; Linsley, 1967; Singh, 1981). Some representative models are the Hamon model (Hamon, 1963), the S-D model (Singh and Dickinson, 1975a, 1975b), the multi-capacity accounting model (Kohler and Richards, 1962; Kohler, 1963a, 1963b), the Haan model (Haan, 1971, 1972), the SCS curve number model (Soil Conservation Service, 1964, 1975), the SCS-WL Model (Williams and LaSeur, 1976), and coaxial graphical correlation model (Linsley, Kohler and Paulhus, 1949, 1975; Kohler and Linsley, 1951). All of these models are conceptual. Only the coaxial graphical corrrelation model is empirical.

Except for the SCS curve number model, all other models require either measurements of or compute potential evaporation. The Hamon model (Hamon, 1961; Hartman, et al., 1960) and the multi-capacity accounting model (Kohler and Richards, 1962; Kohler, Nordenson and Fox, 1966) compute it from duration of sunshine and saturated vapor density; the remainder of the models require its measurements. Each model hypothesizes a soil moisture index at the beginning of a computational time step. The Hamon model defines an antecedent soil moisture index (AMI) which is equal to the amount of moisture in the selected upper horizons of the soil profile in excess of the amount existing under extreme drought conditions. The S-D model defines an AMI in terms of antecedent soil moisture deficiency which is obtained by using a soil moisture model (Singh, 1970, 1971; Singh and Dickinson, 1975b). The multi-capacity accounting model also defines AMI in terms of moisture deficiency. The SCS and SCS-WL models define it in terms of curve numbers derived from soil vegetation-land use complexes. All of these models estimate retained rainfall from AMI.

It is apparent that the above conceptual models have a great deal in common and follow a general scheme in their development. These models differ in their manner of considering the various hydrologic variables but not conceptually. All the conceptual models are relatively simple and are easy to apply if appropriate hydrologic data are available. The S-D model, the SCS model and the SCS-WL model can be usefully applied to water management as well as hydrologic modeling. The SCS-WL model has been applied to ungauged watersheds. The multi-capacity model is mode useful in flood forecasting. However, all of these models contain parameters that have little physical significance and are therefore not amenable to either direct measurement or estimation from physically measurable quantities. Consequently they have limited value for ungauged watersheds.

2.2 Monthly volumetric rainfall-runoff models

The problem of relating long-term volumes of rainfall and runoff is easier. Over longer periods of time the averaging of a variety of rainfall storms tends to minimize the effect of rainfall intensity and antecedent moisture conditions on the volumetric relationship. In many cases a simple plot may be adequate to define the relationship between annual volumes of rainfall and runoff if the water year is properly selected (Brakensiek, 1959).

Some representative monthly water yield models are the V-B model (Van Der Beken and Byloos, 1977), the Haan model (Haan, 1971, 1972) and the TVA model (Snyder, 1963). The governing equation of the first two models is equation (3). These two models are similar in structure. The TVA model is however based on different hypotheses. Although these models are simpler, the steps involved in computing monthly water yield are similar to those for computing daily water yield.

Both the Haan model and the V-B model compute actual evaporation based on the status of moisture storage in the upper soil profile. The V-B model uses an exponential function to transform potential evapotranspiration into actual evapotranspiration, whereas the Haan model uses a linear function. The V-B model subtracts actual evapotranspiration from precipitation to determine the effective precipitation. The Haan model does not calculate it explicitly. The V-B model computes the direct runoff as a linear function of the moisture storage and the effective precipitation. The Haan model computes infiltration and then subtracts it from precipitation to determine surface runoff. The V-B model as well as the Haan model compute return flow and add it to direct runoff to obtain total runoff. It is thus clear that these two models are similar and are comparable. Both contain parameters that need to be determined by optimization or experimentally.

The TVA model, on the other hand, is an analytical model. It partitions runoff into immediate runoff, delayed runoff and a time function. These components do not necessarily express physically measureable quantities. Each of these components is expressed as a linear function of pertinent variables. The resulting equation for streamflow contains 15 parameters, which must be determined by optimization. Because of the empirical nature of these parameters, this model is not suitable for application to ungauged basins.

2.3 Seasonal/annual volumetric rainfall-runoff models

Although equation (3) is equally valid for yearly water yield modeling, its much simpler form is more frequently utilised:

$$V_Q = V_P - E \tag{4}$$

where, V_Q is annual runoff volume, V_P annual mean areal precipitation, and E annual evaporation. This type of relationship has been used by several investigators (Sutcliffe and Rangeley, 1960; Pike, 1964; Marsh and Littlewood, 1978). The difference between annual rainfall and runoff in a watershed is principally comprised of evapotranspiration. Thus the key to determination of annual water yield is the accurate determination of annual evapotranspiration.

Ayers (1962) suggested that annual evaporation is approximatley half the annual precipitation in temperature and sub-humid regions. Several types of models have been proposed for estimating annual evapotranspiration (Pike, 1964; Solomon, 1967). The simplest of all is:

$$E = a\,V_P + b \tag{5}$$

where, a and b are coefficients estimated by regression analysis. Schreiber, referred to by Budyko (1948), suggested in 1904 the following relationship:

$$E = V_P \left[1 - \exp\left(-PE / V_P\right)\right] \tag{6}$$

where, PE is potential evaporation.

Another formula for determining E is the Kritzki and Menkel formula (Kritzki and Menkel, 1949) which employs saturation deficit instead of temperature,

$$E = V_P \left[1 - \frac{K}{\left(1 + \frac{d}{2}\right)3.5} \right] \tag{7}$$

where, K is a coefficient depending upon local conditions (K<1) and d saturation vapor pressure at the recorded air temperature and the actual vapor pressure. Employing Bouchet's concept of actual and potential evaporation (Boucher, 19673; Morton, 1965), Solomon (1967) derived on expression for computation of E.

These models do not incorporate seasonal differences in evaporation demands, which may deplete soil moisture storage. Consequently, there may be significant errors in estimation of actual evaporation and soil moisture. Therefore, Glasspoole (1960) suggested a multiple linear regression for water yield utilizing seasonal precipitation values,

$$V_Q = a_0 + a_1 V_{PS0} + a_2 V_{PW0} + a_3 V_{PS1} + a_4 V_{PW1} \qquad (8)$$

Where a_I, I = 0, 1, 2, 3 and 4 are regression coefficients, V_{PSI}, I = 0, 1, summer precipitation for the previous and current years, and V_{PWI}, I = 0, 1, winter precipitation for the previous and current years. Glasspoole (1960) applied it to the Thames River of England and was able to account of 92.9 percent of its variability. A similar study was conducted by Mustonen (1967) for Finnish watersheds which included fall, winter and summer precipitation, average annual temperature, potential evapo-transpiration in summer, frost depth, percentage of drainage area with coarse soils, volume of forest growing stock and change of soil moisture during water year in a multiple linear regression analysis to determine annual water yield. He found that 89 per cent of the flow variability was explained by his analysis.

Along similar lines, Haan and Read (1970) correlated mean annual runoff with mean annual precipitation and morphometric parameters such as watershed perimeter, and water relief ratio for small agricultural watersheds in Kentucky. The method explained 91% of variation in the mean annual runoff. On the other hand, Sutcliff and Carpenter (1967) used annual precipitation and elevation in their correlation study on a mountainous and semi-arid area in western Iran, where the method accounted for 66% of variation in the mean annual runoff. Wang and Huber (1967) estimated water yields in Utah by principal component analysis. Physiographic and topographic parameters were related to mean annual runoff of Utah watersheds. This study is an extension of the work done by Bagley Jeppson and Milligan (1964) and Jeppson (1960) and is applicable to ungauged watersheds. This and other statistical studies are similar in their construction.

2.4 Models for Indian river basins

Several empirical models and runoff tables that are specific to Indian basins, have been proposed by several hydrologists (Khosla, 1949; Narayana Pillai, 1964; Majumdar, 1965; Sehgal and Ghulati, 1969; Bhalerao et al., 1977; NIH, 1986).

Khosla (1949) proposed relationships for monthly and annual runoff and believed them to be of universal nature:

$$R = P - L \tag{9}$$

where, R represents mean annual runoff, P mean annual precipitation and L loss (all in units of inches).

$$L = X*T \tag{10}$$

where, X represents basin constant and T mean annual temperature in F. If the concurrent data of R, P and T are available for a few years, the value of x can be determined. It usually varies between 0.43 and 0.57 and can be taken as 0.50 when no data is available.

In the years that followed, several attempts have been made to modify the original formula proposed by Khosla with varying degree of success in obtaining better results (Panchang, 1954; Sehgal and Ghulati, 1967). However, Raja rao and Pentaiah (1971) found that neither the original Khosla formula nor the modified versions yielded results that are comparable with the observed runoff data in some river basins of Andhra Pradesh..

It is clear from the experience that such empirical formulae are not universally applicable and therefore volumetric runoff models have to be developed on a regional scale. Such models need not only be simpler but also sufficiently account for the variations in the runoff from the catchment. This can be achieved by developing constrained linear regression models with loss due to evaporation as one parameter.

3.0 STATEMENT OF THE PROBLEM

The objective of the study is to develop annual rainfall-runoff relationship for Saurashtra region and part of Narmada river basin. The study would provide annual volumetric rainfall – runoff relationship, which would be used in generating the long-term annual volumetric runoff values. The scope of the relationship has been extended for its application to ungauged catchments. The available records of data have been divided into two parts. First part of the records are considered as pertaining to gauged catchments and has been utilised in developing the regional annual rainfall - runoff relationship. The second part is considered as pertaining to ungauged catchments and has been utilised for testing the performance of the regional annual rainfall – runoff relationship developed.

4.0 METHODOLOGY

In the present study, regional models for estimating the seasonal volumetric runoff from the river basins located in the Saurashtra region have been developed. The models will be applicable to the rainfall data pertaining to the monsoon season (June to September).

The rainfall and runoff data for twelve sub-basins of Saurashtra regions have been used for the study. The average areal seasonal rainfall for each sub-basin has been estimated from the data pertaining to different raingauge stations by using the Thiesen Polygon method.

In all, three more models viz., bivariate linear type (equation 11), bivariate non-linear type (equation 12) and multi-variate linear type (equation 13) were attempted in the present work.

$$R = a*P \tag{11}$$

$$R = P^b \tag{12}$$

where, R = mean seasonal runoff (mm)

P = mean seasonal rainfall (mm)

a, b = regional parameters

$$R = a_1*P+a_2*AET+a_3 \tag{13}$$

Where, R = mean seasonal runoff (mm)

P = mean seasonal rainfall (mm)

AET = Seasonal evapotranspiration

a1,a2,a3= regional parameters

5.0 DATA AVAILABILITY

The monthly rainfall, runoff and pan evaporation data from twelve catchments in the Saurashtra region have been used in the present study. They are: Aji, Bhadar, Dhatarvadi, Fulzar, Godhat, Khambad, Kodiyar, Machchu, Moj, Raval, Sasoi and Und (Fig. 1). Since the daily pan evaporation data for some of the catchments were not available they have been substituted by those available for the nearest station. The stations for which the pan evaporation data are available are: Jamnagar, Junagarh, Bhuj, Rajkot and Kalavad. Missing daily values of pan evaporation data have been filled by using the mean julian day values for the corresponding station. The evapo-transpiration data has been estimated by multiplying the pan evaporation data with a ET – coefficient (Upadhyay, 1987). The monsoon seasonal (June to September) values of rainfall, observed runoff and pan evaporation data available for different time-periods and that have been used in different models in the present work are presented in Tables 1 to 12. The mean seasonal rainfall, evaporation, evapo-transpiration and observed runoff have shown in Figs 2 to 5.

Table 1. Monsoon seasonal hydrological data for Aji Irrigation Scheme.
All values in mm

Year	1958	1959	1960	1961	1962	1963	1964	1965	1966	1967
Rainfall	x	x	x	x	455.5	454.4	219.2	397.2	528.2	469.4
Runoff	x	x	x	x	216.3	141.8	66.1	73	153.4	126.7
Evaporatio	x	x	x	x	860	860	860	860	860	860
Year	1968	1969	1970	1971	1972	1973	1974	1975	1976	1977
Rainfall	348.1	481.2	518.9	263	1013.4	466	368.9	323.9	242.8	654.8
Runoff	30.9	123.2	201.1	23.4	472.8	120.8	37.2	32.6	71	201.8
Evaporatio	860	860	860	860	860	840	1140	840	800	800
Year	1978	1979	1980	1981	1982	1983	1984	1985	1986	1987
Rainfall	475.5	714.3	485.5	920.7	1012.6	783.3	251.8	577.7	550.2	117.3
Runoff	263.1	304.8	83.1	557	469.8	134.3	55.2	238.3	150.5	11.9
Evaporatio	750	890	750	860	900	780	810	860	920	1120
Year	1988	1989	1990	1991	1992	1993	1994	1995		
Rainfall	261.4	116.4	1179.4	472.4	472.2	x	x	x		
Runoff	44.9	11.2	577.2	107.6	120.5	x	x	x		
Evaporatio	830	770	950	900	890	x	x	x		

Table 2. Monsoon seasonal hydrological data for Bhadhar Irrigation Scheme. All values in mm.

Year	1958	1959	1960	1961	1962	1963	1964	1965	1966	1967
Rainfall	x	x	x	x	x	x	x	x	x	x
Runoff	x	x	x	x	x	x	x	x	x	x
Evaporati	x	x	x	x	x	x	x	x	x	x
Year	1968	1969	1970	1971	1972	1973	1974	1975	1976	1977
Rainfall	x	x	x	x	x	x	x	x	x	597.1
Runoff	x	x	x	x	x	x	x	x	x	101.8
Evaporati	x	x	x	x	x	x	x	x	x	820
Year	1978	1979	1980	1981	1982	1983	1984	1985	1986	1987
Rainfall	354.6	747.1	615.1	588.9	243.8	798.2	465.7	117	187.2	214.2
Runoff	71.2	281.2	215.1	153.3	56.4	231.6	104.9	15.7	19.7	33.8
Evaporati	990	910	910	910	910	910	910	910	910	910
Year	1988	1989	1990	1991	1992	1993	1994	1995		
Rainfall	891.2	543.5	351.2	x	x	x	x	x		
Runoff	296.8	139.9	65.8	x	x	x	x	x		
Evaporati	910	910	910	x	x	x	x	x		

Table 3. Monsoon seasonal hydrological data for Dhatarvadi Irrigation Scheme. All values in mm.

Year	1958	1959	1960	1961	1962	1963	1964	1965	1966	1967
Rainfall	x	x	x	x	x	x	x	x	x	x
Runoff	x	x	x	x	x	x	x	x	x	x
Evaporati	x	x	x	x	x	x	x	x	x	x
Year	1968	1969	1970	1971	1972	1973	1974	1975	1976	1977
Rainfall	x	x	x	x	x	x	x	x	x	489.9
Runoff	x	x	x	x	x	x	x	x	x	177.2
Evaporati	x	x	x	x	x	x	x	x	x	710
Year	1978	1979	1980	1981	1982	1983	1984	1985	1986	1987
Rainfall	388.4	407	407.4	386.3	352	904.4	381.7	176.3	317.3	188.5
Runoff	72.9	88.2	73	91.1	49.4	509.4	99.5	21.1	88.4	22.8
Evaporati	670	830	800	1000	1010	1000	1000	1000	590	1000
Year	1988	1989	1990	1991	1992	1993	1994	1995		
Rainfall	892.1	745.5	460.9	267.2	616.4	x	x	x		
Runoff	491.9	170.3	62.4	84.7	155.8	x	x	x		
Evaporati	810	640	700	660	1000	x	x	x		

Table 4. Monsoon seasonal hydrological data for Fulzar Irrigation Scheme. All values in mm.

Year	1958	1959	1960	1961	1962	1963	1964	1965	1966	1967
Rainfall	x	x	x	x	x	x	x	x	x	x
Runoff	x	x	x	x	x	x	x	x	x	x
Evaporati	x	x	x	x	x	x	x	x	x	x
Year	1968	1969	1970	1971	1972	1973	1974	1975	1976	1977
Rainfall	x	x	x	x	x	535.4	170.6	410.5	658.2	698
Runoff	x	x	x	x	x	177.51	12.1	49.01	179.8	149.4
Evaporati	x	x	x	x	x	920	1360	1010	1020	870
Year	1978	1979	1980	1981	1982	1983	1984	1985	1986	1987
Rainfall	379.6	943	622.1	658.2	219.9	832.8	493.5	206.3	403.4	55.4
Runoff	43.9	527.76	354.6	270.3	71.51	367.7	105.5	7.42	255.81	9.91
Evaporati	830	990	890	1040	1040	1040	1040	1040	1040	1040
Year	1988	1989	1990	1991	1992	1993	1994	1995		
Rainfall	854.2	530.6	304.2	250.6	x	x	x	x		
Runoff	161.6	119.8	38	17.71	x	x	x	x		
Evaporati	1040	1040	1040	1040	x	x	x	x		

Table 5. Monsoon seasonal hydrological data for Godhat Irrigation Scheme. All values in mm.

Year	1958	1959	1960	1961	1962	1963	1964	1965	1966	1967
Rainfall	x	x	x	x	x	x	x	x	x	x
Runoff	x	x	x	x	x	x	x	x	x	x
Evaporati	x	x	x	x	x	x	x	x	x	x
Year	1968	1969	1970	1971	1972	1973	1974	1975	1976	1977
Rainfall	x	x	x	x	x	x	x	x	x	x
Runoff	x	x	x	x	x	x	x	x	x	x
Evaporati	x	x	x	x	x	x	x	x	x	x
Year	1978	1979	1980	1981	1982	1983	1984	1985	1986	1987
Rainfall	x	x	x	x	84	181.5	155.5	97.8	84.7	517.7
Runoff	x	x	x	x	38.6	29.5	11.52	6	12.1	383.1
Evaporati	x	x	x	x	820	800	730	850	800	830
Year	1988	1989	1990	1991	1992	1993	1994	1995		
Rainfall	244.2	141.1	32.9	1041.7	x	x	x	x		
Runoff	70.5	23.5	1.8	612.3	x	x	x	x		
Evaporati	820	740	680	810	x	x	x	x		

Table 6. Monsoon seasonal hydrological data for Khambad Irrigation Scheme. All values in mm.

Year	1958	1959	1960	1961	1962	1963	1964	1965	1966	1967
Rainfall	x	x	x	x	x	x	x	x	x	x
Runoff	x	x	x	x	x	x	x	x	x	x
Evaporati	x	x	x	x	x	x	x	x	x	x
Year	1968	1969	1970	1971	1972	1973	1974	1975	1976	1977
Rainfall	x	x	x	x	x	x	x	x	x	x
Runoff	x	x	x	x	x	x	x	x	x	x
Evaporati	x	x	x	x	x	x	x	x	x	x
Year	1978	1979	1980	1981	1982	1983	1984	1985	1986	1987
Rainfall	x	x	x	x	x	x	x	x	x	292
Runoff	x	x	x	x	x	x	x	x	x	33.7
Evaporati	x	x	x	x	x	x	x	x	x	1120
Year	1988	1989	1990	1991	1992	1993	1994	1995		
Rainfall	744.7	587	416	192	634	x	x	x		
Runoff	190.1	75.9	45.63	6.9	138.7	x	x	x		
Evaporati	830	770	950	900	890	x	x	x		

Table 7. Monsoon seasonal hydrological data for Khodiyar Irrigation Scheme. All values in mm.

Year	1958	1959	1960	1961	1962	1963	1964	1965	1966	1967
Rainfall	x	x	x	x	x	x	x	x	x	x
Runoff	x	x	x	x	x	x	x	x	x	x
Evaporati	x	x	x	x	x	x	x	x	x	x
Year	1968	1969	1970	1971	1972	1973	1974	1975	1976	1977
Rainfall	465.1	306.3	508.9	543.1	145.3	664.4	319.5	320.8	686.9	551
Runoff	64.1	59.3	86.2	100.7	1.9	161.5	57.2	17	118.3	98.8
Evaporati	870	810	840	1000	1000	1000	1000	770	900	710
Year	1978	1979	1980	1981	1982	1983	1984	1985	1986	1987
Rainfall	398.7	589.8	739.4	376.8	345.5	1606.8	260.9	291.9	409.5	243.7
Runoff	76.9	182.3	209	21.16	52.92	698.96	11.89	21.82	38.33	8.57
Evaporati	670	830	800	1000	1010	1000	1000	1000	590	1000
Year	1988	1989	1990	1991	1992	1993	1994	1995		
Rainfall	1000.9	364.3	x	x	x	x	x	x		
Runoff	333.37	57.85	x	x	x	x	x	x		
Evaporati	810	640	x	x	x	x	x	x		

Table 8. Monsoon seasonal hydrological data for Machchu Irrigation Scheme. All values in mm.

Year	1958	1959	1960	1961	1962	1963	1964	1965	1966	1967
Rainfall	x	x	x	432.6	199.3	394	548	516.8	361.5	415.9
Runoff	x	x	x	53.67	20.54	57.02	75.93	101.15	52.34	128.48
Evaporati	x	x	x	860	860	860	860	860	860	860
Year	1968	1969	1970	1971	1972	1973	1974	1975	1976	1977
Rainfall	540.7	309.5	1097.1	512.8	314.6	305.5	208.8	652.8	696.4	694.1
Runoff	108.94	57.88	430.13	77.42	55.77	15.82	29.85	106.03	124.5	246.95
Evaporati	860	860	860	860	860	840	1140	840	800	800
Year	1978	1979	1980	1981	1982	1983	1984	1985	1986	1987
Rainfall	401.2	962.1	396.6	268.88	115.5	248.69	207.86	x	x	x
Runoff	27.58	703.26	101.94	138.79	17.98	144.64	73.69	x	x	x
Evaporati	750	890	750	860	900	780	810	x	x	x
Year	1988	1989	1990	1991	1992	1993	1994	1995		
Rainfall	1000.9	364.3	x	x	x	x	x	x		
Runoff	333.37	57.85	x	x	x	x	x	x		
Evaporati	810	640	x	x	x	x	x	x		

Table 9. Monsoon seasonal hydrological data for Moj Irrigation Scheme. All values in mm.

Year	1958	1959	1960	1961	1962	1963	1964	1965	1966	1967
Rainfall	x	x	403.6	1064.3	419.6	255	569.2	539.8	529.3	738.3
Runoff	x	x	119.5	250.7	103.1	36.4	150.5	156.5	144.3	144.6
Evaporati	x	x	910	910	910	910	910	910	910	910
Year	1968	1969	1970	1971	1972	1973	1974	1975	1976	1977
Rainfall	386.1	523.2	735.4	487.3	506.9	319	146.6	430.4	617.1	506.6
Runoff	63.6	202.4	270.4	96.3	97.3	40.1	31.8	101.9	186.6	148.3
Evaporati	910	910	990	910	910	910	910	910	830	820
Year	1978	1979	1980	1981	1982	1983	1984	1985	1986	1987
Rainfall	381.2	1361.7	990.4	1168.1	609.9	837.2	494.4	265.5	406.2	344.2
Runoff	64.9	534	385.9	271.3	190.8	352.8	46.8	31.2	35	64.8
Evaporati	990	910	910	910	910	910	910	910	910	910
Year	1988	1989	1990	1991	1992	1993	1994	1995		
Rainfall	891.8	602.9	x	x	x	x	x	x		
Runoff	222.8	101.1	x	x	x	x	x	x		
Evaporati	910	910	x	x	x	x	x	x		

Table 10. Monsoon seasonal hydrological data for Raval Irrigation Scheme. All values in mm.

Year	1958	1959	1960	1961	1962	1963	1964	1965	1966	1967
Rainfall	x	x	x	x	x	x	x	x	x	x
Runoff	x	x	x	x	x	x	x	x	x	x
Evaporati	x	x	x	x	x	x	x	x	x	x
Year	1968	1969	1970	1971	1972	1973	1974	1975	1976	1977
Rainfall	x	x	x	x	x	x	x	x	x	755.4
Runoff	x	x	x	x	x	x	x	x	x	288.9
Evaporati	x	x	x	x	x	x	x	x	x	710
Year	1978	1979	1980	1981	1982	1983	1984	1985	1986	1987
Rainfall	542.1	827.4	798.6	609.3	379.1	1146.5	505	417.8	427.7	212.8
Runoff	160.4	253.7	316.4	92.1	47.1	501.1	31.5	101.1	56.6	19.4
Evaporati	670	830	800	1000	1010	1000	1000	1000	590	1000
Year	1988	1989	1990	1991	1992	1993	1994	1995		
Rainfall	945.9	357.5	416.6	345.8	675.7	463.5	1214.5	595.6		
Runoff	423.4	57.2	17.4	13.4	122.3	45.6	870.9	195.3		
Evaporati	810	640	700	660	1000	1000	1000	810		

Table 11. Monsoon seasonal hydrological data for Sasoi Irrigation Scheme. All values in mm.

Year	1958	1959	1960	1961	1962	1963	1964	1965	1966	1967
Rainfall	387.5	663	432.1	1028.8	668.4	264.9	576.6	386.6	250.7	769.6
Runoff	65.5	319.9	132.9	415.2	138.1	30.6	156.4	72.7	64.8	119.2
Evaporati	1040	1040	1040	1030	1180	1270	940	1110	1350	940
Year	1968	1969	1970	1971	1972	1973	1974	1975	1976	1977
Rainfall	368.9	380	652.9	488.7	216.4	398.8	197.4	699.9	487.2	519.8
Runoff	150	109.2	180	85.6	54.2	47	11.4	115.9	88.4	128.7
Evaporati	1100	1070	920	920	1080	920	1360	1010	1020	870
Year	1978	1979	1980	1981	1982	1983	1984	1985	1986	1987
Rainfall	453.6	1197.7	792.1	780.3	487.2	997.4	641.2	167.6	254	66.2
Runoff	54.9	251.9	188.3	273.4	145.3	523.4	128.3	16.5	104.1	7
Evaporati	830	990	890	1040	1040	1040	1040	1040	1040	1040
Year	1988	1989	1990	1991	1992	1993	1994	1995		
Rainfall	805.3	517.5	308.3	265.6	538.9	x	x	x		
Runoff	242.7	79.3	44.8	28	99.5	x	x	x		
Evaporati	1040	1040	1040	1040	1040	x	x	x		

Table 12. Monsoon seasonal hydrological data for Und Irrigation Scheme. All values in mm.

Year	1958	1959	1960	1961	1962	1963	1964	1965	1966	1967
Rainfall	x	x	447.8	807.7	255.2	245.6	483	469.4	338	593.8
Runoff	x	x	10.76	39.72	3.03	2.84	12.72	11.97	5.77	20.1
Evaporati	x	x	860	860	860	860	860	860	860	860
Year	1968	1969	1970	1971	1972	1973	1974	1975	1976	1977
Rainfall	465.6	439.4	775.2	610.3	264.1	264.5	116.5	638.7	719.5	523.2
Runoff	11.74	10.32	36.26	21.35	3.35	3.35	0.55	23.62	30.74	15.2
Evaporati	860	860	860	860	860	840	1140	840	800	800
Year	1978	1979	1980	1981	1982	1983	1984	1985	1986	1987
Rainfall	623.2	1420.6	810.1	823.2	577	748.1	397.9	123.6	217.9	106.7
Runoff	22.37	130.64	39.98	41.31	18.87	33.51	8.31	0.63	2.2	0.45
Evaporati	750	890	750	860	900	780	810	860	920	1120
Year	1988	1989	1990	1991	1992	1993	1994	1995		
Rainfall	878.1	479	x	x	x	x	x	x		
Runoff	47.78	12.49	x	x	x	x	x	x		
Evaporati	830	770	x	x	x	x	x	x		

Figure 2. Map showing mean seasonal rainfall characteristics in the study area

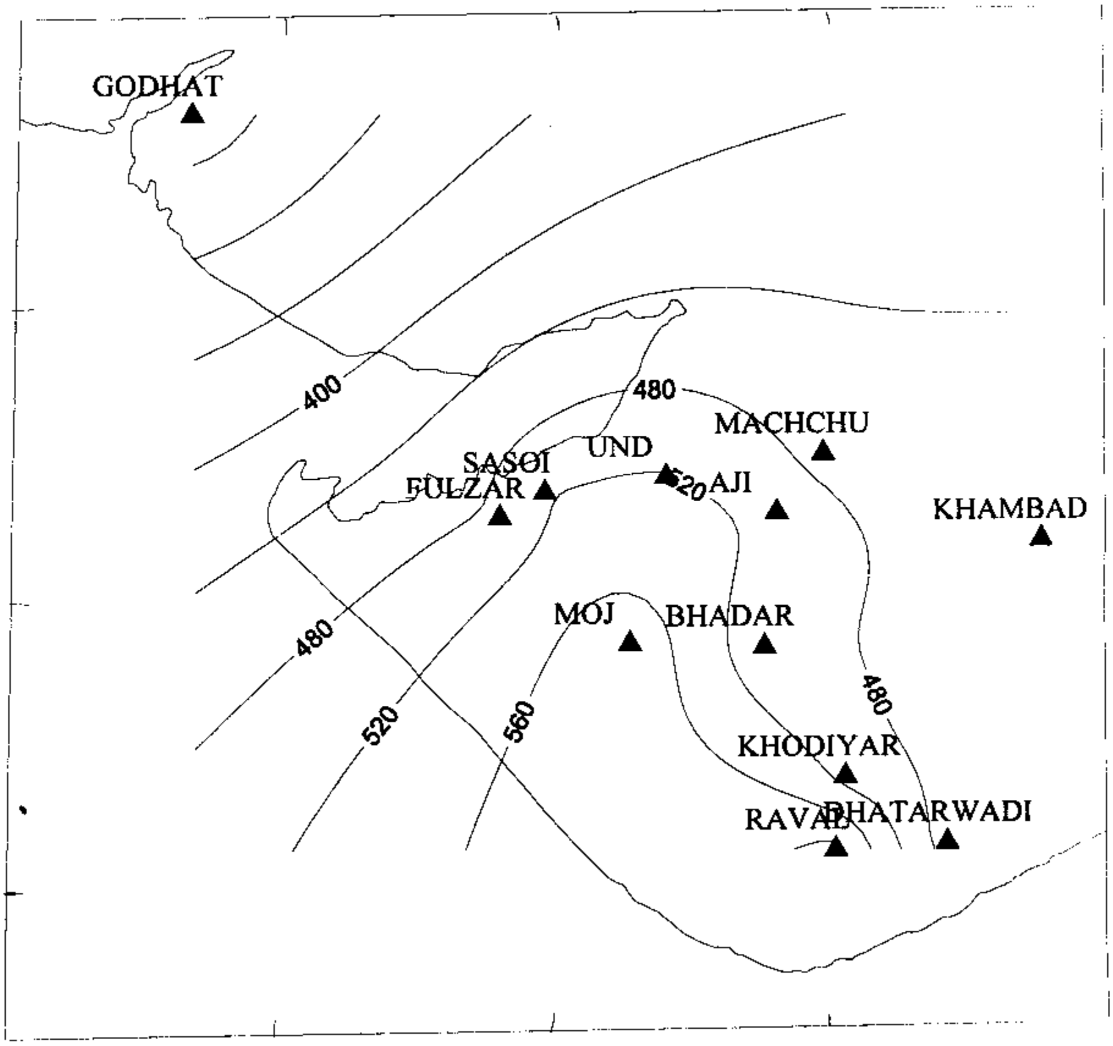


Figure 3. Map showing mean seasonal pan evaporation in the study area

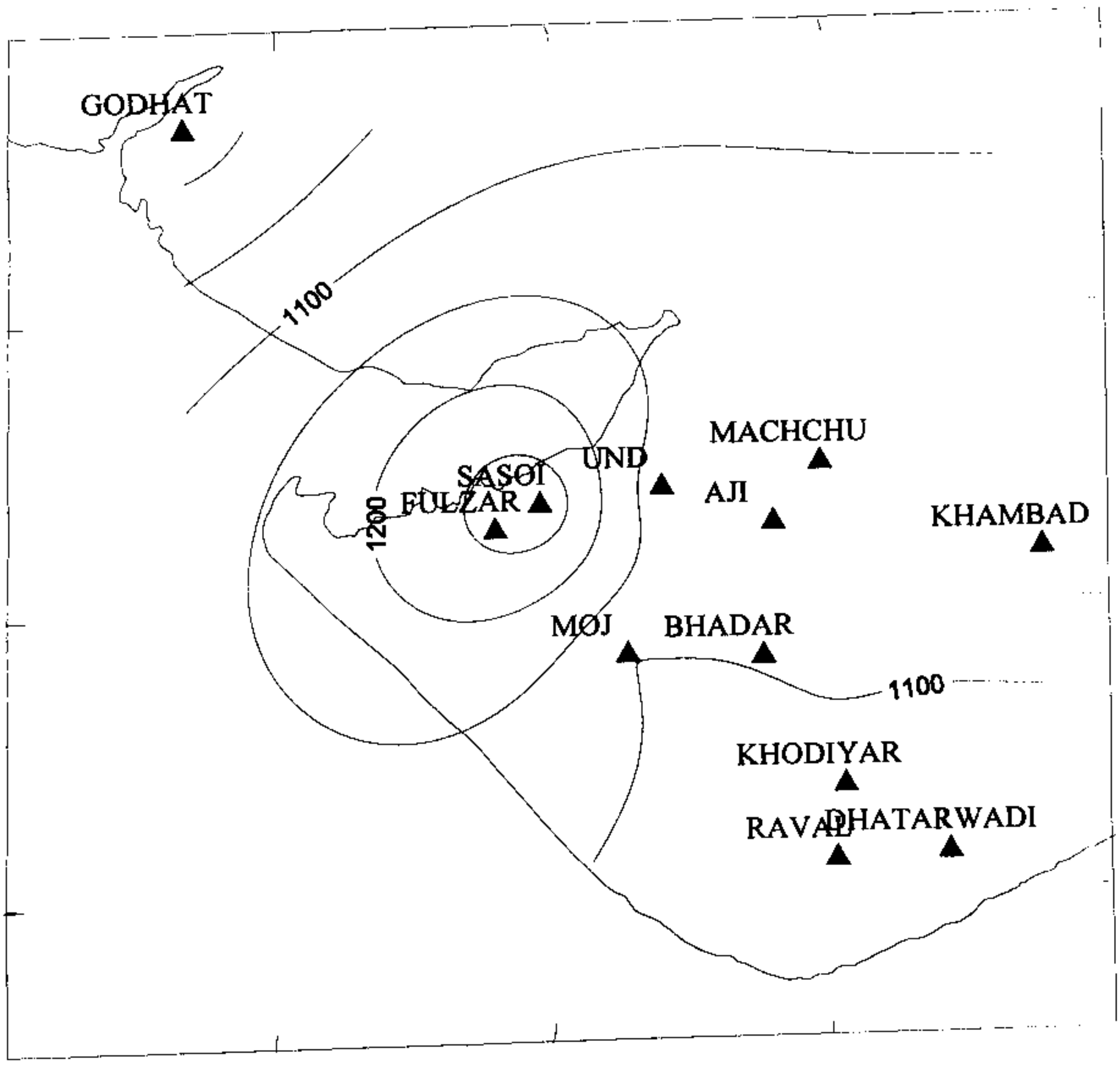


Figure 4. Map showing mean seasonal actual evapo-transpiration in the study area

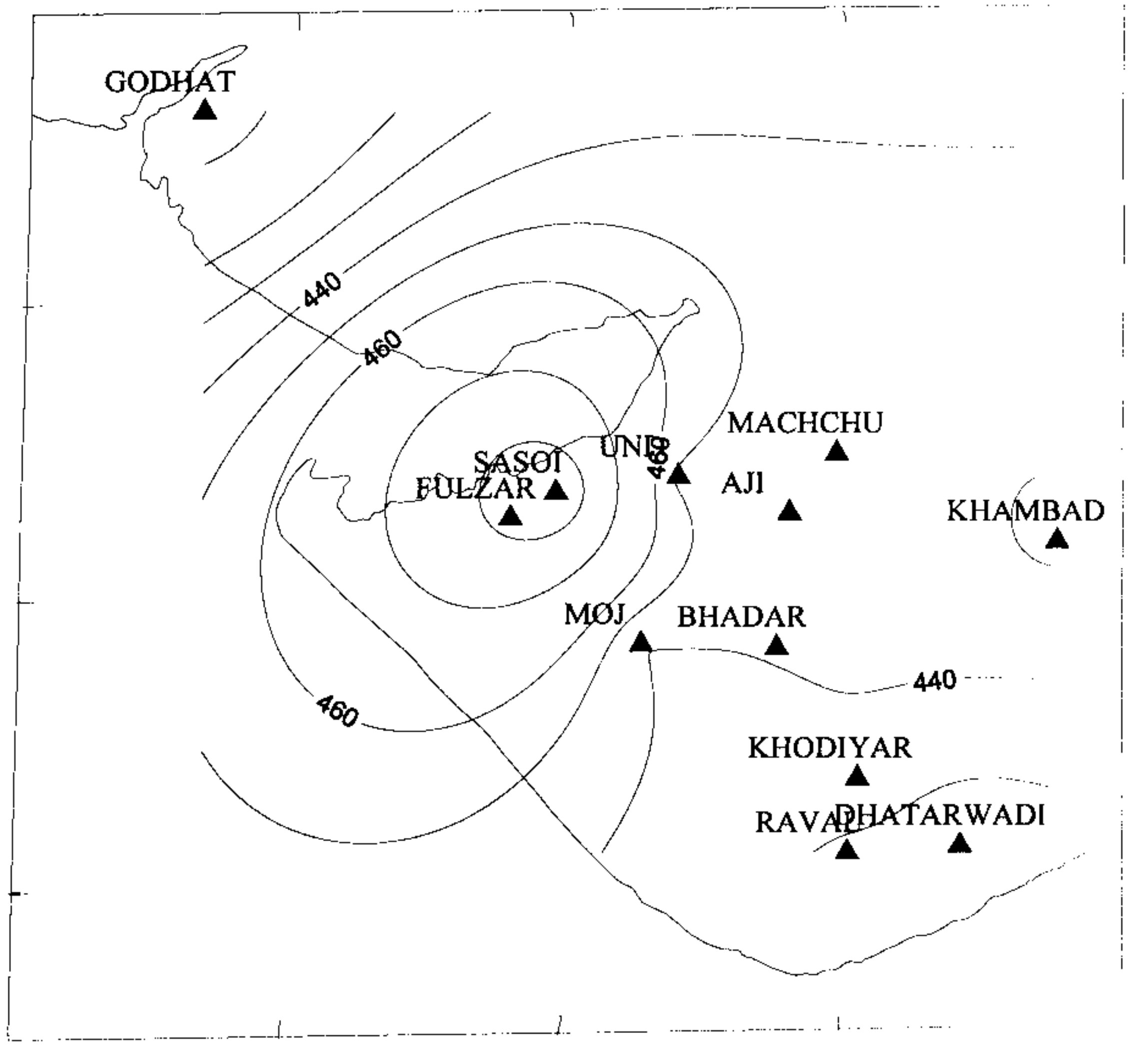
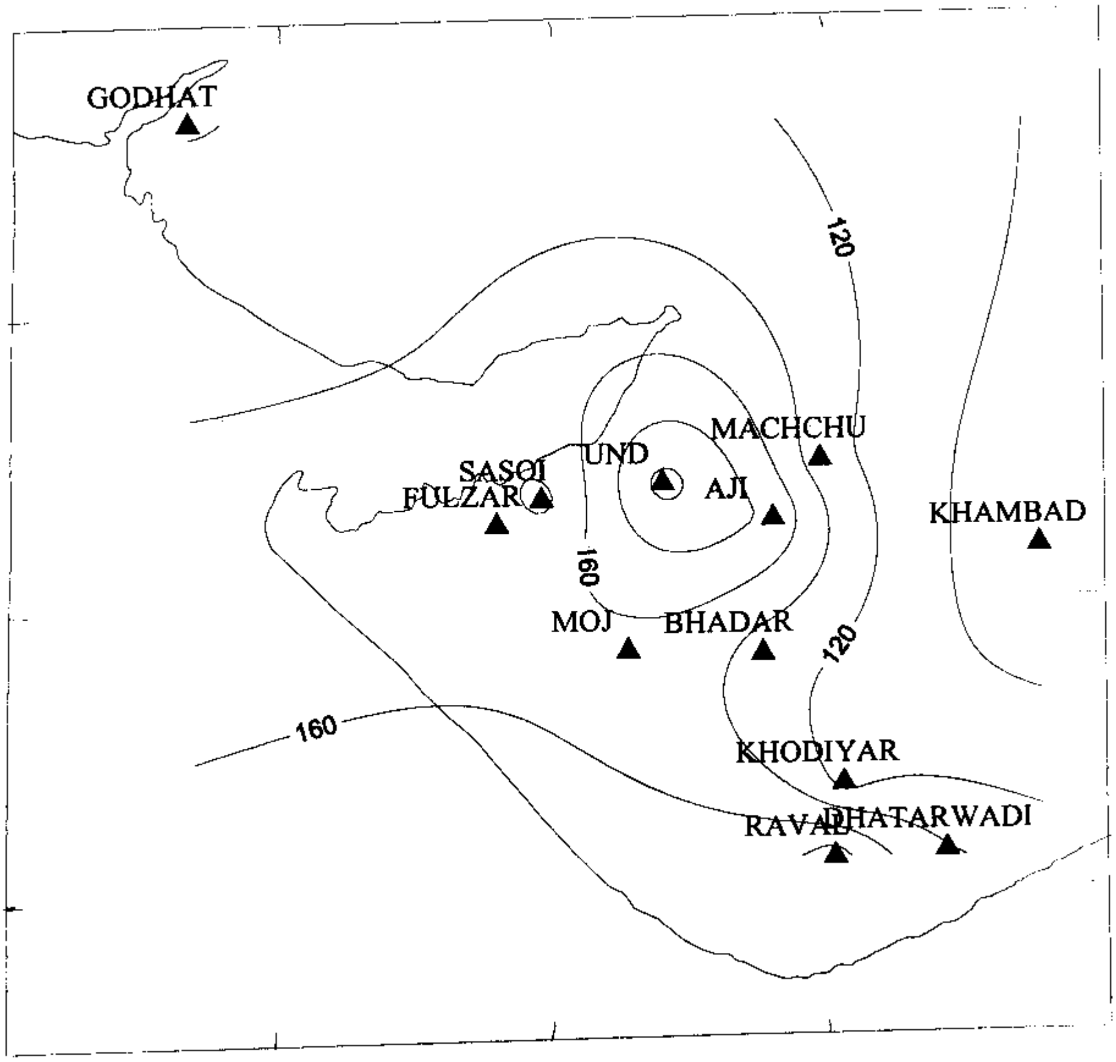


Figure 5. Map showing mean seasonal runoff characteristics in the study area



6.0 RESULTS AND DISCUSSION

As described in Section 4.0, three different models have been used in the present study. In the first model viz. the bi-variate linear model the seasonal values of different catchments have been regressed to obtain the regression parameter, a by optimisation. The arithmetic mean value (0.34) of regression parameter for all the catchments has been taken as the regional parameter. The model was validated using the regional parameter and the efficiency of the model has been evaluated using standard procedures. The results of the model are presented in Table 13, where in the values of regression parameter of the individual catchments and the regional parameter, and the efficiency of the bivariate linear model are presented. The variations in observed and computed run-off are shown in Fig. 6.

In the Second model viz. the bi-variate non-linear model the seasonal values of different catchments have been regressed to obtain the regression parameter, b, by optimisation. The arithmetic mean value (0.757) of regression parameter for all the catchments has been taken as the regional parameter. The model vas validated using the regional parameter and the efficiency of the model has been evaluated using standard procedures. The results of the model are presented in Table 14, where in the values of regression parameter of the individual catchments and the regional parameter, and the efficiency of the bivariate non-linear model are presented. The observed and computed run-off are shown in Fig. 7.

The third model which is a the multi-variate non-linear model uses the seasonal values of different catchments by regression of observed runoff as independent variable and rainfall and evapotranspiration as dependent variables. In this case all the available data for

Table 13a. Results of bivariate linear model- Calibration

	Parameter value	Efficiency	Rainfall	Observed runoff	Computed runoff
		%	mm	mm	mm
Aji	0.39	73.3	512.4	177.2	199.9
Bhadar	0.28	83.2	490.1	130.2	139.7
Dhatarvadi	0.36	64.7	461.3	141.1	166.1
Flzar	0.34	60.2	485.6	153.7	167.5
Godhat	0.57	91.9	258.1	118.9	148.4
Khambad	0.19	73.5	477.6	81.8	90.8
Kodiyar	0.26	84.5	506.3	112.6	139.4
Machchu	0.31	49.0	464.8	127.7	146.4
Moj	0.28	75.3	584.4	154.9	166.6
Raval	0.38	61.5	612.5	190.2	232.7
Sasoi	0.27	62.6	517.5	133.5	142.3
Und	0.49	68.4	522.1	207.3	255.8
Average	0.34	70.7	491.1	144.1	166.3

Table 13b. Results of bivariate linear model- Validation

	Parameter value	Efficiency	Rainfall	Observed runoff	Computed runoff
		%	mm	mm	mm
Aji	0.34	69.8	512.4	177.2	174.2
Bhadar	0.34	72.9	490.1	130.2	166.6
Dhatarvadi	0.34	64.3	461.3	141.1	156.9
Flzar	0.34	60.1	485.6	153.7	165.1
Godhat	0.34	70.6	258.1	118.9	87.8
Khambad	0.34	40.5	477.6	81.8	162.4
Kodiyar	0.34	75.6	506.3	112.6	176.9
Machchu	0.34	48.4	464.8	127.7	158.0
Moj	0.34	66.2	584.4	154.9	198.7
Raval	0.34	60.1	612.5	190.2	208.2
Sasoi	0.34	52.0	517.5	133.5	175.9
Und	0.34	55.2	522.1	207.3	177.5
Average	0.34	61.3	491.1	144.1	167.4

Figure 6. Comparison of observed and computed mean runoff using the bivariate - linear model

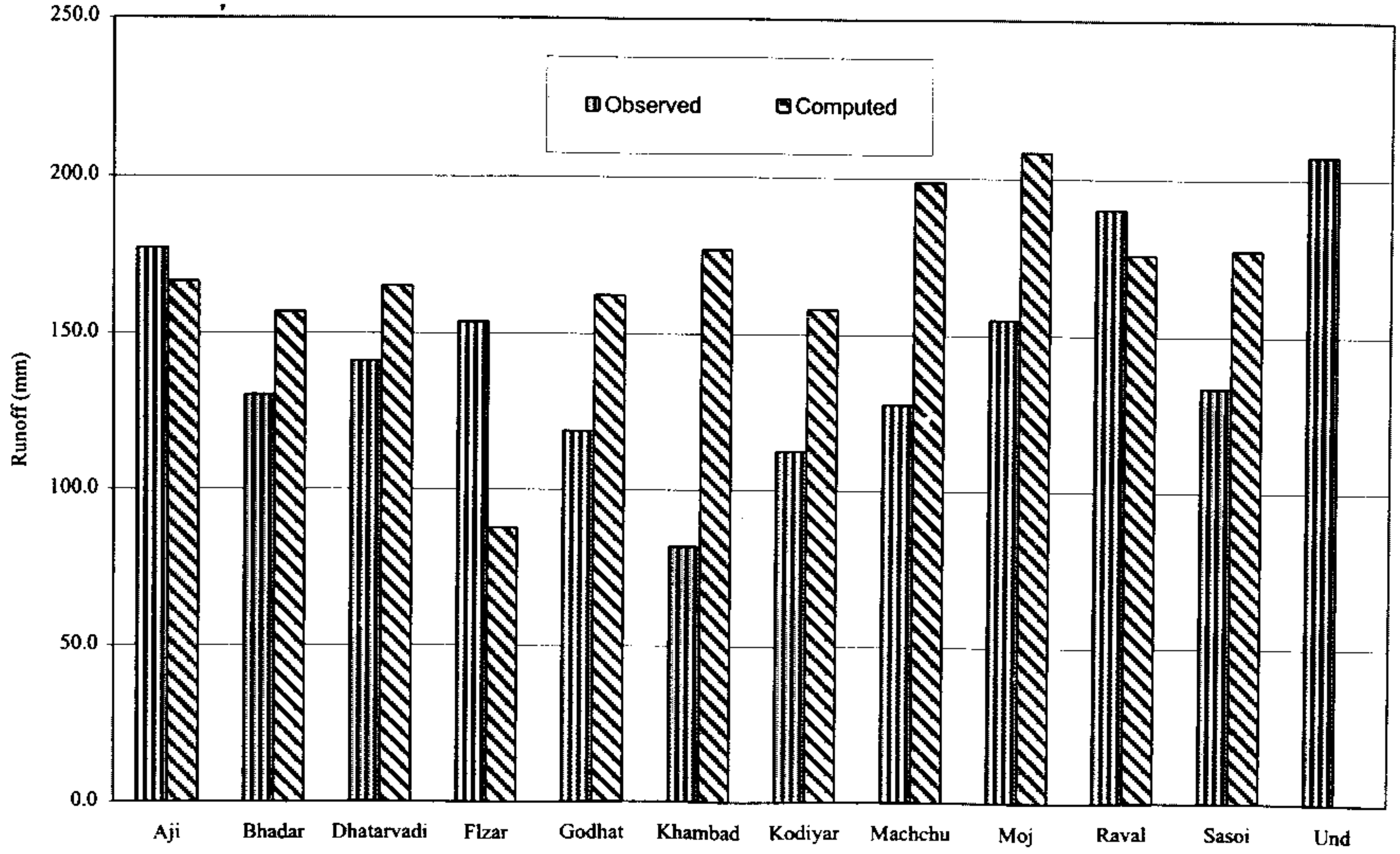
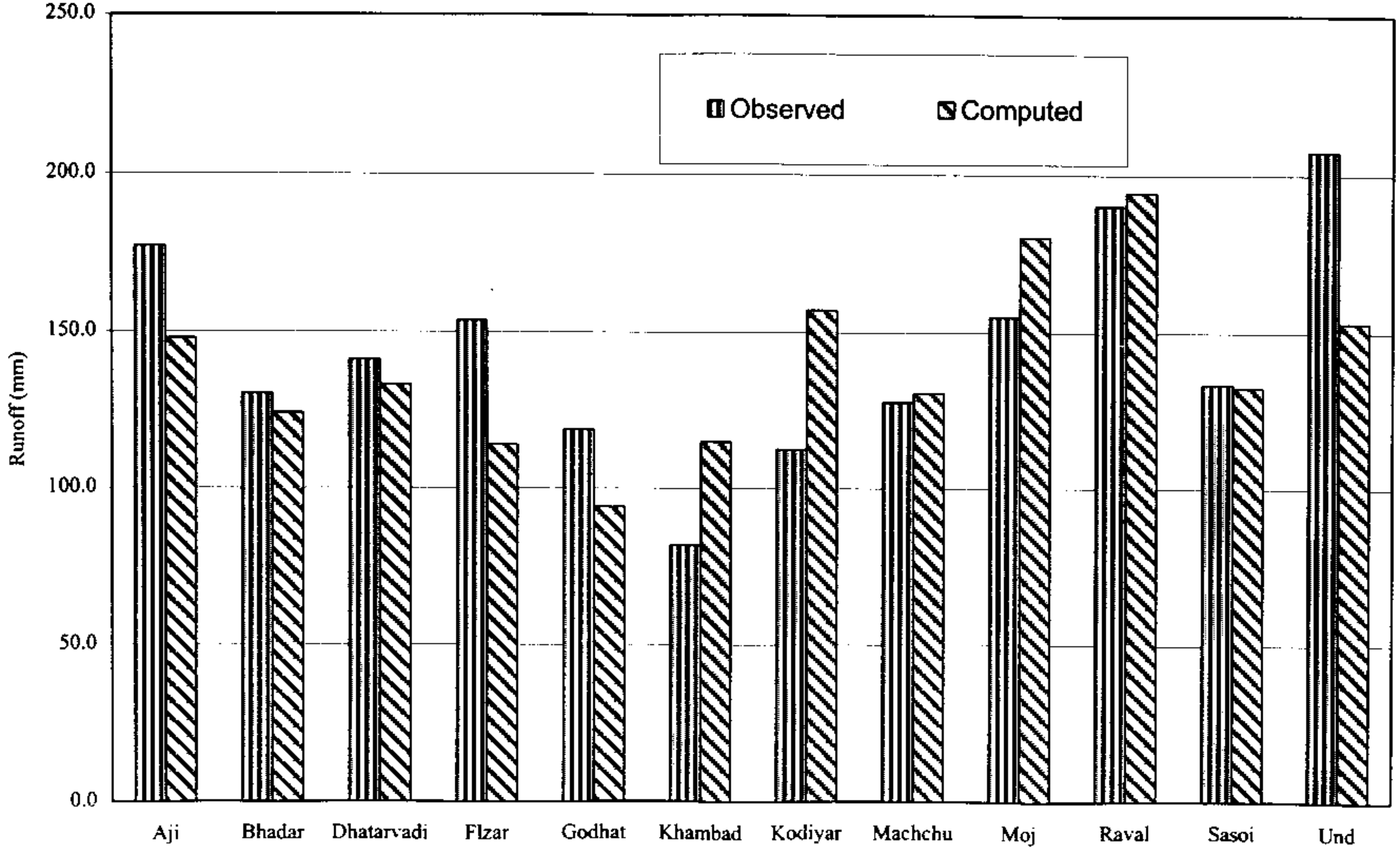


Table 14a. Results of bivariate non-linear model- Calibration					
	Parameter valu	Efficiency	Rainfall	Observed runoff	Computed runoff
		%	mm	mm	mm
Aji	0.80	82.6	512.4	177.2	183.8
Bhadar	0.77	83.6	490.1	130.2	137.1
Dhatarvadi	0.76	74.2	461.3	141.1	148.7
Flzar	0.82	66.4	485.6	153.7	164.8
Godhat	0.90	90.1	258.1	118.9	148.5
Khambad	0.61	83.7	477.6	81.8	84.3
Kodiyar	0.73	93.6	506.3	112.6	121.6
Machchu	0.73	70.6	464.8	127.7	126.9
Moj	0.80	71.4	584.4	154.9	175.0
Raval	0.65	89.4	612.5	190.2	194.5
Sasoi	0.81	56.2	517.5	133.5	150.0
Und	0.74	94.5	522.1	207.3	211.8
Average	0.76	79.7	491.1	144.1	153.9

Table 14b. Results of bivariate non-linear model- Validation					
	Parameter valu	Efficiency	Rainfall	Observed runoff	Computed runoff
		%	mm	mm	mm
Aji	0.76	76.2	512.4	177.2	147.9
Bhadar	0.76	80.7	490.1	130.2	124.1
Dhatarvadi	0.76	67.1	461.3	141.1	133.1
Flzar	0.76	48.7	485.6	153.7	114.1
Godhat	0.76	78.3	258.1	118.9	94.2
Khambad	0.76	62.4	477.6	81.8	115.0
Kodiyar	0.76	72.8	506.3	112.6	157.1
Machchu	0.76	69.3	464.8	127.7	130.7
Moj	0.76	26.1	584.4	154.9	180.2
Raval	0.76	84.1	612.5	190.2	194.5
Sasoi	0.76	46.5	517.5	133.5	132.5
Und	0.76	78.8	522.1	207.3	153.1
Average	0.76	65.9	491.1	144.1	139.7

Figure 7. Comparison of observed and computed mean runoff using the bivariate non-linear model



all the stations, but for the last three available years for each catchment, have been considered together to estimate the regression parameters. This approach enables direct estimation of the regional parameters. In addition to this the remaining data have been used for validation of the model.

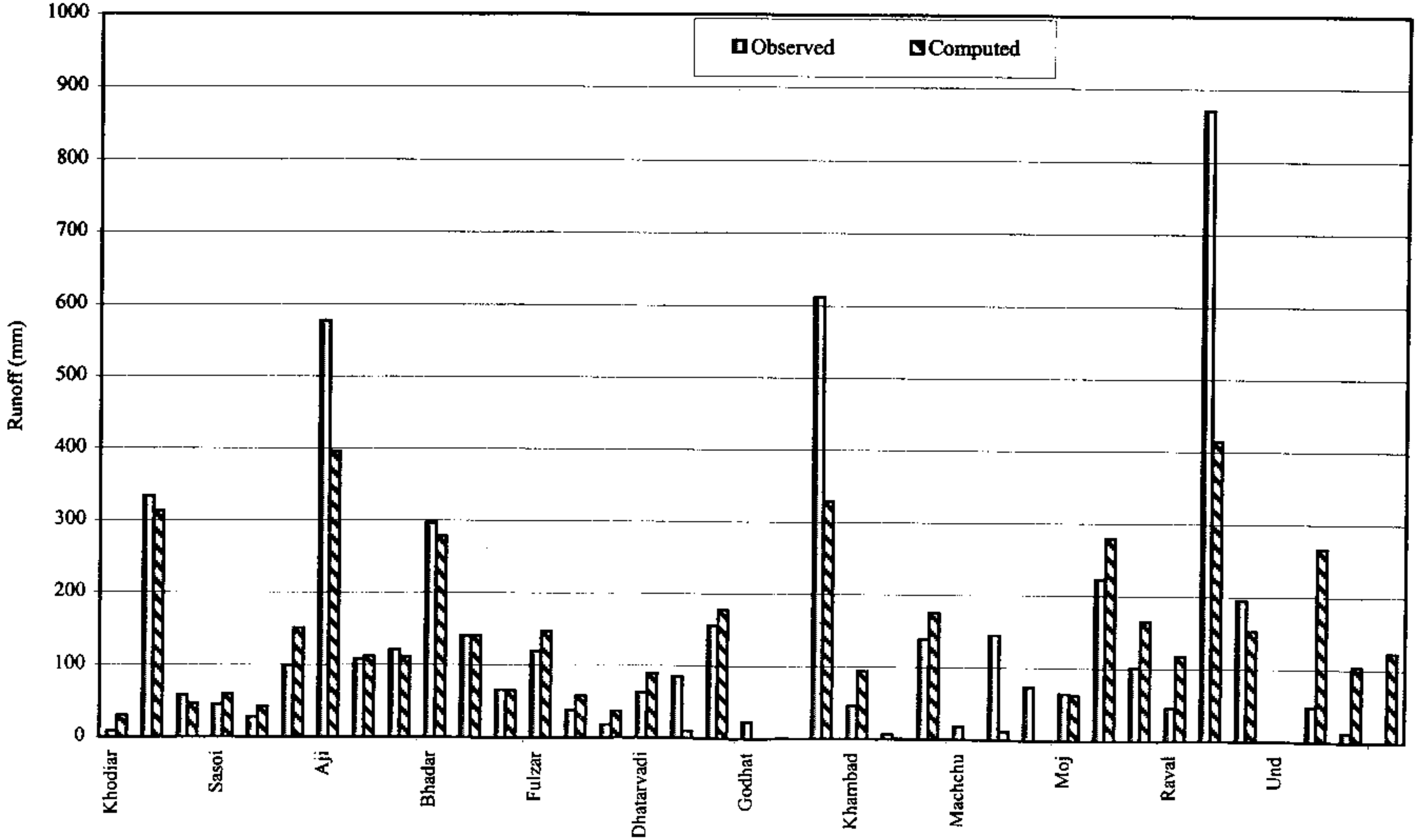
The evapo-transpiration has been estimated by optimising the pan-coefficient such as to get maximum correlation between the observed runoff values and the difference of the rainfall and estimated evapotranspiration values. The value thus derived is well within the range of pan – coefficient values by Upadhyay (1987). The results of the model are presented in Table 15, where in the values of regression parameters and the efficiency of the model are presented.

Table 15. Average values of the hydro-meteorological parameters used in the multivariate linear model along with the computed values, number of observations and efficiency of the model.

	Average Observed runoff (mm)	Average rainfall (mm)	Average ET (mm)	Average computed runoff (mm)	Efficiency (%)	Number of observations
Calibration	126.7	507.2	363.7	128.5	60.24	220
Validation	138.5	490.8	358.1	123.3	65.44	36

Fig. 8 shows the plot of observed runoff and that computed using the multi-variate model.

Figure 8. Comparison of observed and computed runoff using multivariate linear model



7.0 CONCLUSIONS

Three different volumetric runoff models for Saurashtra region of Gujarat have been developed. They are bivariate linear type, bivariate non-linear type and a multivariate linear type. These models have been developed using available long term hydrological and meteorological records pertaining to 12 catchments in the Saurashtra region.

The first model viz., the bivariate linear model of the type R = a.P (where, a=0.34), has the model efficiency ranging from 48.4% to 75.6% for different catchments in the region. The average efficiency is about 61.3% during validation. The second one viz., the bivariate non-linear model of the type $R=P^b$ (where, b=0.757) has the model efficiency ranging from 46.5% to 80.7% for different catchments in the region. The average efficiency is about 65.9% during validation. The third model, viz. the multivariate model of the form R=a.P+b.ET+c (where, a=0.3954, b=0.2237 and c=-155.5) has been developed by considering all the data pertaining to 12 catchments in the region as one unit. The efficiency is about 65.4% during validation.

Considering the efficiency of the models discussed above, the bivariate non-linear model has a distinct advantage over the multivariate model as it requires only the rainfall data but has an efficiency comparable to that of the multivariate model that requires pan-evaporation data in addition to rainfall data.

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