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COMPARISON OF MONTHLY RAINFALL-RUNOFF MODELS

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Preface

The term 'modelling of hydrologic system' is usually indicated to mean the application of mathematical and logical expressions which define the quantitative relationships between the flow characteristics and flow forming factors.

Models can be classified in different ways. Conceptual models are very efficient computationally and pose very small computational requirements in terms of computer CPU time and memory. Many conceptual models can be easily run on a personal computer. In spite of some limitations these models are incresengly used in hydrology for various purposes.

Monthly rainfall-runoff models (or water balance models) are useful tools in the hands of engineers in charge of water resources projects. Such models are helpful in computing forecasts and in generation arbitrarily long runoff series. The latter can be used to estimate return periods of relatively rare hydrological events such as droughts.

In this report, prepared by Sh. R. Mehrotra, Scientist of the Institute, structures of some of the currently available rainfall-runoff models are discussed and tested on some of the catchments.

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ABSTRACT

The present report summarizes about hydrologic models, their classifications and stages involved in hydrologic modelling, covering conceptual modelling in detail. Structures of some of the most commonly used hydrologic conceptual models of monthly time scale are discussed and tested on some of the catchments of Central and Western India lying in arid, semi-arid, humid and sub-humid agro-climatic zones. Study indicates that a water balance type model can reproduce catchment behaviour in a better manner as compared to a statistical model. Also, 2-5 parameters in a model are sufficient to represent the rainfall-runoff relationship of a catchment on a monthly scale. Efficiency of a model is found directly proportional to the runoff factor of the catchment. Report also discusses development and performance of a regional conceptual model developed for these regions.

1.1 Hydrologic modelling

The hydrologic behavior of catchment is a very complicated phenomenon which is controlled by an unknown large number of climatic and physiographic factors that vary with both time and space. The basic problem in hydrology is the establishment of relationships between rainfall and runoff. The application of system concept has led to studies in hydrology using deterministic, probabilistic and stochastic approaches to deal with problems of hydrological analysis, simulation and synthesis. A hydrologic model is a simplified description of the hydrologic cycle. During the last three decades, advancements in computers and analysis techniques have led to significant developments and application of mathematical and conceptual models in hydrology.

Hydrologic models are required not only for deciding about water yields or design parameters, but also for understanding and evaluating effects of developmental and other activities on hydrological regime of river basins. For comprehensive planning of water resources projects besides data in respect of various uses, adequate hydrological information is necessary. The use of modelling approach can provide such information and could also incorporate scenarios of proposed/ likely land use changes in the river basin for use in planning/ operation of water resources projects.

Hydrological models can be classified in different ways. Broadly many of the models presented in the literature can be divided into deterministic and stochastic categories. A deterministic model is one in which the processes are modelled based on definite physical laws and no uncertainties in prediction are admitted. It has no component with stochastic behavior i.e. the variables are free from random variation and have no distribution in probability. Deterministic models can be further classified according to whether the model gives a spatially lumped or distributed description of the catchment area, and whether the description of the hydrological processes is empirical, conceptual or fully physically based.

Another classification of stream flow models is : (i) Event based stream flow simulation models, and (ii) Continuous stream flow simulation Models (CSS). The event based stream flow simulation models are applied to simulate the flood events. On the other hand, continuous stream flow simulation (CSS) models are capable of providing the continuous output of stream flow generally at daily interval. An extensive listing of types of the CSS models and event based models is given by V. P Singh (1989). Since the development of the famous Stanford Watershed Model (SWM-IV) (Crawford and Linsley, 1966), numerous CSS models have been developed for particular purposes; many of them are variants of the SWM.

The familiar classification of models is to classify them in three categories : a) Black box models, b) Lumped models and, c) Physically based models.

The physically based models are based on our understanding of the physics of the hydrological processes which control the catchment response and use physically based equations to describe these processes. Also, these models are spatially distributed since the equations from which they are formed generally involve one or more space coordinates. Such models require much of computational time and also require advance computers as well as a broad data base. As a result of this, the use of these models for real-time forecasting has not reached the 'production stage' so far, particularly for data availability situations prevalent in developing countries like India.

The conceptual model approach to rainfall-runoff modelling lies intermediate between physically based models and black box models. Generally, the term "conceptual" is used to describe models which rely on a simple arrangement of a relatively small number of interlinked conceptual elements, each representing a segment of the land phase of the hydrological cycle. Besides simplifications in the representation of hydrologic processes, temporal as well as spatial lumping of these processes is often considered in the analysis for sake of simplicity and/or because of limited data availability. In spatial lumping, catchment is regarded as one unit. The inputs, variables and parameters represent average values for the whole catchment. In temporal lumping, various hydrological processes may be lumped in different time frame such as a minute, hour, month, season or a year, depending upon the requirement or availability of data.

Field of applicability of different deterministic simulation model Empirical (black box) models are mainly of interest as single event models or as sub components of more complicated models. Lumped, conceptual models are especially well suited to simulation of the rainfall-runoff process when hydrological time series sufficiently long for a model calibration exist. Thus typical fields of application are : Extension of short term records based on long rainfall records. Real time rainfall -runoff simulation i.e flood forecasting.

Other fields of possible application, to which the lumped conceptual models are not especially well suited, but where they can be used if no better model or method is available, are : prediction of runoff from ungauged catchment, general water balance studies, availability of groundwater resources, irrigation needs and, analyses of variation in water availability due to climatic variability, etc.

It is not surprising that most of the existing catchment models currently in use are lumped parameters models because of limited data requirements, less CPU time and memory in terms of computer and simplified description of various processes.

1.2 Literature review

Hydrologic simulations models of catchment based on physical and mathematical concepts have been developed since the beginning of the 1960's. According to Dooge (1957, 1973), during the last part of the 19th century and earlier part of th 20th, most engineers used either empirical formulas, derived for particular cases and applied to other cases under the assumption that conditions were similar enough, or the "rational method" which may be seen as the first attempt to approach rationally the problem of predicting runoff from rainfall. During the 1920s, when the need for a corresponding formula for larger catchment was perceived, many modifications were introduced in the rational method in order to cope with the non-uniform distribution, in space and time, of rainfall and catchment characteristics. The modified rational method, based on the concept of isochrones, or lines of equal travel time, can be regarded as the first rainfall-runoff model based on a transfer function, whose shape and parameters were derived by means of topographic maps and the use of Manning formula to evaluate the different travel times.

Later on, Sherman (1932) introduced the concept of unit hydrograph on the basis of superposition principle. The unit hydrograph principle so evolved, accelerated the interest of hydrologists who were now able to estimate not only the peak discharge but also approximate shape of the hydrograph. Nash (1959) expressed the unit hydrograph in terms of parameters, to be estimated from catchment characteristics or by means of statistical procedures. Based upon these lines a number of solutions were proposed : a cascade of linear reservoirs, linear channels, linear channels and reservoirs, nonlinear reservoirs etc. Although many rainfall-runoff conceptual models have been set in a real time forecasting mode there is not yet a clear understanding on the advantages (or disadvantages) of recalibrating in real time all model parameters.

Problems related to the use of conceptual and physically based equations have been pointed out by Klemes (1988) and Beven (1989), respectively. Conceptual models have been discussed at length by Ciriani et al. (1977) and Blackie & Eeles (1985). Ibbitt & O'Donnel (1971) have given a comprehensive discussion on the various aspects of the calibration of conceptual models. Franchini & Pacciani (1991) pointed out that automatic calibration, rather than capitalizing on prior knowledge intrinsic to the model, avoids prior knowledge and thus emphasizes the uncertainty inherent in every statistical analysis.

One of the major area of concern in rainfall-runoff modelling is determination of number of parameters of the model, sufficient to simulate streamflows similar to observed one. Many researchers have worked on this aspect in the past (Moore and Mein 1975; Weeks and Hebbert 1980; Loague and Freeze 1985; Hooper et al. 1988; Beven 1989 and Jackman and Hornberger 1993). It is uncommon to find any systematic application and comparison of models on the same catchment. The World Meterological Organisation (1975) has conducted a study in which the performance of 10 rainfall-runoff models was compared. But in that study first, catchments were relatively large and second, only two models were applied to all the catchments. Chiew at el. (1993) compared six different modelling approaches for simulation of streamflows. They concluded that simpler methods may provide adequate estimates of monthly and annual yields in wetter catchments. However, in these studies emphasis has not been laid on the performance of models with respect to aridity or humidity of a catchment. Mimikou et al. (1992) and Hughes (1995) have applied some models to different arid and semi arid regions for prediction of streamflows.

In this report, complexity in rainfall-runoff model is analysed with respect to efficiency of a model and aridity of the catchment. Some simple model structures, operating on monthly time step have been applied on 12 catchments lying in arid, semi-arid ,sub-humid and humid regions of Central India and the results compared. Also, development and performance of a regional conceptual model is discussed for arid and semi arid and, humid and sub-humid regions.

2.1 Study area

In the present report, twelve catchments, lying in Western and Central India have been considered for study. India is divided into 6 main agro-climatic zones, based on climatological characteristics (K. N. Rao et al. 1972). Details of catchments considered for the present study, along with their agro-climate zones are presented in Table 1 whereas their location is marked in Figure 1. Out of twelve catchments, six lie in arid zone, three in semi-arid zone and one each in dry sub humid, moist sub humid and humid zones. The catchment areas vary from 85 to 4980 Square Kilometers and number of raingauge stations from 3 to 12. The use of a conceptual model requires a number of hydrometeorological data as input parameters. In general, rainfall, runoff, temperature and evapotranspiration data along with some catchment characteristics are needed for model calibration. Monthly areal rainfall is computed by applying Thiessen polygon. Rainfall and runoff data availability varies from 6 to 35 years. The normal evapotranspiration values as derived by India Meteorological Department for the respective districts/ zones are used as at no station, within or outside the catchments, meteorological data for the complete period was available. As practically all rainfall occurs during the monsoon season in most of the catchments, four monsoon months from June to September, are considered in the analysis. To define aridity or humidity of a catchment, ratio of observed runoff to observed rainfall, known as runoff factor (RF), is computed for monsoon period only, for each catchment from the available period of records. RF so computed might be influenced by the length of data but owing to non availability of normal values of rainfall and runoff for these catchments, this procedure was adopted. These values are shown in Table 1.

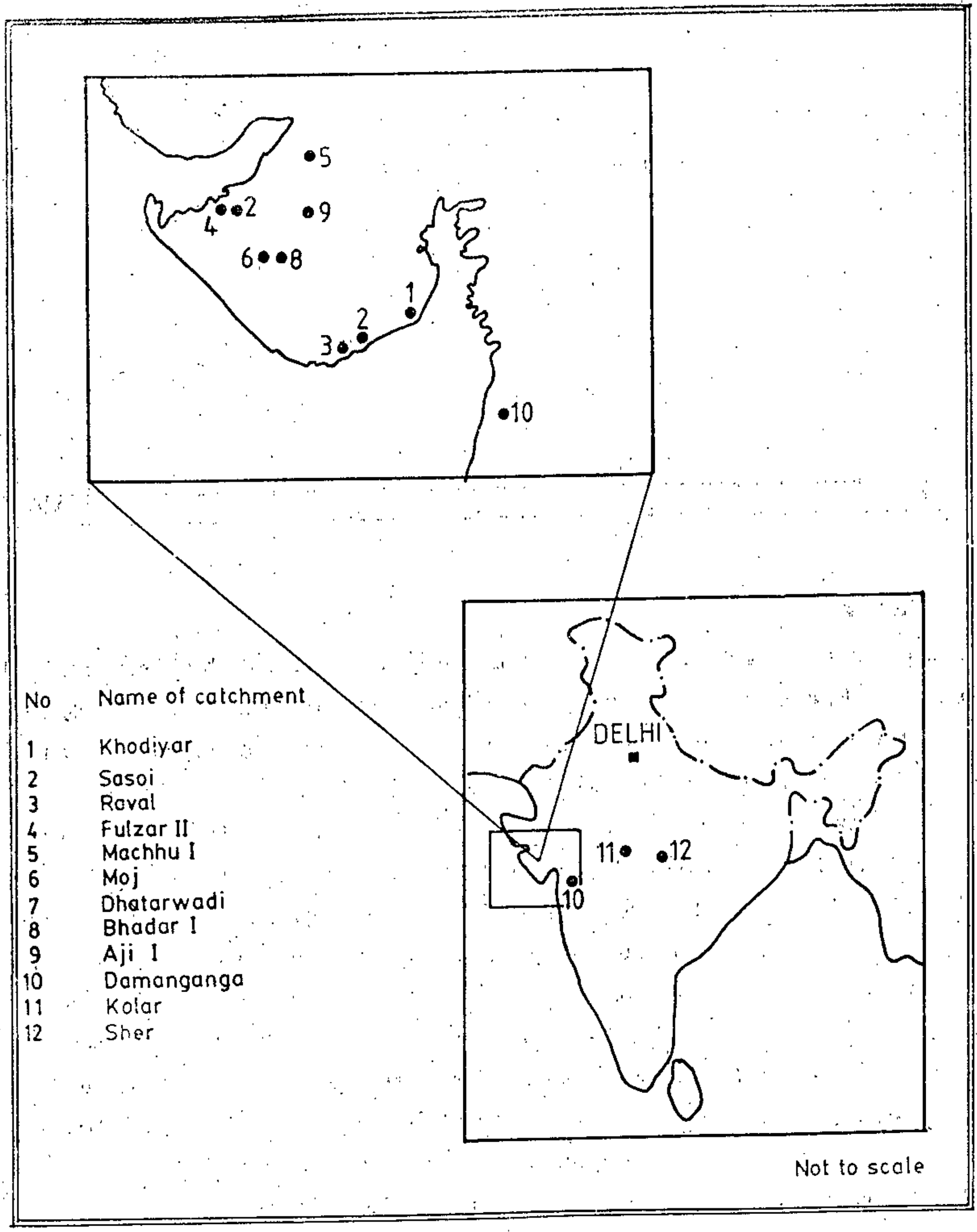


Fig. 1 Index map showing locations of catchments used in the study

Table 1 : Catchment area and other details.

Name of catchment	State	Agro-climatic zone	Runoff Factor (RF)	Area in Sq. Km.	Total length of record available in years	Years From - To	No. of years used for calibration	No. of years used for verification
Khodiyar	Gujarat	Semi-arid	0.2071	383.32	22	1968-89	15	7
Sasoi	- do -	Arid	0.2650	562.00	35	1958-92	24	10
Raval	- do -	Semi-arid	0.3106	239.80	19	1977-95	13	6
Fulzar	- do -	Arid	0.3164	85.43	19	1973-91	13	6
Machhu-I	- do -	Arid	0.2749	699.00	24	1961-84	16	8
Moj	- do -	Arid	0.2650	440.00	30	1960-89	20	10
Dhatarwadi	- do -	Semi-arid	0.3059	432.91	16	1972-92	11	5
Bhadar	- do -	Arid	0.2980	2434.59	14	1977-90	10	4
Aji-I	- do -	Arid	0.3348	142.00	31	1962-90	21	10
Sher	M.P.	Dry sub humid	0.4236	2900.00	9	1978-86	6	3
Kolar	- do -	Moist sub humid	0.4737	4980.00	6	1983-88	4	2
Daman-ganga	Gujarat	Humid	0.6540	2253.00	10	1974-83	7	3

All of the arid and semi arid catchments are from Saurashtra region of the Gujarat state. Saurashtra is a peninsular region, having areal extent of about 60,000 sq. km. A large part of the region is a centrally elivated basaltic plateau, rising from about 100 m to 200 m above the sea level, with the result that the rivers flow radially and are of short lengths. Thus the region is hydrologically more or less a homogeneous one. Annual rainfall of this region is about 52 cm. Mostly the soil belongs to silty clay loam with 65% average water holding capacity. Groundnut is the major crop grown in the region. Apart from this, other crops like Jowar, Bajra in Kharif and Wheat in Rabi are also harvested in the region. Two seasonal crops like cotton and perennial crop like sugarcane also substantially add to the agricultural aspect.

The catchment area of river Damanganga can be physiographically divided into five units namely, hill slopes, hill plateaus, upper and lower foot slopes, valley plains and local depressions, river and stream. The average forest area is about 41% and the agricultural area is about 47% of the total geographical area of the basin. Agriculture is the main occupation of the people in the basin.

The upper four-fifth part of the Kolar basin is predominantly covered by deciduous forest. The channel beds are rocky or graveled. Agriculture activity is carried out in relatively large areas in the north western part and in small pockets elsewhere in which the main crops are wheat and gram. Lower part of the basin is predominantly cultivable area. The soils are deep in this area and ground slopes are flat. Part of this area comes under the command of Kolar dam. The average forest area is about 71% and the agricultural area is about 27% of the total geographical area of the basin.

The Sher basin is identified with hilly terrain and is heavily intersected by streams and rivers. The vegetation of the basin consists of forests of medium density, scrub land, spread pockets of cultivation on undulating land and some denuded land. The average forest area is about 66% and the agricultural area is about 31% of the total geographical area of the basin.

3.1 General

A conceptual catchment model usually includes the following elements: 1. Input parameters representing the behaviour of the catchment; 2. Input of precipitation and other meteorological data; 3. Calculation of water flows, most probably both surface and sub surface; 4. Calculation of water storages, both surface and sub surface; 5. Calculation of water losses and ; 6. Catchment outflow and other outputs, if desired.

Main processes to be considered in these models may be broadly divided into two groups namely (a) land phase, and (b) climate phase. Climate phase deals with precipitation, radiation, temperature, humidity, and potential evaporation (evapotranspiration) etc. Land phase deals with all processes and storages which are encountered during the movement of water on land and below it. Generally climate phase remains more or less same in all the models. Formulation of a model differs in land phase only. Main meteorological parameters like temperature and precipitation are subjected to adjustment with respect to elevation and distance from observed points.

In the present report catchment models considered consist of one to two storages with number of parameters varying from one to seven.

3.2 Models used in the study

Some common models based on simple statistical equations to some complicated conceptual structures of monthly time scale have been selected and applied to some catchments of arid, semi-arid and humid and semi humid regions of Central India. In all, six different models have been tried to 12 catchments. Number of parameters used in these models is given in Table 2.

Table 2 : No of parameters used in different models.

Model Name	No. of Parameters used	Model Name	No. of Parameter used
STAT	4	STP1	1
STP2	2	SCS	6
WBSIMP	5	WBCOMP	7

3.2.1 STAT Model

Most simple statistical structure is to represent the runoff as a linear fraction of rainfall. In the STAT model runoff of a particular month is considered as a fraction of the rainfall. Thus for each month one parameter is required.

The governing equation of the model takes the form:

$$Q_j = X_j * P_j \tag{1}$$

Here Q, P, X are runoff, rainfall and runoff coefficient of the jth month respectively.

3.2.2 STP1 Model

This model considers only soil storage. Single parameter SMAX is used to represent the soil moisture holding capacity of the soil storage. Fast surface runoff (FSR) is the portion of rainfall in excess of the soil moisture deficit of the soil storage. Quick surface runoff (QSR) depends on the average soil moisture condition of the soil storage. It follows an exponential function. Evaporation from the soil storage is governed by the average soil moisture available in the soil storage.

3.2.3 STP2 Model

This is a two parameter model and is extension of STP1 model. Here, in addition to maximum soil moisture holding capacity parameter (SMAX), one additional parameter is used to define the threshold value for FSR.

Structure of STP1 model and STP2 model is given in Figure 2.

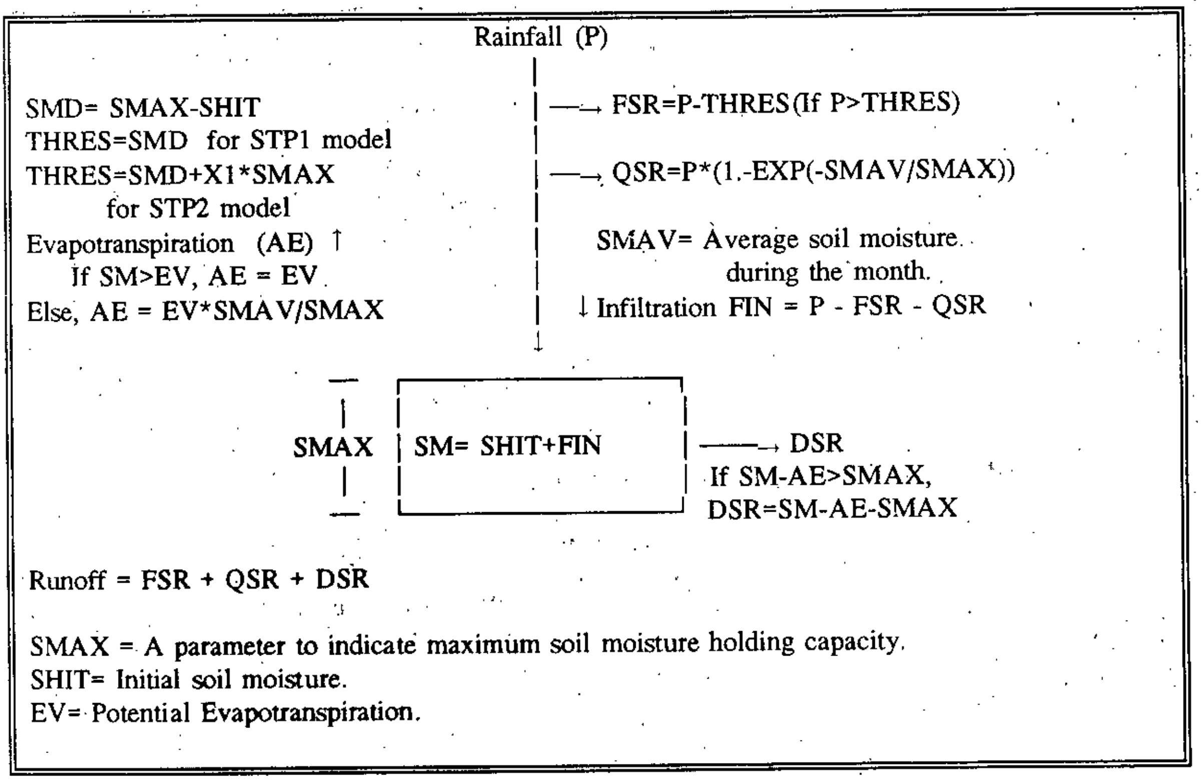


Fig. 2 : Structure and schematic representation of STP1 and STP2 models.

3.2.4 SCS Model

This model is a six parameter model and operates on curve number concept. Here two storage are considered. Surface runoff, evapotranspiration and baseflow are governed by two parameters each. The relationship according to SCS model (USDA SCS 1984) is :

$$Y = (X-\lambda Z_p)^2 / X+(1-2\lambda)Z_p \qquad (2)$$

Here λ is a constant and Z_p potential value of variable Z. Y is a dependent variable.

Using the above equation runoff (RF) is calculated considering Z_p as maximum infiltration capacity. Final soil moisture storage is calculated considering Z_p as potential evapotranspiration. Finally, baseflow (BF) is calculated considering Z_p as maximum groundwater storage. Equations and structure of the model are presented in Figure 3.

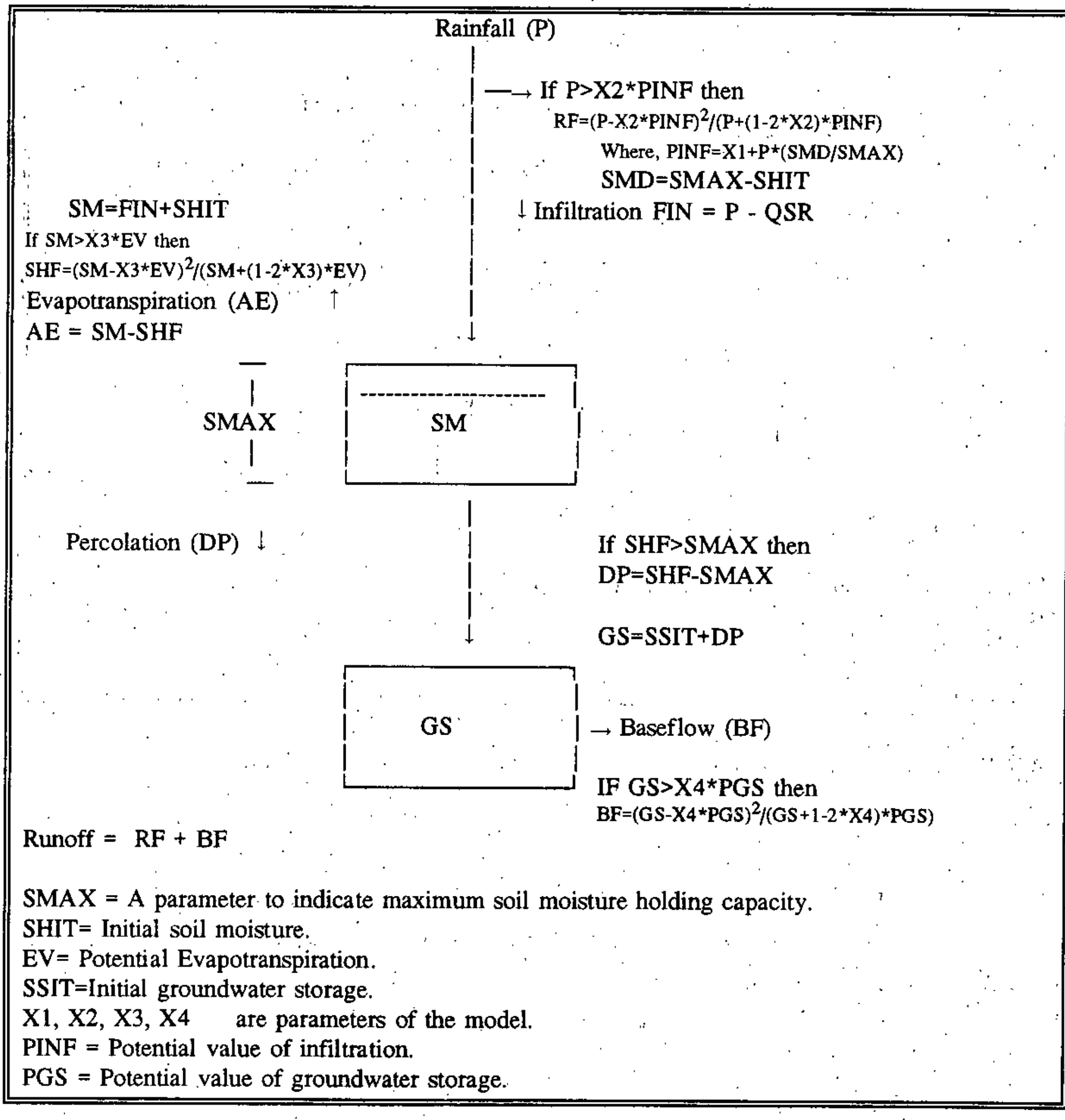
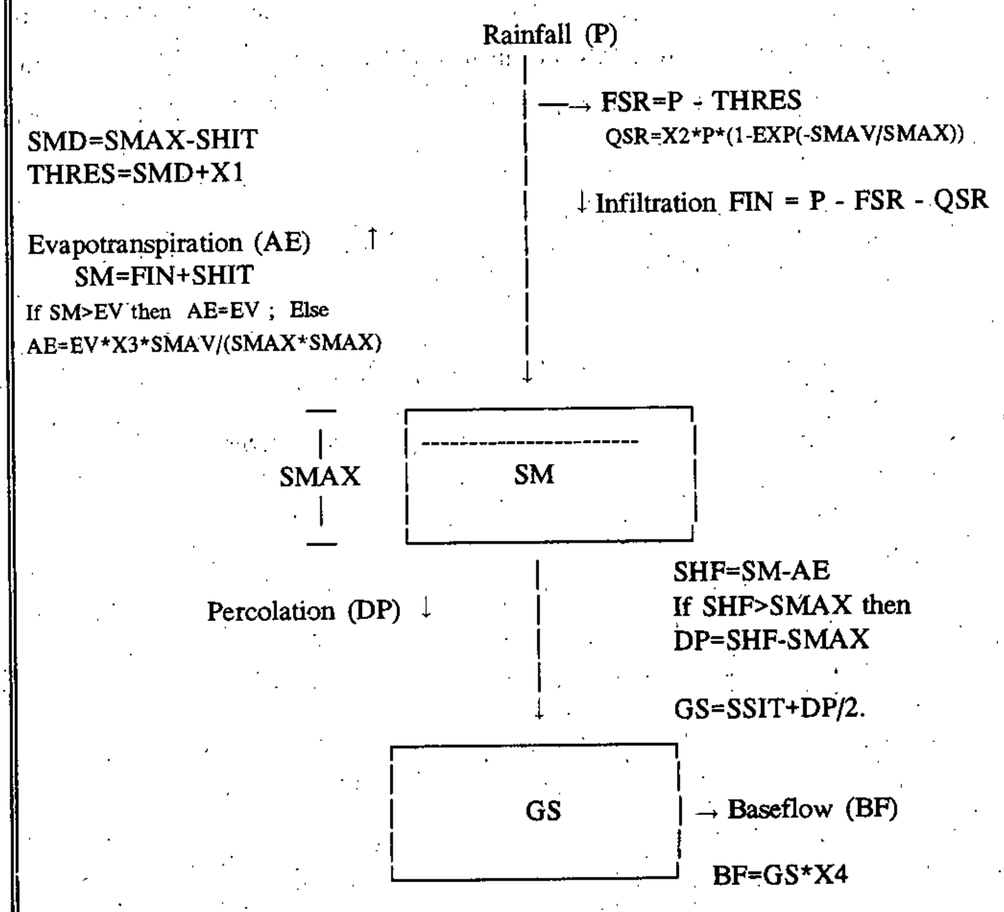


Fig. 3 : Structure and schematic representation of SCS model.

3.2.5 WBSIMP Model

This model consists of 5 parameters. Two storages namely soil and ground water storage, are considered. First parameter SMAX relates to moisture holding capacity of the soil. Second parameter THRES defines the threshold value of rainfall such that rainfall greater than this value will appear directly as runoff, referred here as Fast surface runoff (FSR). Third parameter decides the portion of the remaining rainfall which will appear as surface runoff (QSR) depending upon the average soil moisture available in the soil storage. Fourth parameter SMAX1 decides the evapotranspiration (AE) occurring from the soil storage. Fifth parameter is a constant which governs baseflow (BF) from the groundwater storage. Structure of the model and governing equations are given in Figure 4.



Runoff = FSR + QSR + BF

SMAX = A parameter to indicate maximum soil moisture holding capacity.
SHIT = Initial soil moisture.
SHF = Final soil storage
EV = Potential Evapotranspiration.
SSIT = Initial groundwater storage.
X1, X2, X3 and X4 are parameters of the model.

Fig. 4 : Structure and schematic representation of WBSIMP model.

3.2.6 WBCOMP Model

This model operates on seven parameters. Out of seven parameters four parameters are related to soil characteristics. One parameter relates to impermeable portion of the catchment. Also, one parameter governs threshold value of rainfall above which whole rainfall appears as runoff (FSR). Quick surface runoff (QSR) appears from the impermeable portion of the catchment and is controlled by a parameter and the average soil moisture deficit. Similarly, evapotranspiration (AE) from the catchment is also governed by potential evapotranspiration, average soil moisture and a parameter defining threshold value of soil moisture for evapotranspiration. If infiltrated water is in excess of SMAX, deep percolation occurs. Delayed runoff or interflow (DSR) occurs if percolated water is in excess of a limit SMAX2. Baseflow from the groundwater storage is outflow from a linear reservoir. Figure 5 describes the structure of the model and equations used.

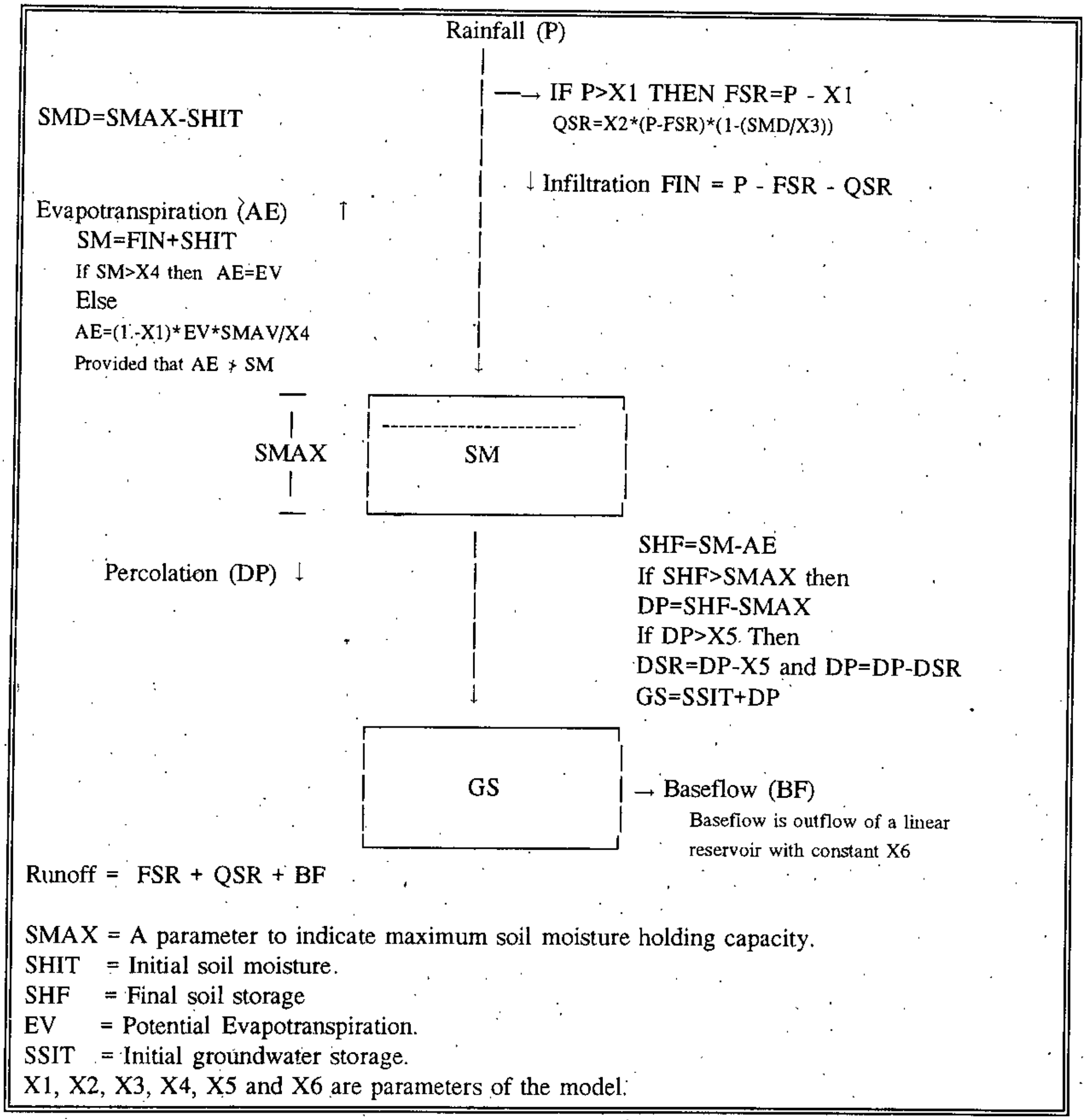


Fig. 5 : Structure and schematic representation of WBCOMP model.

3.3 Methodology for calibration and verification of models

The process by which parameters of the model are determined is called calibration of a model. To calibrate a model one needs to consider a criteria of performance of the model to see how good the model is simulating the "real world".

When the first simulation models were proposed in hydrology the main criteria for judging the model (model structure and parameters) was the graphical comparison between the observed streamflow hydrograph at specified points in the catchment versus the corresponding simulated hydrographs. In this approach the objective was to obtain the set of model parameters which produce a simulated hydrograph which best approximates the observed hydrograph. Therefore, judgement of the modeller was a very important factor determining the final set of parameters during the calibration process. A limitation in the approach was that for the same problem at hand, different answers would be obtained by different modellers because of the subjective qualitative nature of the "objective". Another limitation was that the parameter estimation had to be done by trial and error.

3.3.1 Objective function

In order to ameliorate these limitations some quantitative objectives in the form of "objective functions" were proposed (Lichty et al.,1968). If $QHIS_j$ j=1, N is the historical hydrograph and $QCOM_j$, j=1, N is the simulated hydrograph then the difference $QHIS_j$-$QCOM_j$ is the error produced by the model at time j. N is the total number of observations. An objective function to calibrate the model may be to minimize these errors for j=1, N.

Several numerical criteria are available and described in the literature to judge the performance of a rainfall-runoff model based on some objective functions. However, none of them can be described as fully efficient one. In the present report, following objective function is adopted.

Minimisation of the sum of squares of error, SUM1 which is determined as :

$$SUM1 = \sum_{j=1}^{N} (QHIS_j - QCOM_j)^2 \qquad (3)$$

Where QHIS(j) and QCOM(j) are historical and computed runoff of the jth month respectively and N is total number of observations.

To judge the performance of a model the following criteria were adopted:

(1) For each year of calibration and verification, Nash parameter (NTD) (WMO, 1986) is computed to judge the performance of the model. It is given by,

$$NTD = 1 - \frac{\sum_{j=1}^{N} (QCOM_j - QHIS_j)^2}{\sum_{j=1}^{N} (QHIS_j - ABOBS_i)^2} \qquad (4)$$

Here $AVOBS_i$ is the mean annual runoff of the ith year.

(2) An overall efficiency (EFFI) is calculated as follows,

$$EFFI(\%) = \frac{\frac{(QHIS_j - AVOBS_i)^2}{NM - 1} - \frac{(QHIS_j - QCOM_j)^2}{NM - NP}}{\frac{(QHIS_j - AVOBS_i)^2}{NM - 1}} * 100 \qquad (5)$$

Where $AVOBS_i$ is the mean annual runoff for the ith year. NM is the number of observations and NP is the number of parameters of the model.

(3) Another criterion based on monthly mean values (EFFIM) is as follows

$$EFFIM(\%) = \frac{\frac{(QHIS_j - QMOBS_j)^2}{NM - NM1} - \frac{(QHIS_j - QCOM_j)^2}{NM - NP}}{\frac{(QHIS_j - QMOBS_j)^2}{NM - NM1}} * 100 \qquad (6)$$

Where QMOBS j is the mean value of runoff for the jth time period. NM1 is the total number of observations considered in a year.

3.4 Guidelines for estimation of parameters

For the calibration of the model the historical data of precipitation, runoff, potential evapotranspiration, infiltration, soil type etc. are required along with initial values of various storages, initial values of model parameters and other parameters concerning the optimisation technique. Though all the parameters of a model could be included in the optimization algorithm, great care is required to include only those parameters in the optimization which are independent.

The first guidelines for the model calibration concerns the overall approach for determining the parameters and some of the initial variables of the model. It is advisable not to rely completely on one objective function. Another advise is that, even when trying alternative objective functions, one should always use the graphical comparison of the historical and simulated streamflows. Another guide line for model calibration concerns the estimates of those parameters, which are not included in the optimization algorithm. Likewise, the initial values of storages must be estimated based on some physical considerations of the basin. For example if initial value of surface storage is to be estimated it would be advisable to begin the simulation at the end of dry season so that a reasonable estimate of this storage would be zero. Also, soil storage may also be taken zero. Other factors such as type of land cover and the slope of the watershed would be important as well. For instance, basins with steeper slopes would have smaller surface storages than basins of milder slopes.

Another approach commonly used in simulation models to estimate the values of the initial storages is to run the model for some years. Then the initial storage values can be obtained from the simulated values of the model as the average values of the storages. This can be done until more or less constant values of storages are obtained.

3.5 Optimization algorithm and other criteria used in the study

Constrained Rosenbrock optimisation technique which is basically a search algorithm proposed by Rosenbrock (1960) is used to calibrate the parameters of the models. It involves the minimisation of an objective function computed, based on the deviations of observed and simulated monthly runoff values, within the given range of parameter values. Provision is also made to calibrate some or all the parameters of the model using trial and error method if their approximate values are known prior to the calibration.

Also, performance of various models is compared on the basis of values of Nash parameter (NTD), over all efficiency (EFFI) and efficiency based on monthly mean (EFFIM) calculated (using equations 4, 5 and 6 described earlier) for each model and each catchment.

4.1 Comparison of models

As a first step, all the models have been run considering total available records of monthly rainfall runoff for all the catchments. Then, the data of first two third period is considered for calibration and remaining one third period is used for verification of each model. Details of calibration and verification period used, are given in Table 1. To define aridity or humidity of a catchment, ratio of observed runoff to observed rainfall, known as runoff factor (RF), is computed for each catchment and presented in Table 1. For the analysis purpose all the twelve catchments are divided into two categories: (a) arid and semi arid category and (b) humid and semi humid category. All the nine catchmensts of arid and semi arid zones are considered in the first category, and all other catchments lying in humid, dry sub humid and moist sub humid category, are considered in the second category.

Comparison of various model structures has been performed on the basis of NTD, EFFI and EFFIM values. These values for all the models and for all the catchments are presented in Table 3A to Table 3C respectively for calibration, verification and complete periods . The best model out of six models, identified for each catchment as well as for each zone, based on NTD, EFFI and EFFIM criteria during calibration, verification and complete periods is given in Table 4. Also, average values of NTD, EFFI and EFFIM are computed for (i) arid and semi-arid, (ii) sub-humid and humid zones and (iii) for all 12 catchments (Tables 3A-3C).

To study the effect of basin aridity on the performance of a model, for each catchment, graphs between RF and NTD (other criteria, EFFI and EFFIM are not considerd as there is not much difference in the performance of a model based on these criteria as discussed later in this section) are plotted for calibration, verification and complete periods for all the models, and are reported here in the from of Figure 6 (part A, B and C). Also for each model, a best fit regression line is drawn through the plotted points, for calibration, verification and complete periods. The slope and intercept of the best fit lines drawn for each model are given in Table 5.

From the Tables 3A and 3B, it is indicated that for arid and semi arid catchments, efficiency (EFFI or EFFIM) generally varies from 65% to 85% for most of the catchments and models with average values from 60% to 80%. For humid and semi humid catchments, it generally varies from 75% to 95% with average values 70% to 90%. Considering average of all the catchments, it varies from 67% to 80%. Some models perform well during calibration and some during verification. From the Table 3C, it is indicated that value of NTD varies widely from 0.20 to 0.86 for arid and semi-arid region catchments with average values from 0.40 to 0.69. For semi-humid and humid catchments it varies from 0.41 to 0.98 with average values from 0.71 to 0.96. It is observed that in general, WBSIMP, STP2 and WBCOMP models perform well for most of the catchments and for calibration, verification and complete periods. It is also indicated from the Tables that on average basis, for semi-arid and arid catchments, for calibration and complete periods, NTD values and efficiencies are similar and higher than the values for verification periods. While, for semi-humid and humid catchments, average NTD values and efficiencies are highest for complete periods and lowest for verification periods.

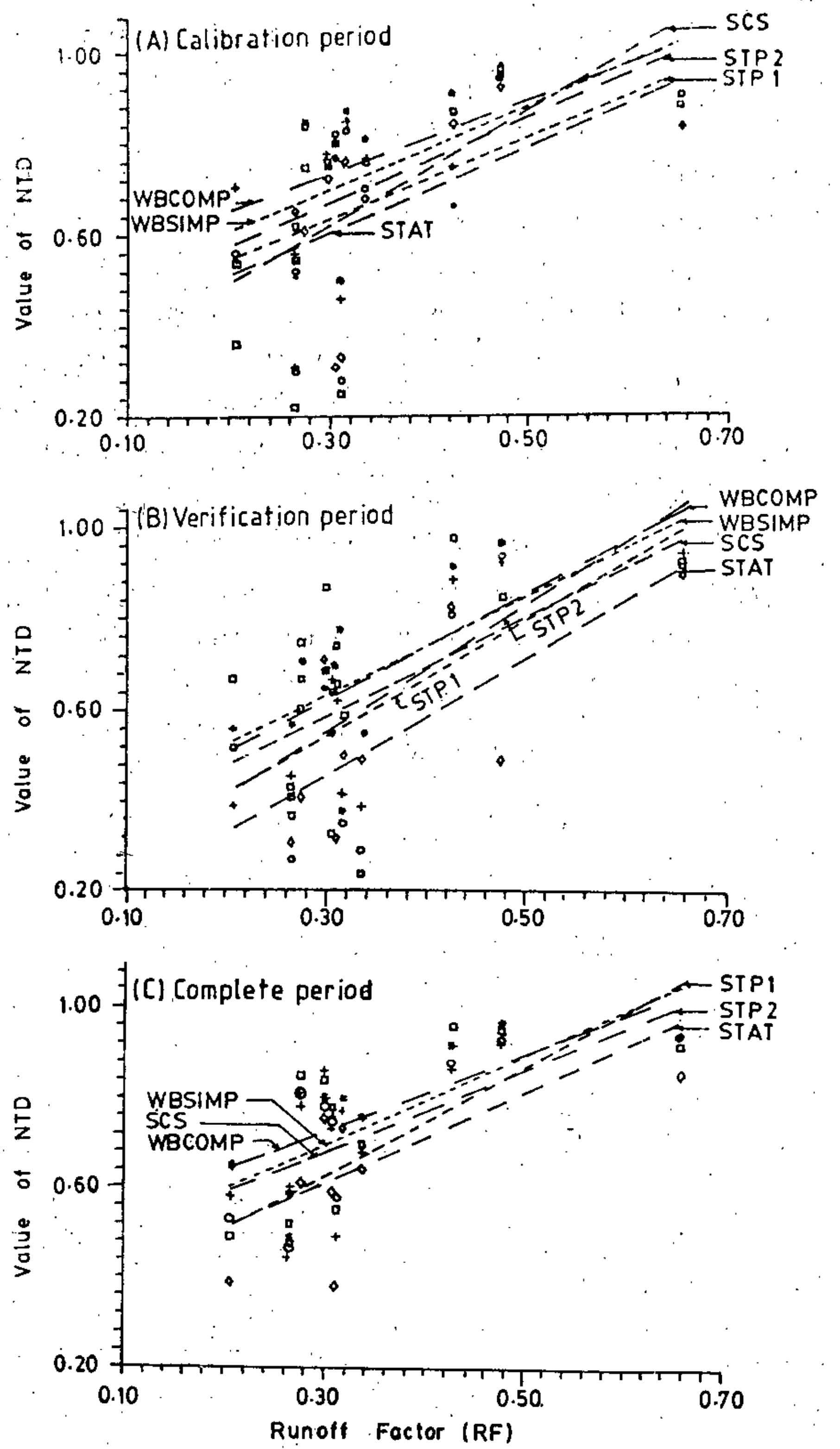


Fig. 6 Plots of efficency (NTD) and catchment runoff factor (RF) for (A) Calibration (B) Verification and (C) Complete periods.

Table 3A : Comparison of different models based on overall efficiency criterian.

Sr. No.	Basin Name	STAT C	STAT V	STAT T	STP1 C	STP1 V	STP1 T	STP2 C	STP2 V	STP2 T	SCS C	SCS V	SCS T	WBSIMP C	WBSIMP V	WBSIMP T	WBCOMP C	WBCOMP V	WBCOMP T
(i)	Arid and Semi-arid catchments																		
1	Khodiyar	67.2	42.3	61.1	70.8	77.4	66.2	69.2	69.9	70.1	53.2	80.6	66.6	72.6	77.0	76.0	78.2	73.1	76.1
2	Sasoi	65.7	60.2	67.4	47.8	60.8	31.0	48.5	70.2	57.1	39.2	61.4	59.2	60.5	72.1	58.0	61.6	62.4	63.8
3	Raval	67.4	57.0	66.3	66.8	85.6	74.1	74.6	78.0	74.5	61.4	76.0	75.0	71.4	74.4	79.8	73.9	83.7	82.2
4	Fulzar - II	79.6	51.8	77.7	86.2	45.8	82.7	87.4	49.8	81.1	88.1	59.2	82.3	87.9	36.4	82.5	88.2	30.4	82.5
5	Machhu - I	74.3	50.1	70.9	90.1	75.2	85.5	88.9	68.7	82.6	82.9	77.0	88.3	89.8	74.2	85.0	89.8	72.8	85.6
6	Moj	79.6	65.0	74.2	73.4	60.9	68.0	75.0	61.9	75.7	77.7	56.8	69.5	78.9	60.3	72.3	77.8	66.4	73.5
7	Dhatarwadi	68.5	60.6	75.1	92.5	73.8	85.5	91.2	74.2	83.7	90.4	23.5	86.0	80.3	78.8	79.7	88.9	68.2	84.7
8	Bhadar - I	77.7	73.1	79.5	82.3	74.9	83.1	83.2	73.4	89.2	78.8	83.6	86.5	84.0	86.7	82.1	78.6	56.1	82.8
9	Aji - I	77.4	68.4	76.6	79.6	59.8	76.7	84.4	64.4	79.3	82.7	52.1	80.0	85.6	68.4	83.3	86.4	69.5	83.9
Average		73.0	58.7	72.1	76.6	68.2	72.5	78.0	67.8	77.0	72.7	63.3	77.0	79.0	69.8	77.6	80.4	64.7	79.5
(ii)	Humid and semi-humid catchments																		
10	Sher	82.6	78.7	87.1	69.1	82.0	89.0	75.8	88.2	87.6	84.3	96.8	95.3	87.8	90.7	92.8	89.0	83.9	91.2
11	Kolar	90.8	26.9	87.3	94.4	94.2	93.4	93.6	92.2	92.5	94.3	67.7	93.7	97.6	89.2	96.5	95.3	80.0	96.6
12	Daman-ganga	86.1	86.8	88.1	91.4	92.3	95.0	93.2	94.3	94.1	91.3	88.1	92.3	93.6	91.1	94.8	93.7	89.0	94.6
Average		86.5	64.1	87.5	85.0	89.5	92.5	87.5	91.6	91.4	90.0	84.2	93.8	93.0	90.3	94.7	92.7	84.3	94.1
Average of 12 catchment		76.4	60.1	75.9	78.7	73.6	77.5	80.4	73.8	80.6	77.0	68.6	81.2	82.5	74.9	81.9	83.4	69.6	83.1

Note : C indicates Calibration period; V indicates Verification period and; T indicates Complete period.

Table 3B : Comparison of different models based on monthly efficency criterian.

Sr. No.	Basin Name	STAT C	STAT V	STAT T	STP1 C	STP1 V	STP1 T	STP2 C	STP2 V	STP2 T	SCS C	SCS V	SCS T	WBSIMP C	WBSIMP V	WBSIMP T	WBCOMP C	WBCOMP V	WBCOMP T
(i)	Arid and Semi-arid catchments																		
1	Khodiyar	67.5	47.4	62.4	71.1	79.4	65.4	69.5	72.6	69.3	53.7	82.3	67.8	72.9	79.0	75.0	78.4	75.5	77.4
2	Sasoi	64.1	60.9	62.2	44.2	61.4	20.0	46.2	70.7	50.4	36.5	62.0	52.8	57.8	72.5	55.5	59.9	63.1	61.7
3	Raval	66.6	57.1	64.5	66.1	85.6	71.6	74.1	78.1	73.6	60.6	76.0	73.7	70.7	74.4	78.8	73.4	83.8	81.3
4	Fulzar - II	79.1	55.3	77.8	85.9	49.8	82.7	87.1	53.5	81.1	87.8	57.9	82.3	87.7	41.2	82.6	88.0	35.6	82.5
5	Machhu - I	73.6	49.5	69.7	89.8	74.9	84.5	88.6	68.4	81.5	82.4	76.7	87.8	89.5	73.9	84.0	89.5	72.5	85.0
6	Moj	76.7	58.4	70.2	69.7	53.5	63.0	71.5	54.7	72.0	74.5	48.6	64.8	75.9	52.9	68.0	74.6	60.1	70.0
7	Dhatarwadi	70.3	45.5	73.6	92.9	63.8	84.6	91.7	64.3	82.7	91.0	21.8	85.1	81.4	70.7	78.5	89.5	56.1	83.8
8	Bhadar - I	77.7	73.2	77.5	80.9	74.1	81.6	82.5	72.5	88.1	77.1	83.1	85.1	82.8	86.3	81.4	76.9	56.3	81.2
9	Aji - I	76.6	68.1	75.6	78.9	59.4	75.6	83.8	64.1	78.4	82.1	52.5	79.2	85.1	68.1	82.5	86.0	69.2	83.2
	Average	72.5	57.3	70.4	75.5	66.9	69.9	77.2	66.5	75.2	71.7	62.3	75.4	78.2	68.8	76.2	79.6	63.6	78.4
(ii)	Humid and semi-humid catchments																		
10	Sher	69.7	64.2	78.9	46.0	69.8	82.0	57.8	80.2	80.0	72.6	94.7	92.4	78.7	84.4	88.3	80.8	72.9	85.7
11	Kolar	87.4	25.6	82.0	92.5	90.1	91.0	91.2	89.0	89.3	92.3	44.4	91.1	96.8	81.4	95.0	93.5	40.1	95.1
12	Daman-ganga	80.8	75.1	88.8	88.2	85.6	92.0	90.6	89.3	90.6	88.0	77.6	87.5	91.2	83.3	91.6	91.3	79.4	91.2
	Average	79.3	55.0	83.2	75.5	81.8	88.3	79.9	86.2	86.6	84.3	72.2	90.3	88.9	83.0	91.6	88.6	64.1	90.7
	Average of 12 catchment	74.2	56.7	73.6	75.5	70.6	74.5	77.9	71.4	78.1	74.9	64.8	79.1	80.9	72.3	80.1	81.8	63.7	81.5

Note : C indicates Calibration period; V indicates Verification period and; T indicates Complete period.

Table 3C : Comparison of different models based on Nash Parameter (NTD) criterian.

Sr. No.	Basin Name	STAT C	STAT V	STAT T	STP1 C	STP1 V	STP1 T	STP2 C	STP2 V	STP2 T	SCS C	SCS V	SCS T	WBSIMP C	WBSIMP V	WBSIMP T	WBCOMP C	WBCOMP V	WBCOMP T
(i)	Arid and Semi-arid catchments																		
1	Khodiyar	0.54	0.18	0.39	0.56	0.52	0.53	0.55	0.39	0.58	0.36	0.67	0.49	0.62	0.59	0.67	0.71	0.56	0.65
2	Sasoi	0.55	0.31	0.58	0.30	0.27	0.09	0.31	0.46	0.44	0.22	0.37	0.48	0.49	0.53	0.40	0.51	0.40	0.49
3	Raval	0.33	0.32	0.38	0.28	0.74	0.58	0.46	0.62	0.49	0.25	0.66	0.55	0.43	0.61	0.63	0.50	0.78	0.69
4	Fulzar - II	0.76	0.50	0.73	0.83	0.35	0.78	0.85	0.42	0.77	0.87	0.59	0.79	0.86	0.37	0.79	0.87	0.38	0.80
5	Machhu - I	0.61	0.41	0.61	0.84	0.67	0.81	0.83	0.60	0.78	0.75	0.75	0.85	0.85	0.70	0.81	0.85	0.71	0.81
6	Moj	0.65	0.51	0.58	0.52	0.41	0.47	0.56	0.44	0.60	0.62	0.43	0.52	0.64	0.46	0.56	0.63	0.57	0.59
7	Dhatarwadi	0.31	0.55	0.59	0.82	0.64	0.75	0.80	0.67	0.73	0.80	0.33	0.78	0.58	0.77	0.68	0.77	0.70	0.76
8	Bhadar - I	0.72	0.71	0.75	0.76	0.69	0.78	0.78	0.69	0.86	0.75	0.87	0.84	0.81	0.88	0.73	0.75	0.65	0.80
9	Aji - I	0.68	0.49	0.64	0.70	0.29	0.64	0.77	0.39	0.68	0.76	0.24	0.70	0.80	0.50	0.75	0.81	0.55	0.76
	Average	0.57	0.44	0.58	0.62	0.51	0.60	0.66	0.52	0.66	0.60	0.54	0.67	0.67	0.60	0.67	0.71	0.59	0.71
(ii)	Humid and semi-humid catchments																		
10	Sher	0.84	0.83	0.87	0.66	0.81	0.88	0.75	0.89	0.87	0.87	0.98	0.96	0.89	0.94	0.98	0.91	0.92	0.92
11	Kolar	0.92	0.49	0.88	0.94	0.94	0.93	0.94	0.93	0.92	0.96	0.85	0.95	0.98	0.94	0.97	0.97	0.97	0.97
12	Daman-ganga	0.83	0.90	0.86	0.88	0.92	0.94	0.91	0.95	0.93	0.90	0.93	0.92	0.92	0.94	0.94	0.93	0.95	0.94
	Average	0.86	0.74	0.87	0.83	0.89	0.92	0.86	0.92	0.91	0.91	0.92	0.94	0.93	0.94	0.96	0.94	0.95	0.94
	Average of 12 catchments	0.64	0.52	0.66	0.67	0.60	0.68	0.71	0.62	0.72	0.68	0.64	0.74	0.74	0.69	0.74	0.77	0.68	0.77

Note : C indicates Calibration period; V indicates Verification period and; T indicates Complete period.

Table 4: **Catchment wise the best performance of a model based on efficiencies and NTD criteria.**

Sr. No. Basin Name	Model No.								
	Overall efficiency			Efficiency based on monthly mean			NTD values		
	Calibration	Validation	Whole	Calibration	Validation	Whole	Calibration	Validation	Whole
(i) Arid and semi-arid catchments									
Khodiyar	WBCOMP	SCS	WBCOMP	WBCOMP	SCS	WBCOMP	WBCOMP	SCS	WBSIMP
Sasoi	STAT	WBSIMP	STAT	STAT	WBSIMP	STAT	STAT	WBSIMP	STAT
Raval	STP2	STP1	WBCOMP	STP2	STP1	WBCOMP	WBCOMP	WBCOMP	WBCOMP
Fulzar - II	WBCOMP	SCS	STP1	WBCOMP	SCS	STP1	WBCOMP	STAT	WBCOMP
Machhu - I	STP1	SCS	SCS	STP1	SCS	SCS	WBCOMP	WBCOMP	WBCOMP
Moj	STAT	WBCOMP	STP2	STAT	WBCOMP	STP2	STAT	WBCOMP	STP2
Dhatarwadi	STP1	WBSIMP	SCS	STP1	WBSIMP	SCS	STP1	WBSIMP	SCS
Bhadar - I	WBSIMP	WBSIMP	STP2	WBSIMP	WBSIMP	STP2	WBCOMP	STP2	STP2
Aji - I	WBCOMP	WBCOMP	WBCOMP	WBCOMP	WBCOMP	WBCOMP	WBCOMP	WBSIMP	WBCOMP
Average	WBCOMP	WBSIMP	WBCOMP	WBCOMP	WBSIMP	WBCOMP	WBCOMP	WBCOMP	WBCOMP
(ii) Humid and semi-humid catchments									
Sher	WBCOMP	SCS	SCS	WBCOMP	SCS	SCS	WBCOMP	WBSIMP	WBSIMP
Kolar	WBSIMP	STP1	WBCOMP	WBSIMP	STP1	WBCOMP	WBSIMP	WBCOMP	WBCOMP
Damanganga	WBCOMP	STP2	STP1	WBCOMP	STP2	WBSIMP	WBCOMP	WBCOMP	WBCOMP
Average	WBSIMP	STP2	WBSIMP	WBCOMP	STP2	WBSIMP	WBCOMP	WBCOMP	WBSIMP
Av. of all catchment	WBCOMP	WBSIMP	WBCOMP	WBCOMP	WBSIMP	WBSIMP	WBCOMP	WBCOMP	WBSIMP

Table 5 : Slopes and intercepts of regression lines (Eq. $Y = mX + C$).

Model	Calibration		Verification		Complete	
	Intercept C	Slope m	Intercept C	Slope m	Intercept C	Slope m
STAT	0.3266	0.93	0.0721	1.29	0.2988	1.04
STP1	0.3699	0.88	0.1620	1.28	0.2594	1.23
STP2	0.3896	0.93	0.1367	1.41	0.4010	0.93
SCS	0.2473	1.25	0.2625	1.10	0.3842	1.02
WBSIMP	0.4295	0.90	0.3111	1.09	0.3965	1.01
WBCOMP	0.4941	0.79	0.2667	1.96	0.4622	0.88

Further examination of the performance of models may be done from Table 4. STP2 and WBCOMP models generally perform well for all the basins and for all the three criteria. Especially, during calibration WBCOMP model performs well while, during verification STP2 model and, for complete period again WBCOMP model perform well. On average basis, WBCOMP model performs well for semi-arid and arid, and also semi-humid and humid catchments.

Figure 6, part A to part C indicate that increase in RF is in proportion to the model performance. Table 5 presents intercepts (C) and slopes (m) of the best fit regression lines drawn in Figure 6. The superior model should have more C and less m, if it is not influenced by aridity, as m indicates relative performance of a model with regard to RF. Thus, if a model is good for higher values of RF and poor for low values of RF, it should have positive m. In the present case, all the models show positive m, thereby indicating that efficiency increases as RF increases. Value of C is highest for WBCOMP model for calibration and complete periods. Table also indicates that WBCOMP and WBSIMP are least influenced by the variation in RF.

STAT Model which utilises statistical relationships, exhibits poor performance as compared to other models, during calibration, verification and complete periods (Figure 6, part A to part C). It may be attributed to the structure of the model i.e. statistical equations, which are not adequate enough to have the same flexibility as possessed by other water balance models in preserving the behaviour of the catchment. For all the models except STAT model, as RF increases, relative performance of a model in comparison to other models, also increases. STP1 model perform poorly in arid region perhaps because it is a single parameter model and may not be able to represent adequately, the catchment processes, intervening between rainfall and runoff. When an additional parameter to account for fast (quick) surface runoff mechanism is added in the structure (STP2 model), its performance improves (Figure 6, part A to part C). For semi-humid and humid regions, almost all models work well with the exception of STAT model (Figure 6, part A to part C). From these figures, it is clear that WBSIMP and WBCOMP models perform equally well. Perhaps because of the fact that, WBSIMP model is a 5 parameter model and WBCOMP model is a seven parameter model and therefore all the required predominant processes are represented adequately by the model structures. In general, it is observed that for arid regions, where not only evapotranspiration plays a major role, other process such as surface runoff (fast and quick) also become predominant, WBSIMP model which contains 5 parameters may be recommended. Jakeman and Hornberger (1993) have also recommended that rainfall-runoff response of a catchment is well represented using a two - component linear model i.e. quick flow and slow flow response of the catchment. Also for monthly time period, only one storage is usually sufficient (Littlewood and Jakeman 1992). For regions other than arid region, STP2 model which needs only two parameters seems to be better choice in representing the behaviour of the catchment.

4.2 Development of a regional model

Some of these models which consider limited number of parameters, can also be used for development of a regional model. In the study, STP1 model which consider only single parameter SMAX is considered for development of a regional model for arid and semi arid and, for humid and semi humid regions considering only selected catchments. Graphs between objective function and value of SMAX for different catchments are plotted and presented in Figure 7 and Figure 8 for arid and semi arid and, humid and semi humid regions respectively. From these Figures a representative value of parameter SMAX, for minimum value of objective function is selected (450 mm for arid and semi arid region and 380 mm for humid and semi humid region). These representative values of parameter for respective regions are then used to get the values of NTD, EFFI, EFFIM and other statistics for various catchments (Table 6). Data of two more catchments, Godhat for arid and semi arid regions and, Manot for humid and semi humid region, are also used. Results show that performance of models based on regional values are encouraging and thus the model can be used for ungauged catchments also located in these regions.

Table 6: Statistics of different catchments using STP1 model and keeping the constant value of parameter of the model.

Name of Catchment	Area in Sq. Km.	No of years of data	Overall Effi.	Effi. based on monthly mean	Value of NTD	Value of Obj. Func. For whole period	Value of Obj. Func. per year	Historical flow percentage	Computed flow percentage	Computed evaporation percentage	Historical and computed flow percent difference
(i) Arid and semi-arid catchments			(Parameter value = 470 mm)								
Khodiyar	383.32	22	83.25	83.76	0.66	40224.00	1828	22.25	24.12	63.00	1.87
Sasoi	562.00	35	50.94	48.67	0.26	159823.00	4566	25.80	23.87	62.00	1.93
Raval	239.80	19	78.91	77.83	0.59	94375.00	4967	31.06	26.05	61.00	5.01
Fulzar - II	85.43	19	78.46	78.51	0.73	100762.00	32	25.02	60.00	51.00	34.98
Machhu - I	699.00	24	84.16	83.52	0.78	73863.00	3078	27.31	22.95	60.00	4.36
Moj	440.00	30	62.63	56.51	0.38	96345.00	3212	26.50	24.19	64.00	2.31
Dhatarwadi	432.91	16	66.46	64.47	0.43	66175.00	4136	30.59	19.84	63.00	10.75
Bhadar - I	2434.59	14	69.65	69.48	0.46	47289.00	3378	26.23	23.63	65.00	2.60
Aji - I	142.00	31	73.91	73.03	0.59	134384.00	4335	32.85	25.58	59.00	7.27
Godhat	165.76	11	85.94	84.87	0.81	52386.00	4762	46.07	33.55	41.00	12.52
Regional average			73.43	72.07	0.57		3429.37				8.36
(ii) Humid and semi-humid catchments			(Parameter value = 380 mm)								
Sher	2900.00	9	87.75	80.06	0.87	66655.00	7406	43.79	43.94	42.00	0.15
Kolar	4980.00	6	87.95	82.91	0.87	82245.00	13708	46.76	53.45	43.00	6.69
Damanganga	2253.00	10	94.03	84.60	0.94	383524.00	38352	65.21	66.10	34.00	0.89
Manot	600.00	5	80.91	65.03	0.80	88716.00	17743	61.87	54.84	24.00	7.03
Regional average			87.66	78.15	0.87		19302				3.69
Average of all catchment			77.50	73.80	0.65		7964.49				7.03

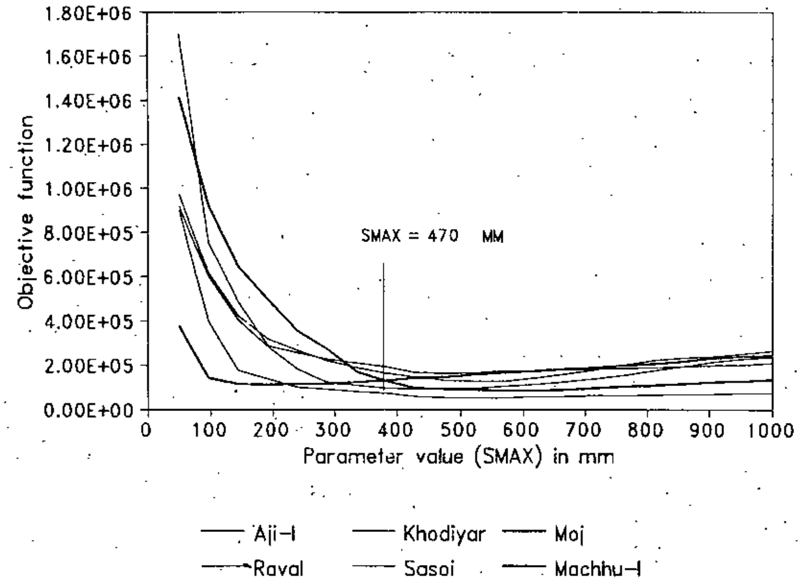


Figure 7 : Plot of objective function vs SMAX value for arid and semi arid region.

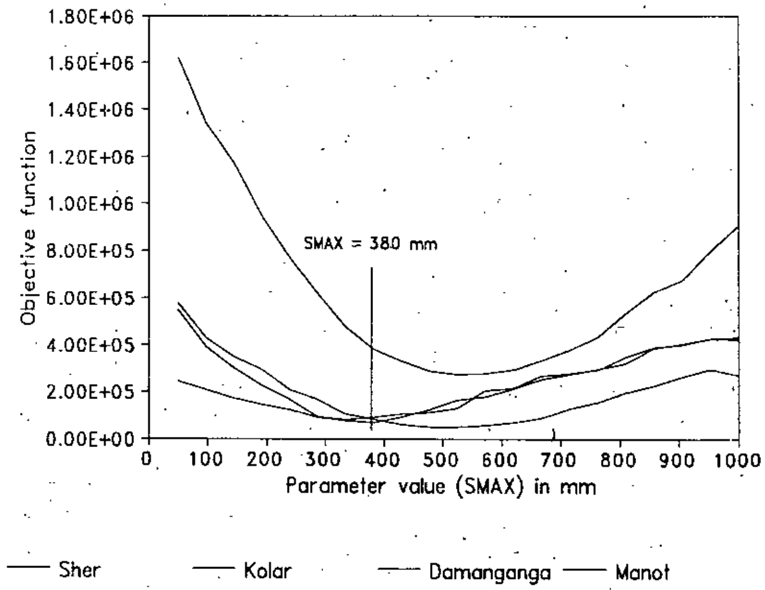


Figure 8 : Plot of objective function vs SMAX value for humid and semi humid region.

5.1 Conclusion

Advances in computers and analysis techniques have led to significant developments and application of mathematical and conceptual models in hydrology during the last three decades. The mathematical functions or conceptual elements employed to simulate the natural hydrological processes are subject to limitations of the present state of knowledge of physical behavior, mathematical constraints, data availability, its quality and, user requirements. In spite of rapid advances in hydrology particularly in catchment hydrology and modelling, it is not always possible to make universal use of such models because local problems predominate over other factors. However, there is need to develop suitable yet simple models for smaller regions so that these can be used in situations where little or no data is available.

Keeping in view the above limitations and requirements, some simple structures operating on monthly time step have been developed and tested on 12 catchments lying in arid, semi-arid, sub-humid and humid regions of Western and Central India. As mentioned above, results of the study to some extent may be influenced by the quality of data as these have been used as such. It is uncommon to find any systematic application and comparison of models on the same catchment. The World Meteorological Organisation (1975) has conducted a study in which the performance of 10 rainfall-runoff models was compared. But in that study first, catchments were relatively large and second, only two models were applied to all the six catchments.

Dynamic response characteristics of the catchment can be explained by its quick or fast response and slow response. Fast response mainly depends on the volume of rainfall and catchment characteristics. In arid regions, evapotranspiration losses plays a major role thus, rainfall-runoff relationship becomes complicated. On the other hand, the more humid catchment, rainfall-runoff relationship, becomes more efficient and simple. Analysis of different model structures suggests that runoff mechanism is rainfall in excess of infiltration. However, rainfall, consequently runoff is frequently localized which means that it is region specific. The implication is that runoff generation process on monthly scale is strongly dependent on volume of rainfall and soil moisture characteristics of the catchment. It may be because of this fact that statistical model fails to perform well in the analysis specifically during verification period.

The results of the study indicate that for humid and semi-humid catchments almost all water balance structures simulate well. Overall performance of WBCOMP Model, which contains seven parameters was found superior in simulating the streamflows, as compared to other models. However, this model contains seven parameters, calibration of which may require some knowledge of catchment characteristics, sound guesses and different parameter perturbations. STP2 Model, which operates on only two parameters and, STP1 Model which operates on single parameter also work reasonable well and may be recommended for these catchments.

STP1 model used for development of a regional model for the arid and semi-arid and humid and semi humid regions has shown encouraging results. Results show that performance of model based on regional values are satisfactory and thus the model can also be used for ungauged catchments located in the regions.

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