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Application of Sacramento river forecast model to an Indian catchment

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ABSTRACT. Sacramento model, which is a conceptual watershed model, has been applied successfully to the upper Yamuna catchment for runoff simulation at Kalanaur outlet point. The model enables the calculation, in six hourly values, of water transfer (interception, evapotranspiration percolation etc) of the state of different phases of water cycle and of the flow at the oulet of the area (direct runoff, surface runoff, interflow and baseflow). Mathematical functions used in the model formulation in order to represent the physical processes taking place in the catchments, have been described in detail. The physical description of various model parameters and method of their evaluation are also given.

1. Introduction

The problem of determining the river flows from the meteorological data, *i.e.*, rainfall, evaporation etc has been of utmost importance to hydrologists. Despite the availability of long-term meteorological data and the dedicated attentions which this problem has attracted over several years, the present status is still not upto the accepted standard. Simplifications and assumptions made in the techniques developed before mid 1950's, which dates the start of computer application in hydrology, is understandable as hydrologic analysis requires lot of calculations. With widespread availability of digital computers, the hydrological modelling has expanded creditably over the last two decades. Many complex models of the rainfall runoff phase of the hydrologic cycle have been presented.

Mathematical models applicable in hydrological problems are classified depending upon whether the model for linking rainfall and river flow is deterministic, *i.e.*, the model is considered to follow a definite law of certainty, or stochastic, *i.e.*, the chance of occurrence of the variables is taken into consideration. In the other words, concept of probability is introduced in formulating the model. Further the model can be conceptual or empirical depending upon whether the form of the functions used in the model are, or are not, based on the consideration of the physical process acting upon the input variable (s) to produce the output variable (s). Clark (1973) classified these models as :

(*i*) Stochastic — conceptual

(*ii*) Stochastic — empirical

(*iii*) Deterministic — conceptual

(*iv*) Deterministic — empirical.

2. Justification of conceptual model

The rainfall runoff process is deterministic one as it is governed by definite physical laws which, by and large, are known. It might, therefore, seem that solution of the problem in any specific case involves only the application of these laws to the measured rainfall and the boundary conditions which include the physical description of the catchment and initial soil moisture distribution within it. However, due to complexity of the boundary conditions, the solution becomes impractical and some simplifications of the boundary conditions seem necessary.

Nash and Sutcliffe (1973) have discussed in detail the justification of the parameteric approach to the hydrological system. The essence of this approach in the study of the conversion of rainfall into river runoff not by synthesis of physical laws and boundary conditions, but as contained implicity in ranfall runoff records. Hydrologists are aware that these approaches cannot give exact solutions. But they are more concerned with the risk of extrapolating to extreme events not sampled in the record and in

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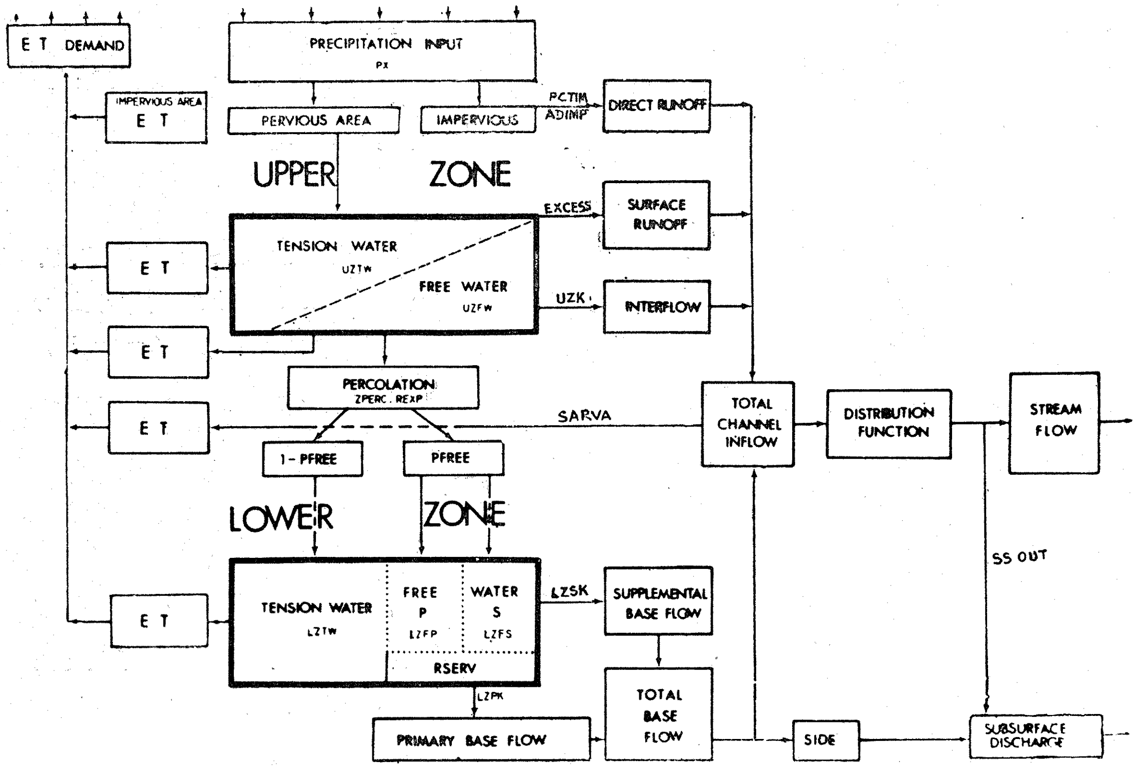

Fig. 1. Block diagram of Sacramento model (Taken from NOAA Tech. Memo NWS HYDRO-31)

the difficulty in extending relation from gauged to ungauged basins.

It has been experienced that neither the co-axial graphical technique for forecasting runoff volumes nor the unit hydrograph technique for forecasting the time distribution of discharge appear capable of further evolution as more efficient tool or as aids to understanding the basin's role in converting rainfall to discharge. The major drawback of these techniques is a prior division of hydrographs into ill defined components, usually known as storm runoff and baseflow. So the necessity of a model to treat the whole hydrograph simultaneously for the conversion of rainfall into river flow is envisaged. Though, the process assumed for this conversion will depend upon the purpose for which the model is to be utilised. Suppose, a model is required only to forecast flow from a particular basin, it would probably be adequate to specify the model's form and parameteric values such that the computed output is a close reproduction of the observed output. On the contrary, if the model is aimed at understanding the process of conversion of rainfall into discharge and the relative importance of different elements in this process, and particularly if it is hoped eventually to use the model for basins without records by establishing relations between the model parameters and basin characteristics, it is desirable that the model should reflect the physical reality as closely as possible and the parameters should be measurable from the physical characteristics of the basins.

In this paper, a deterministic conceptual model developed for stream flow simulation by joint efforts of National Weather Service and Department of Water Resources of California State of U.S.A. (Burnash *et al.* 1973) has been discussed in detail. It is intended to use this model, namely Sacramento model, on some of the Indian catchments, and hence to acknowledge the validity and the efficiency of this model to the catchments which are different in characteristics from those used for its development.

3. Sacramento model

3.1. *Classification*

There is a conceptual model (Burnash *et al.* 1973), *i.e.*, it takes into consideration the physical processes taking place in the catchment. Advantage is that where accurate simulation of the past has been attained, a high degree of conceptuality enhances the capability of predicting future events, specially in the case of extreme events. Models of this type are, therefore, complex and involve a large number of parameters. If the parameters have real physical meaning, good first approximation of their values may be inferred from stream flow records and various observable basin characteristics. These parameters can be altered to reflect changes to the physical characteristics of the catchment.

Further, the model is of the deterministic lumped input, lumped parameter type, *i.e.,* the parameters used in the models are averaged. The originators of the model did, however, include a variable impervious area and an incrementation of lower zone free water when tension water is not completely satisfied. These two features give the model some of the characteristics of a probability distributed parameter model.

3.2. *Model structure*

Two zones, upper and lower are defined. The upper zone represent the upper soil layer and interception storage while the lower zone represents the bulk of the soil moisture and ground water storage. Each zone stores moisture in two forms: "tension water" and "free water". Tension water is closely bound to the soil particles in contrast to the water that is free to move. For any zone, the maximum amounts of tension water and free water which the zone can hold are specified as model parameters and the amounts of water in each of these storages at any time are model variables. The moisture entering the upper zone is stored as tension water until the tension capacity is filled. In the lower zone, however, a portion of the water entering that zone may be diverted to free water storage before tension water is filled. Once tension water capacities are filled, then additional water will be stored as free water. Depletion of free water occurs vertically as percolation, horizontally as channel inflow and non-channel ground water outflow or as evapotranspiration. Tension water is depleted only as evapotranspiration.

For the model to simulate extended periods of fair weather flow accurately, the lower zone free water storage has been considered to be comprised of (*i*) 'Primary' which is slow draining and longer lasting and (*ii*) 'Supplementary' which is faster draining. The two are not equal to each other but their depletion functions are simple and can be identified from the observed stream flow records. The flow of water from the upper zone to the lower zone is expressed by a formula, considered to be the 'heart' of the model, in which a percolation rate 'PBASE' is defined as the maximum lower zone flow-through rate under saturated conditions. Under conditions of unlimited moisture availability in the upper zone the actual percolation rate may vary between 'PBASE' when the lower zone is full and a maximum value which would occur if the lower zone were empty. This maximum rate is defined by a percolation parameter ZPERC such that the maximum rate is equal to the product of PBASE and (1+ZPERC). The variation of percolation rate between the minimum and maximum values occurs as a function of the lower zone deficiency ratio. This ratio (DEFR) is simply the difference between lower zone contents and capacity divided by the capacity. The ratio may vary from zero (lower zone full) to unity (lower zone empty). This deficiency ratio is non-linear and varies with catchments and for this a parameter REXP, depending upon soil type, is applied to the ratio as an exponent. Thus the actual percolation rate under conditions of unlimited moisture availability in the upper zone is given by:

$$\text{RATE} = \text{PBASE}\,(1 + \text{ZPERC}*\text{DEFR}^{\text{REXP}})$$

The true percolation rate is, therefore, the product of 'RATE' and the 'Upper zone driving force', which is the ratio of upper zone free water contents to the upper zone free water capacity.

A portion of the water falling in the basin is deposited on impervious areas directly connected or adjacent to the channel system and thus becomes channel flow. This portion is defined by two parameters representing its minimum and maximum values. The actual areas used in the computation varies between these limits as a function of the amount of water in storage.

3.3. *Flow components*

The model recognises and generates five components of flow:

(1) Direct runoff — from variable impervious area.

(2) Surface runoff — from excess precipitation.

(3) Interflow — lateral drainage from upper zone free water.

(4) Supplementary base flow — lateral drainage from lower zone supplementary free water.

(5) Primary base flow — lateral drainage from lower zone primary free water.

A flow chart is given in Fig. 1.

3.4. *Computational technique*

The movement of moisture through the soil mantle is a continuous process in which the rate of flow at various points varies with the rate of moisture supply and with the contents of various storages. This process is modelled by a quasi-linear computation.

A single time step computation involves the assumption that the movement of moisture during the time step is defined by the conditions at the beginning of the time step. Since this assumption is not valid, a better approximation can be made acceptable only by taking a shorter

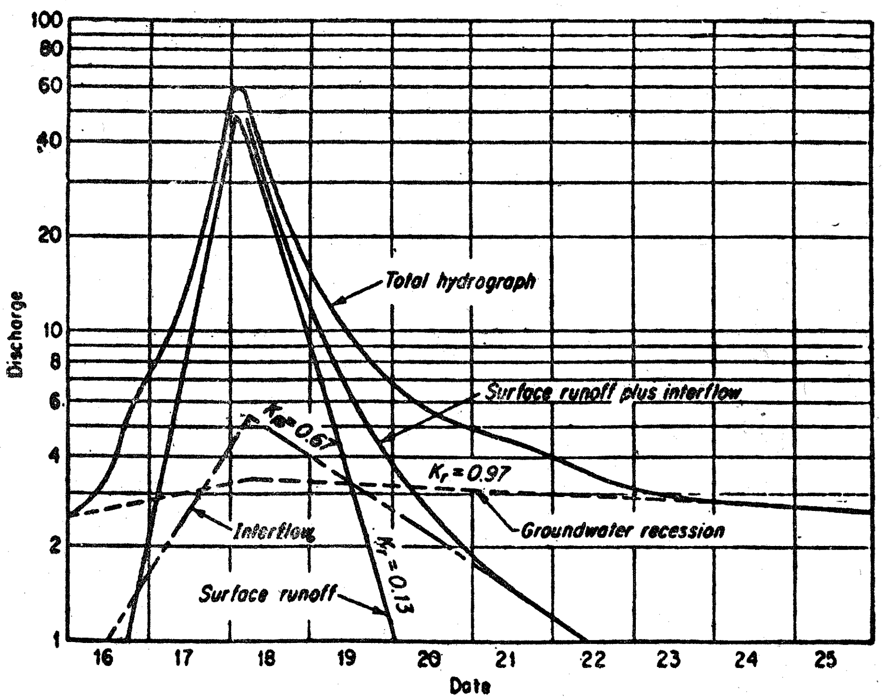

Fig. 2. Semi-logarithmic plotting of a hydrograph, showing method of recession analysis

time step. In the model, the length of the step is volume dependent, *i.e.*, it is selected in such a way that no more than 5 mm of water may be involved in any single execution of computational loop. The 5 mm limit is semi-arbitrary being small enough to logically fulfill its functions and not so small as to consume lot of computer time.

The soil moisture accounting portion of the model involves 17 parameters. The temporal distribution function, which converts runoff volumes to a discharge hydrograph, involves a unit hydrograph and in some application of the model involves moisture input in six hours time periods and computed six hour runoff volumes. The computations are accumulated over six hour period and applied to a unit hydrograph function representing a 6 hour duration event.

3.5. *Calibration*

Calibration or 'parameter optimization' of the hydrologic models is a very difficult problem. Nevertheless, a model is useless if its parameters cannot be evaluated. The problem of calibration becomes more tedious as the parameters increase in number and are interrelated. This model is such that it uses a combination of manual and automatic optimization techniques. The term 'manual' refers here to a procedure in which subjective adjustments to various parameters are made on the basis of specific characteristics of the output of previous computer runs. In the present study of Yamuna basin only manual optimization has been adopted and data for two years have been utilised for calibration purposes.

Calibration of this model requires determination of values of 17 parameters, depicted in Fig. 1. These parameters are defined subsequently. The methods for determining initial parameter values have been described in this paper. The calibrated values of soil moisture parameters for Yamuna catchment are also shown in Table 1.

3.6. *Simulation requirements*

In order to test the validity of the soil moisture parameters, a reasonable estimation of the following three elements is equally important.

These elements are:

(1) *Mean area precipitation* : This includes all the techniques and procedures necessary to arrive at basinwise estimates of mean areal precipitation.

(2) *Estimates of potential evapotranspiration for the basin* : These values can be estimated from meteorological variables or from pan observations. In Sacramento Model, either day by day or long-term values may be used to derive the demand curve.

(3) *Channel routing function* : This may be developed using standard unit

TABLE 1

Manually calibrated values of parameters for Yamuna Basin upto Kalanaur

Parameters		Values
Upper Zone Parameters	UZTWM	90 mm
	UZFWM	50 mm
	UZK	0.30
Percolation Parameters	ZPERC	15
	REXP	2.0
Lower Zone Parameters	LZTWM	40 mm
	LZFSM	105 mm
	LZSK	0.054
	LZFPM	100 mm
	LZPK	0.006
	PFREE	0.50
	RSERV	0.30
	SIDE	0.0
	SSOUT	0.0

hydrograph (UHG) techniques. The UHG can be used to determine a time-delay histogram which provides additional options for varying the shape of the routing function if required.

3.7. *Model parameters*

The parameters for model dealing with various phases of the soil moisture accounting are:

Direct runoff

PCTIM = Fraction of impervious basin contiguous with stream channels.

ADIMP = That fraction of basin which becomes impervious as all the tension water requirements are met.

SARVA = Fraction of basin covered by streams, lakes and riparian vegetation.

Upper soil moisture zone

UZTWM = Upper zone tension water maximum capacity in mm.

UZFWM = Upper zone free water maximum capacity in mm.

UZK = Lateral drainage rate of upper zone free water expressed as fraction of contents per day.

Percolation

ZPERC = A factor used to define the proportional increase in percolation from saturated to dry lower zone moisture conditions.

REXP = An exponent determining the rate of change of the percolation rate as the lower zone deficiency ratio varies from 1 to 0.

Lower Zone

LZTWM = Maximum capacity of lower zone tension water in mm.

LZFSM = Maximum capacity of lower zone supplemental free water storage in mm.

LZSK = Lateral drainage rate of lower zone supplemental free water expressed as fraction of contents per day.

LZFPM = Maximum capacity of lower zone primary free water storage in mm.

LZPK = Lateral drainage rate of lower zone primary free water expressed as fraction of contents per day.

PFREE = The percentage of percolation water which directly enters the lower zone free water without a prior claim by lower zone tension water.

RSERV = Fraction of lower zone free water not available for transpiration purposes.

SIDE = The ratio of unobserved to observed base flow.

SSOUT = A fixed rate of discharge lost from the total channel flow.

3.8. *Parameter groupings*

For a realistic conceptual model, good first approximation for some of the parameters may be inferred from streamflow records, precipitation records and other basin characteristics. A reasonable first approximation shall enhance the chances of obtaining the most representative set of parameters for the basin. The model parameters may be grouped according to the methods for obtaining first approximations as follows:

(1) Parameters readily computed from observed hydrograph and precipitation: LZFPM, LZPK, LZFSM, LZSK, PCTIM.

(2) Parameters more difficult to estimate from observed hydrograph : LZTWM, UZTWM, UZFWM, UZK, SSOUT, PFREE.

(3) Parameters estimated from maps of water area: SARVA.

(4) Relative values could possibly be estimated for the following parameters from soil percolation characteristics. However, the best first estimate is to use values from similar nearby basins that have been previously simulated: ZPERC, REXP.

(5) Nominal starting values used: SIDE, ADIMP, RSERV.

3.9. *Initial parameter estimation*

Semilogarithmic hydrograph plots have been used to separate hydrographs into principal flow components of surface runoff, interflow and ground water recession as shown in Fig. 2. It is believed that the base flow can be modelled with two distinct slopes representing two separate sources of base flow with separate exponential decaying functions. For the model being used, these are supplemental and primary free water storages of the lower zone. Analysis of the recession provide methods for estimating the depletion rates and storages for the two zones. This is accomplished for each free water storage as follows:

Primary (LZPK and LZFPM)

Select a period when the recession is the flattest and calculate a slope during this period. Primary daily recession rate is:

$$K_p = (QP_2/QP_1)^{1/t}$$

where QP_2 and QP_1 are the discharge values at lower and higher point respectively for the selected period of the recession curve. t is the time in days for the selected period.

The daily depletion rate is given by:

$$\text{LZPK} = 1 - K_p$$

A value for the maximum free primary water storages may be obtained by dividing the maximum discharge under only primary flow conditions by the daily depletion rate.

$$\text{LZFPM} = QP_{\max}/\text{LZPK}$$

For any other value of $QP < QP_{\max}$, Lower Zone free primary contents are :

$$\text{LZFPC} = \frac{QP}{\text{LZPK}}$$

Supplemental (LZSK and LZFSM)

Computations similar to those used for the primary storage values are used for the supplemental values. In this case, estimation of flow must be subtracted before the slope representing the supplemental base flow is computed.

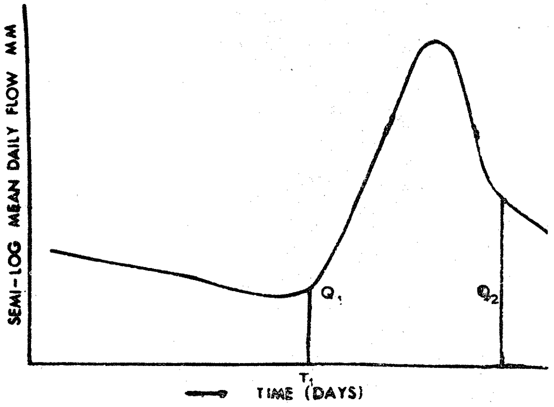

Fig. 3. Hydrograph for determination of LZTWM

Supplemental daily recession rate is :

$$K_s = (QS_2/QS_1)^{1/t}$$

Supplemental daily deplection rate is :

$$\text{LZSK} = 1 - K_s$$

and

$$\text{LZFSM} = \frac{QS_{\max}}{\text{LZSK}}$$

Percent Impervious (PCTIM)

A small rise on the hydrograph during an extended dry period may be used to compute a value for PCTIM.

$$\text{PCTIM} = \frac{\Sigma \text{ Direct runoff}}{\Sigma \text{ Rain}}$$

Direct runoff is computed after subtracting the estimated baseflow from observed flow.

Lower Zone Tension Water Maximum (LZTWM)

Select a period following an extended dry period, as indicated on Fig. 3, where the discharge Q_1 and Q_2 represents only baseflow. A time t_1 should be selected immediately prior to the occurrence of direct and/or surface runoff and time t_2 immediately following a period of interflow.

The discharge Q_1 at t_1 and Q_2 at t_2 can be separated into the supplemental and primary baseflow components by projecting primary baseflow backward from later periods.

At t_1 : $Q_1 = QS_1 + QP_2$ and
at t_2 : $Q_2 = QS_2 + QP_2$

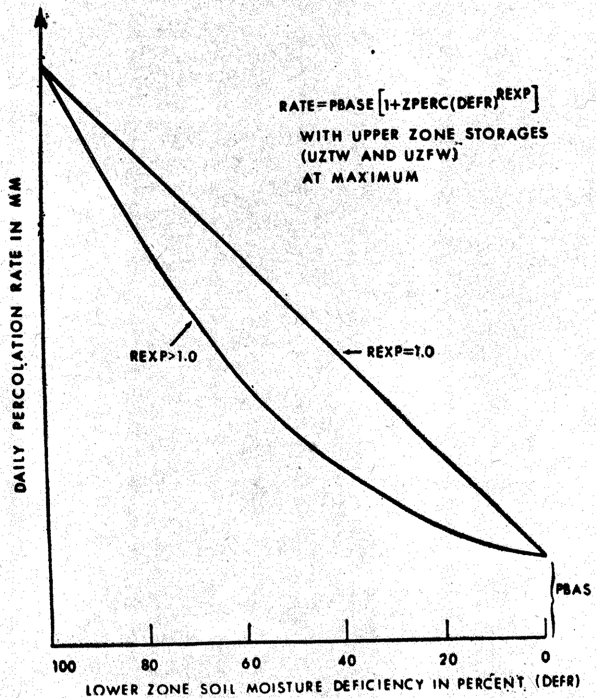

Fig. 4

Primary and supplemental free water storages (LZFPC and LZFSC) for each of two times t_1 and t_2 are computed by dividing the storage by the appropriate drainage rates.

$$LZFPC = QP/LZPK$$
$$LZFSC = QS/LZSK$$

Assuming that UZTW is full and UZFWC is empty at times t_1 and t_2, the water balance for the period may be expressed as:

$$P_X - R_0 - P_E - \triangle LZFSC - \triangle LZFPC - \triangle LZTWC = 0$$

where, P_X is precipitation during the storm in mm.

R_0 is the total runoff in mm.

P_E is the evapotranspiration from the basin in mm.

$\triangle$ LZTWC is the change in the lower zone tension water.

All values except $\triangle$ LZTWC are meaurable or estimated. The $\triangle$ LZTWC represents the increase in the LZTW during time interval considered and not necessarily LZTW being completely filled. Since the LZTW would probably not have been entirely empty prior to the storm, a small percentage (10 to 20 per cent) should be added to $\triangle$ LZTWC to arrive at an estimate for LZTWM.

Upper Zone Tension Water Maximum (UZTWM)

All periods of rain following a dry period are examined to determine the amount of precipitation the previous area can hold without surface runoff occurring. Where the precipitation is associated with more than one period, the entire amount can be used in making the estimate. Suppose there is a 4-day storm of 35 mm precipitation with no overflow, the UZTWM is taken as 35 mm.

Upper Zone Free Water Maximum (UZFWM) and Drainage Rate (UZK)

The upper zone free water storage must satisfy percolation and evapotranspiration demand requirement before any water is discharged to the channel. Thus, it is not a simple depletion as for the lower zone free water storages.

Although UZK cannot be obtained directly from analysis of the hydrograph, since the interflow recession does not produce a straight line on semi-log hydrographs, it is roughly related to the amount of time that interflow occurs following a period with major direct and surface runoff. The longer the period of interflow, the smaller the value of UZK. If we assume that interflow becomes insignificant when its contribution reduces to about 10 per cent of what is at maximum rate, then the following simple relation can be used to compute a value for UZK:

$$(1-UZK)^N = 0\cdot10$$

where, N is the average number of days that interflow is observed.

A value of UZFWM can be determined using the UZK computed above and the discharge, corrected for supplemental and primary baseflow, at the time of the highest interflow without surface water contribution. Then UZFWM:

$$UZFWM = \frac{\text{Max. Interflow}}{UZK}$$

Percolation Water Percentage (PFREE)

An estimate of the relative importance of PFREE can be determined from investigating storms following long dry spells that do produce runoff (UZTW completely filled). If the hydrograph returns to approximately the same baseflow as before (indicating little or no addition to the lower zone free water storages), then PFREE is of little significance and has a very small value ranging from 0 to 0.2. If there is a significant increase in baseflow following this type of storm, then PFREE can have a value as high as 0.5. The nominal value for PFREE is 0.3.

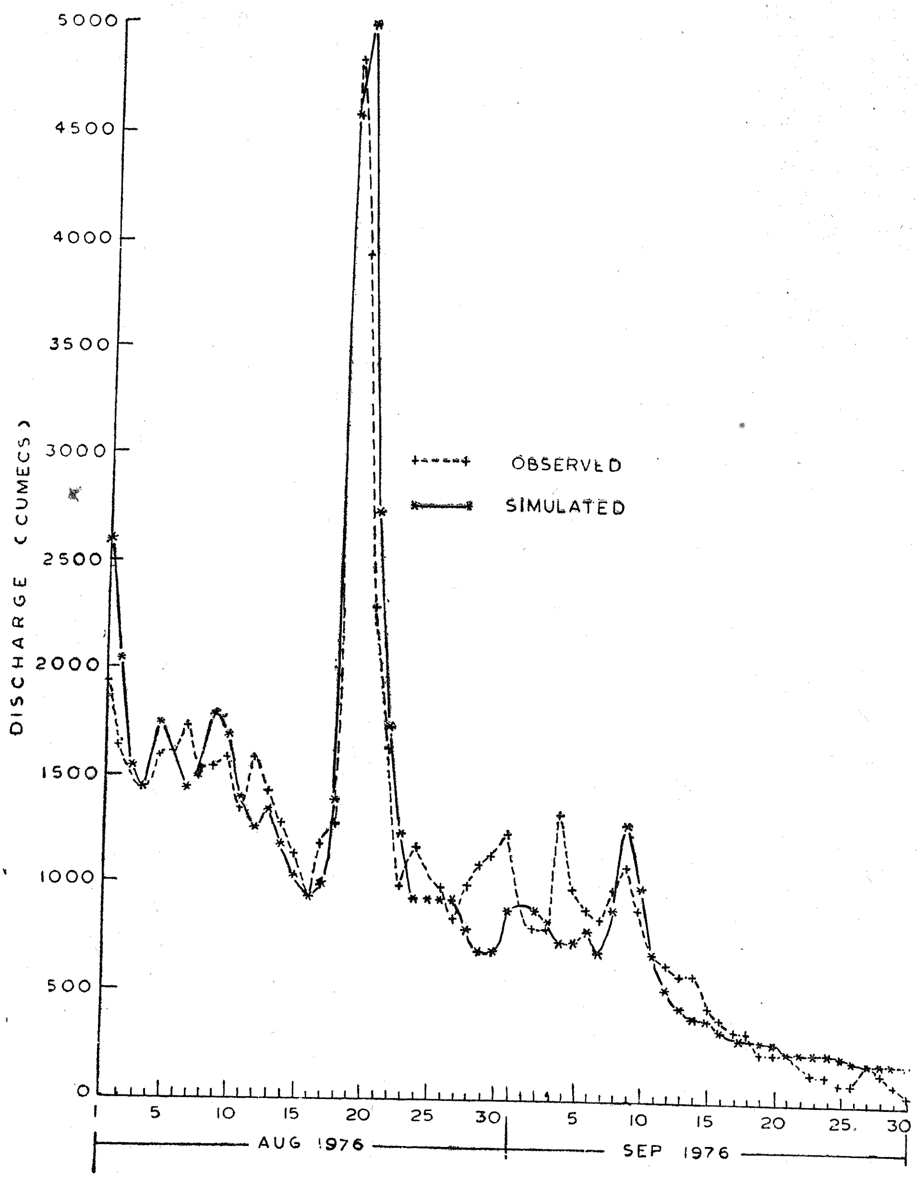

Fig. 5. Daily simulated and observed hydrographs

Sub-surface Outflow Along Stream Channel (SSOUT)

It is recommended that the value of zero be used. A value for SSOUT other than zero can be applied only if the Q-log plot requires a constant addition to the baseflow in order to achieve a valid recession characteristics.

Fraction of Basin Covered by Streams etc (SARVA)

This factor is determined directly from maps showing water and riparian vegetation areas.

Percolation Parameters (ZPERC and REXP)

These are the most important parameters of the model as they are mainly responsible for the interaction between lower zone and upper zone. Fig. 4 demonstrates the part played by the parameters in determining the maximum rate of percolation in relation to the lower zone soil moisture deficiency (DEFR). This curve represents the rate if the upper zone free water is full.

If the lower zone free water storage are full (and the upper zone free water is also at its maximum), then the rate of percolation is equal

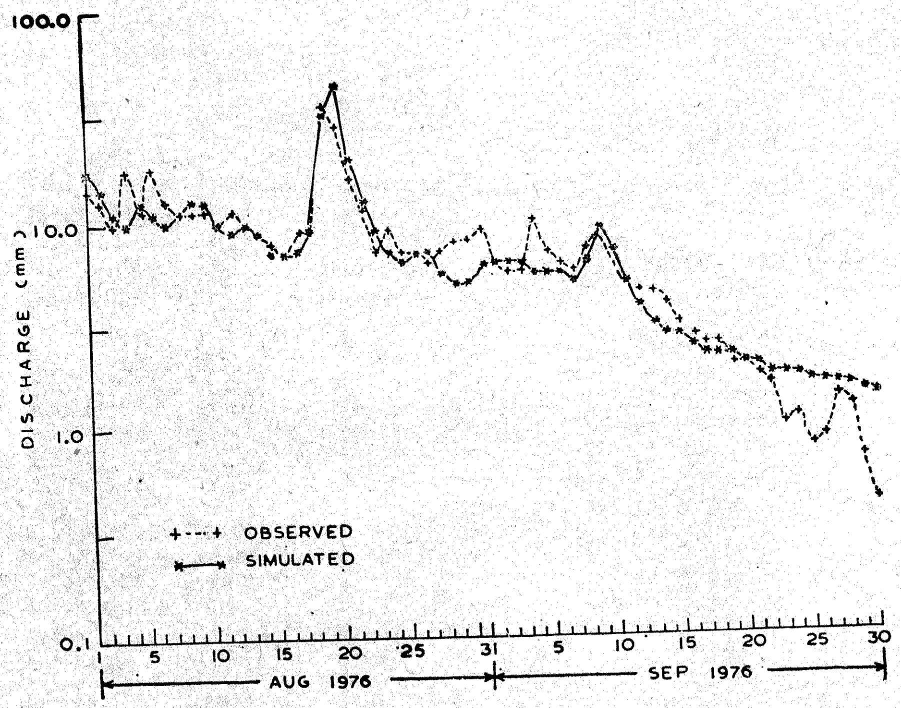

Fig. 6. Semi-log plot of observed and simulated hydrographs

to PBASE, which is defined by:

PBASE = (LZFPM*LZPK + LZFSM*LZSK)

This is the maximum outflow that can occur from lower zones and under steady conditions would represent the percolations to replace the amount removed from the base-flow. As the lower zone soil moisture becomes deficient, the lower free percolation rate increases. When the lower free water storages are completely dry (100 per cent deficient), the percolation rate (assuming UZFW full) occurs at its maximum rate. This is equal to:

Max. percolation rate=(1 + ZPERC)* PBASE

The shape of the percolation curve is determined by the parameter REXP as shown in Fig. 4.

Initial values of ZPERC must be estimated using possible maximum percolation rate that would be expected for the basin when the upper zone free water storage is full. Once an initial simulation is made, the four parameters (ZPERC, REXP, LZFPM, LZFSM) controlling the percolation curve are very important for improving the simulation fit.

Parameters Requiring Nominal Starting Values (SIDE, ADIMP and RSERV)

SIDE = 0 If considerable ground water bypassed the surface channel, a value other than zero should be used.

RSERV=0.3 It is that fraction of the lower zone free water which is unavailable for transpiration.

ADIMP=0.1 This is addition area of the basin which becomes impervious as all tension water requirements are met. Its value may be higher for heavy rainfall areas.

4. Discussion of results

In this study, Yamuna catchment, upstream of Kalanaur has been taken. The area of the catchment is 12150.0 sq km. This study is intended to explore the possibility of applying Sacramento model to Indian catchments. Inspite of scarce data available for this catchment (only high flow data was available), very encouraging results have been obtained. Fig. 5 shows the simulated and observed plot for high flow season for the year 1976 (August and September only) and Fig. 6 shows the semi-log plot for the same period.

For evapotranspiration demand curve, monthly mean evaporation data of Dehra Dun Agro-Meteorological Observatory (India Met. Dep. 1970) is used. It is questionable to use same evapotranspiration demand curve for such a vast and meteorologically heterogeneous area but there was no other alternative due to the non-availability of the data. Considerable improvement in the simulation may be envisaged pertaining to a better data base, *i.e.,* if true mean areal precipitation values, preferably at 6-hr interval from adequate network of raingauges and representative evapotranspiration demand over the catchment area available. Nevertheless, encouraged by the results of this study, with even scarce data, further studies over other Indian basins have been taken up and the first in this series is Krishna basin, for which considerable data are available. The results of these studies will be brought out in subsequent papers.

5. Conclusions

The Sacramento model has the requisite potential for the stream flow simulation based on hydrometeorological data. The only difficulty faced by the authors, at the moment, is the non-availability of adequate hydrometeorological data over the basins.

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