MONTHLY RAINFALL-RUNOFF MODELS USING WATER BALANCE APPROACH

1.0 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. Recent development 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 base 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.

The conceptual model approach to rainfall-runoff modelling lies intermediate between physically based models and black box models. 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. 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.

Lumped, conceptual models are especially well suited for 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.

2.0 USUAL MODEL STRUCTURE

A deterministic watershed model usually includes the following elements: 1. Input parameters representing the relevant physical characteristics of the watershed; 2. Input of precipitation and other meteorological data; 3. Calculation of water flows, both surface and sub surface; 4. Calculation of water storages, both surface and sub surface; 5. Calculation of water losses and ; 6. Watershed outflow and other outputs, if desired.

A deterministic watershed model consists of a series of sub models each representing a particular hydrologic process and usually structured accordingly. The sub models utilise the above types of elements as needed. Each sub model represents basically a flow of water and usually includes a storage. The sub model output is either an outflow to the next sub model or a water loss. Water storages are essential parts of the model, since they play key roles in regulating flow in the watershed itself. Most flows in a model are into or out of a storage.

Model building is a process of choosing appropriate sub models, linking them together to form a watershed model, and making the resulting watershed model work.

3.0 SELECTION OF APPROPRIATE MODEL TYPE

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. It is uncommon to find any systematic application and comparison of models on the same catchment. A large number of hydrological models exists. Thus the question "which model is most appropriate for a particular hydrological problem?" cannot be answered strictly by giving the name of one model. For some hydrological problems the selection of model type is more or less obvious, i.e. probabilistic model for frequency analysis or stochastic time series model for generation of flows. Some of the factors and criteria involved in the selection of a model may be divided into various phases as described in next section.

The World Meterological Organisation (1975) has conducted a study in which the performance of 10 rainfall-runoff models was compared. 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.

4.0 PHASES IN HYDROLOGIC SYSTEM SIMULATION

First phase is commonly known as inventory phase. here we begin with identification of the system components means how may processes are to be considered. This may be limited by the availability of data and quality of data and type of data. Second step involves identification of analysis involving various components. Third step is data requirement as each type of analysis requires a particular type of data. Final consideration is design criteria i.e. for what purpose we are developing the model and what are the objectives and aims. It also helps in determining the time step of model. If it is for reservoir operation then about 10 days time step will be sufficient but for flood forecasting purpose half an hour time step is needed.

Second phase is known as model conceptualization means identification of linkages. Here model structure is decided and also number of processes to be considered. Depending upon the model requirement some finer processes may be overlooked and may be merged in major processes. After finalisation of number of processes and their sequence mathematical equations to represent adequately these processes are formulated. Total number of parameters used in formulation of the processes are counted. More the number of parameters more complex a model will be. No model can be a strict model. There is always some scope in a model for further improvement.

Third phase is implementation phase e.i. calibration of the model. Here certain value to the parameters of the model depending upon the initial conditions and other characteristics of the catchment are allotted. Also probable range of the values of these parameter is identified. Then model is run and results so obtained are compared with the already available results. Sets of parameters of different values are tested and most appropriate one is finally selected. Here it may be noted that at this stage some modification in the structure or formulation of equations may be needed if results are not satisfactory.

Fourth and final phase is validation or testing of the model. Here a separate length of record not used in the calibration phase is applied on the model parameters of which are already been known from the third phase. Results of this run are compared with the available records. If model is still performing satisfactorily then it is treated as final.

5.0 COMMON PROCESSES GENERALLY CONSIDERED IN WATER BALANCE MODELS

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 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.

6.0 SOURCES OF UNCERTAINTY IN SIMULATION MODELLING

The disagreement between recorded and simulated output may be resulted because of four sources of uncertainty : (i) Random or systematic errors in the input data e.g. precipitation, temperature or evapotranspiration used to represent the input conditions in time and space for the catchment. (ii) Random or systematic errors in the recorded output data, e.g. water level or discharge data used for comparison with the simulated output. (iii) Errors due to non-optional parameter values (iv) Errors due to incomplete or biased model structure.

7.0 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 historical streamflow hydrograph as 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 historical 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 qualities nature of the "objective". Another limitation was that the parameter estimation had to be done by trial and error.

7.1 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. Some of the most commonly used objective functions are described hereunder.

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

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

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

Minimisation of the sum of absolute differences, SUMAB which is determined as :

$$SUMAB = \sum_{j=1}^{N} | QHIS_j - QCOM_j | \tag{3}$$

Minimisation of the sum of absolute of the differences, SUMABR which is determined as :

$$SUMABR = \sum_{j=1}^{N} \left| \frac{QHIS_j - QCOM_j}{QHIS_j} \right| \tag{4}$$

Minimisation of the sum of the absolute differences of logarithms, SUMABL which is determined as :.

$$SUMABL = \sum_{j=1}^{N} \mid \log(QHIS_j) - \log(QCOM_j) \mid \tag{5}$$

Minimisation of the sum of maximum differences, SUMMAX which is determined as:

$$SUMMAX = Max(QHIS_j - QCOM_j) \qquad \text{for all } j \tag{6}$$

It has been suggested not to relay completely in one objective function. Some objective functions tend to give better fit for large flows than the low flows and some tend to reverse of it. Therefore, alternative objective functions may also be tried. Another advice is that, even when trying alternative objective functions, one should always use the graphical comparison of the historical and simulated streamflows. Some other criteria may be the comparison based on efficiency.

Following are some of the efficiency based criteria:

(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,

$$NTD = 1 - \frac{\sum_{j=1}^{N} (QCOM_j - QHIS_J)^2}{\sum_{j=1}^{N} (QHIS_j - ABOBS_i)^2} \tag{7}$$

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

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

$$EFFI(\%) = \frac{\dfrac{(QHIS_j - AVOBS_i)^2}{NM - 1} - \dfrac{(QHIS_j - QCOM_j)^2}{NM - NP}}{\dfrac{(QHIS_J - AVOBS_i)^2}{NM - 1}} * 100 \tag{8}$$

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 criterian based on monthly mean values (EFFIM) is as follows

$$EFFIM(\%) = \frac{\dfrac{(QHIS_j - QMOBS_j)^2}{NM - NM1} - \dfrac{(QHIS_j - QCOM_j)^2}{NM - NP}}{\dfrac{(QHIS_j - QMOBS_j)^2}{NM - NM1}} * 100 \qquad (9)$$

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.

8.0 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 to 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 relay completely in 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 lines 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 to begain 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 cover and the slope would be important as well. For instance, basins with steeper slopes would have smaller surface storages than basins of milder slopes. Likewise for groundwater storage, especially if such estimate is for the dry season, is to consider that the flow volume during the dry season is a fraction of the groundwater storage available.

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.

9.0 OPTIMIZATION ALGORITHM

Since the values of computed discharge are obtained by a rather complex sequence of calculations, the minimization problem of the selected objective function can not be done explicitly but by either trial and error or by a more formal optimization procedure.

Constrained Rosenbrock optimisation technique which is basically a search algorithm proposed by Rosenbrock (1960) may be 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. Programme can be suitably modified 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.

10.0 SOME COMMON MODEL STRUCTURES AND THEIR APPLICATIONS TO SOME SELECTED CATCHMENTS OF INDIA

Some common structures based on simple conceptual structures to some complicated conceptual structures of monthly time scale have been discussed in this lecture. This is followed bay a case study.

10.1 Model structures used in the study

10.1.1 *Model 1*

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.

10.1.2 *Model 2*

This is a two parameter model and is extension of model 1. Here, in addition to maximum soil moisture holding capacity parameter (SMAX), one additional parameters is used to define the threshold value for FSR.

Structure of model 1 and model 2 is given in Figure 2.

10.1.3 *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 :

$$Y = (X-\lambda Z_p)^2 / X+(1-2\lambda)Z_p \tag{10}$$

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.

10.1.4 *Water Balance (1) Model*

This model consists of 5 parameters. Two storage 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.

10.1.5 *Water Balance (2) 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. 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.

10.2 Case study

In this study, twelve catchments, laying in central India have been considered. India is divided into 11 agro-climatic zones, based on climatological characteristics. Details of catchments considered for the present study, along with their agro-climate zones are presented in Table 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. Catchment area varies from 85 Sq. Km. to 4980 Sq. Km. Monthly rainfall and runoff data availability varies from 6 to 35 years.

All of the arid and semi arid catchments are from Saurashtra region of the Gujarat state.

10.2.1 *Application of models*

At a first step, all the models as described above, 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 laying 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 2A to Table 2C 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 3. 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 2A-2C).

11.0 CONCLUDING REMARKS

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 or 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.

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.

Results of the study indicate that 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 strongly dependent to volume of rainfall and soil moisture characteristics of the catchment.

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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	Year 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
Damanganga	Gujarat	Humid	0.6540	2253.00	10	1974-83	7	3

Table 2A : Comparison of different models based on overall efficiency criterian.

Sr. No.	Basin Name	STAT			STP1			STP2			SCS			WBSIMP			WBCOMP		
		C	V	T	C	V	T	C	V	T	C	V	T	C	V	T	C	V	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	Damanganga	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 2B : Comparison of different models based on monthly efficency criterian.

Sr. No. Basin Name	Model																	
	STAT			STP1			STP2			SCS			WBSIMP			WBCOMP		
	C	V	T	C	V	T	C	V	T	C	V	T	C	V	T	C	V	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 2C : Comparison of different models based on Nash Parameter (NTD) criterian.

Sr. No.	Basin Name	Model 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 3: 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

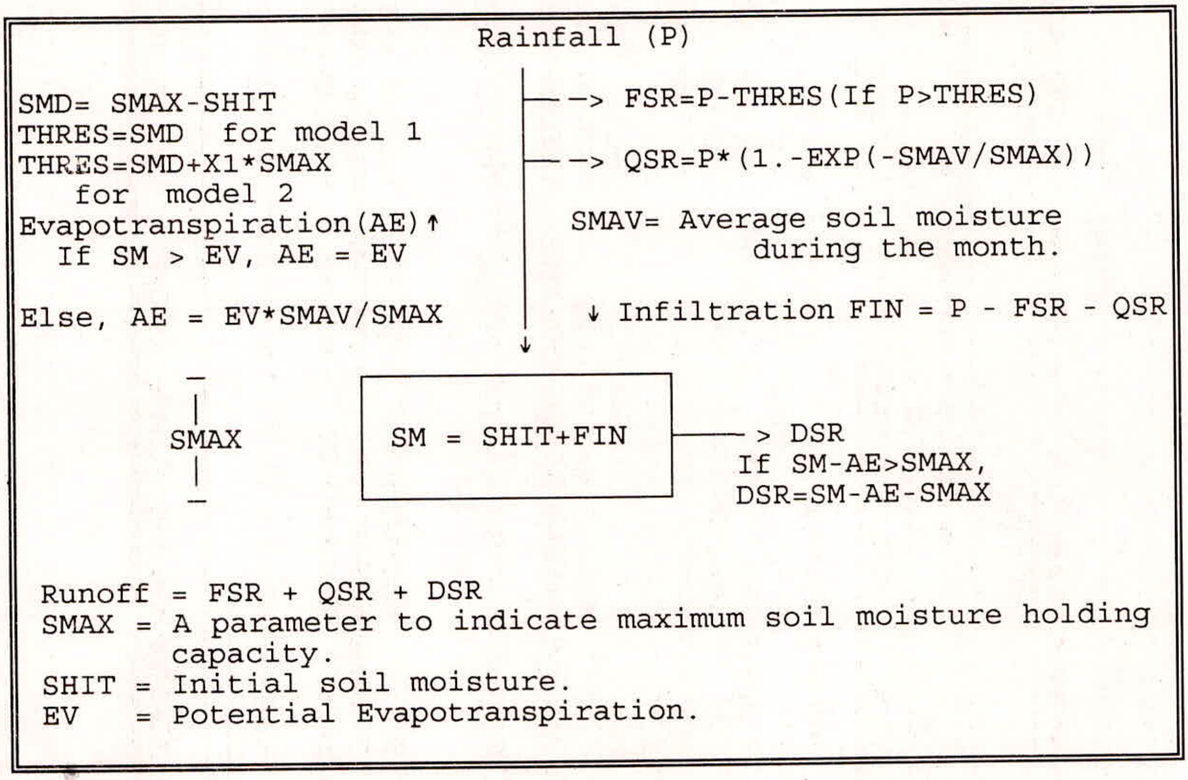
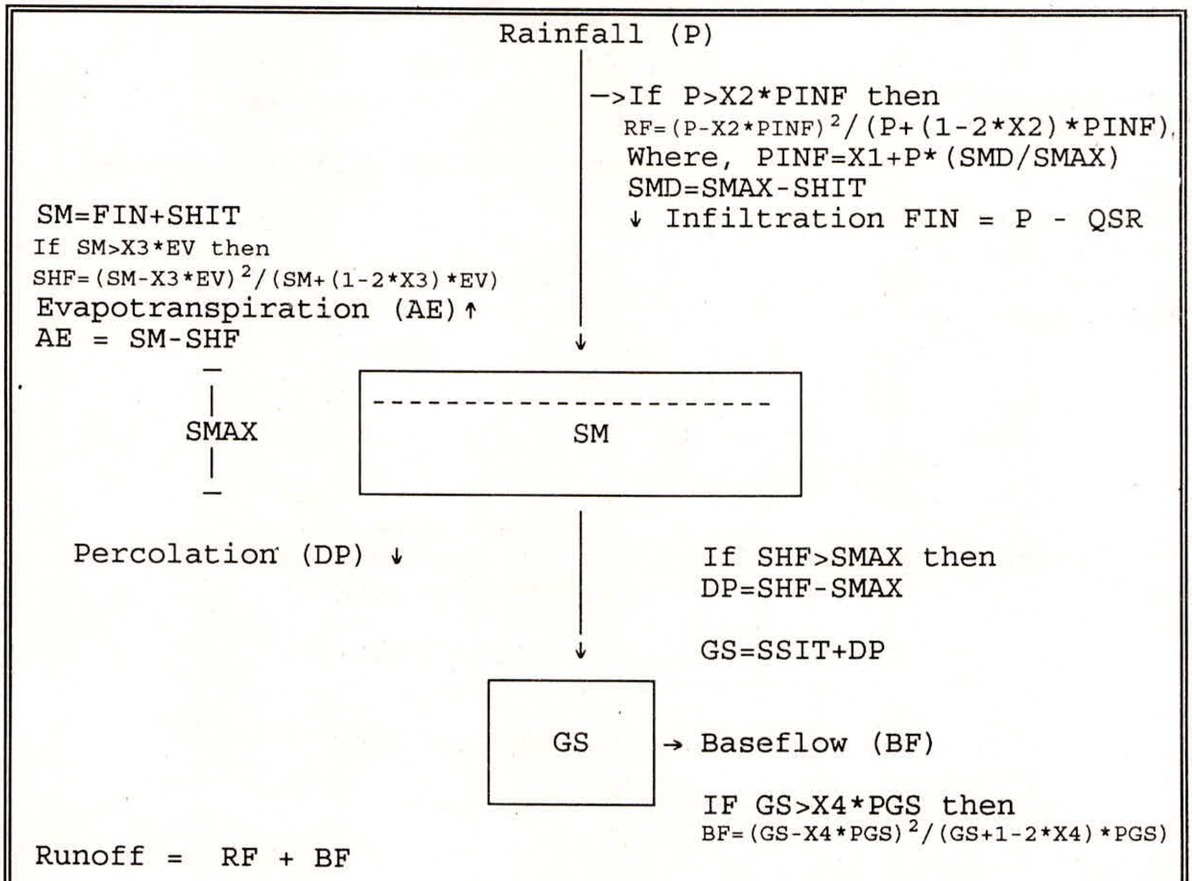
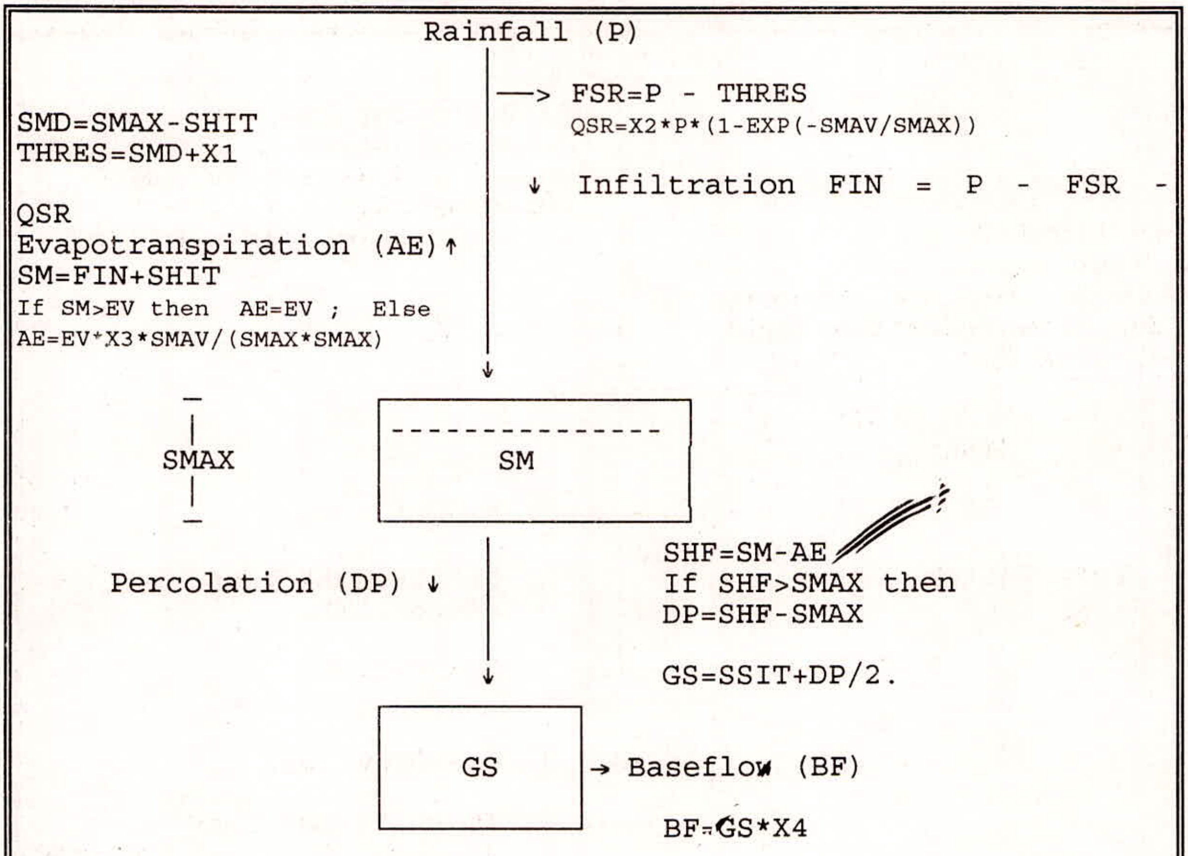


Fig. 1 : Structure and schematic representation of model 1 and model 2.



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

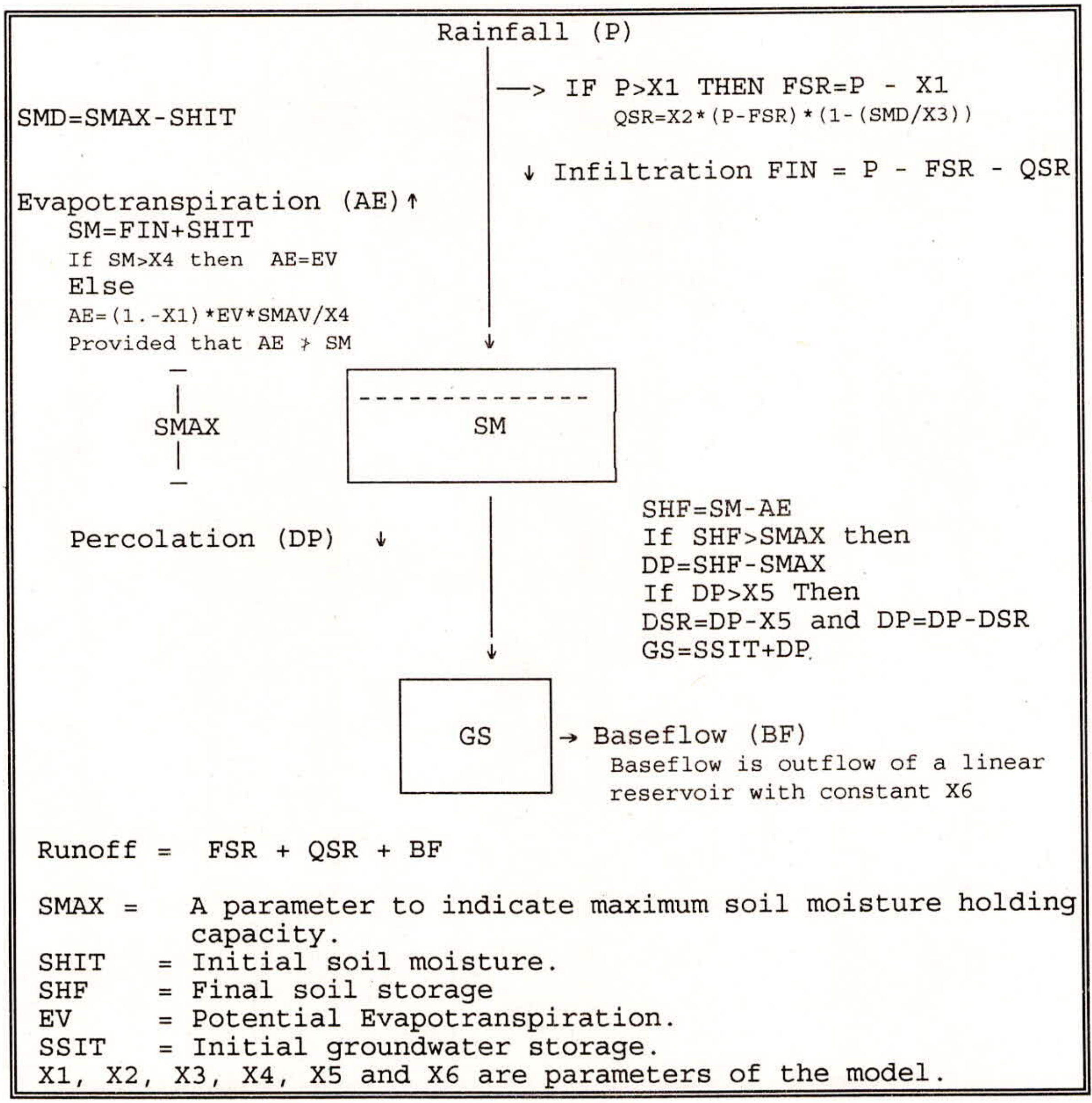
Fig. 2 : Structure and schematic representation of SCS model



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. 3 : Structure and schematic representation of Water Balance (1) model.



Baseflow is outflow of a linear reservoir with constant X6

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, X4, X5 and X6 are parameters of the model.

Fig. 4 : Structure and schematic representation of Water Balance (2) model.