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A Variable Source Area Watershed Model For Western Ghats

R. Yadupathi Putty* and Rama Prasad**

* Research Scholar
** Professor
Department of Civil Engineering
Indian Insitute of Science
Bangalore (INDIA)

ABSTRACT

A simple conceptual lumped parameter watershed model developed in Ketucky for simulating daily streamflow has been modified to suit the conditions of small catchment areas in Western Ghats, in South India. The model is based on the principle of variable source area of streamflow generation. The performance of the model, which takes daily rainfall and potential evapotranspiration as the only inputs, has been tested using data from two catchments. Model parameters have been optimised by trial and error eyeballing best fit procedures. Results being encouraging, the response of the catchments to rainfall input has been studied with the aid of the model. It has been concluded that the model provides scope for further refinement and use in ungauged catchments.

INTRODUCTION

The importance of Western Ghats, as far as surface water resources of the State of Karnataka are concerned, is best realised by noting that about 25% of the total area of the state draining their slopes yields more than 80% of the surface waters of the state (Rama Prasad and Malhotra, 1984). Western Ghats border the west coast of India, throughout its length. The stretch of these Ghats in Karnataka consists of numerous peaks reaching nearly 2000 m. While the western slopes of these ranges in Karnataka are very steep, on the eastern side they extend deep into the plataeu for a width of about 40 kms. These ranges form a physical barrier for monsoon clouds originating in the Indian ocean. Hence these regions experience very heavy and almost continuous rainfall during the South West monsoon, which lasts between the months of June and November. In addition, soils in the region are well developed and hence Western Ghats house some of the richest evergreen forest patches of the country (Pascal, 1988). Because of these reasons, streams in the 'Malnad' area are perrenial sources of surface water locally, in addition to being the source of all major rivers of peninsular India. Hence, Western Ghats form an area of hectic activity.

However, over the years very little attention has been paid to the hydrological aspects of design in planning either water resources projects or watershed development practices being taken up in the area and to the implications of the activities on the hydrology of the area. This is inspite of the fact that the Water Resources Development Organisation of the Karnataka Irrigation Department has been maintaining quite a few daily read stream gauging stations and several other agencies are maintaining a sufficiently large number of rain gauges. Records of these gauges, however, provide scope for studying the catchment response to the rainfall input and then for extending their use to design hydrological elements of ungauged catchments in the area. This is best done by simulating the processes in gauged catchments using a suitable analytical model, which considers the physical characteristics of the watershed as parameters.

Some of the models generally adopted in India for studying rainfall-runoff relationships include the unit hydrograph method (Directorate of Hydrology, 1986) and the curve number method (C.U.S.C., 1972). Although application of more sophisticated conceptual models for hydrological studies has been rather limited, a few have been reported (Ramasastri, 1990, K.E.R.S., 1987 and Veeraiah, 1989). However, all these models are founded on the principle of "infiltration excess over land flow" and hence give more importance to the surface flow component of stream discharge. Such models fail in case of Western Ghat catchments (Prakash, 1991) since delayed flow in these watersheds forms a major component of the total runoff and surface runoff is found to be too low. This calls for use of more sophisticated models, developed based on the "dynamic source area" and "through flow" concepts. This paper explains application of a modified version of such a model developed by Moore et al., 1983, in Kentucky, on two catchments in Western Ghats in Karnataka. The model applied is a lumped parameter conceptual model, capable of generating daily streamflow, taking rainfall and evaporation data (Mohan and Rama Prasad, 1984) as the inputs.

The model is based on the principle of variable source area of streamflow generation developed by Hewlett (Hewlett and Nutter, 1970) and extended by Jones, 1979. According to this theory the quick flow in a stream is contributed mainly by a part of the catchment which gets saturated due to continued rainfall. This contributing area expands and contracts depending on the moisture status of the catchment and hence is called the variable source area. In Western Ghats, the extent of the source area is further influenced by flow of water in pipes formed within the soil mantle. This flow which contributes both to quick flow and delayed flow is often called the lateral through flow.

STRUCTURE OF THE MODEL

The model considers a day's runoff to consists of three components, the saturated source area `quick flow', the unsaturated upper soil zone macropore seepage - the `throughflow' and the saturated soil zone discharge - the `delayed flow'. Rain falling on the catchment in excess of interception is divided between the variable source area runoff and infiltration into the soil, assuming that the infiltration capacity always exceeds the rainfall intensity. The extent of saturated area is estimated as an exponential function of the moisture retained in the catchment. The water absorbed by the ground temporarily remains stored in the upper

Structure of the model

Figure 1. Schematic representation

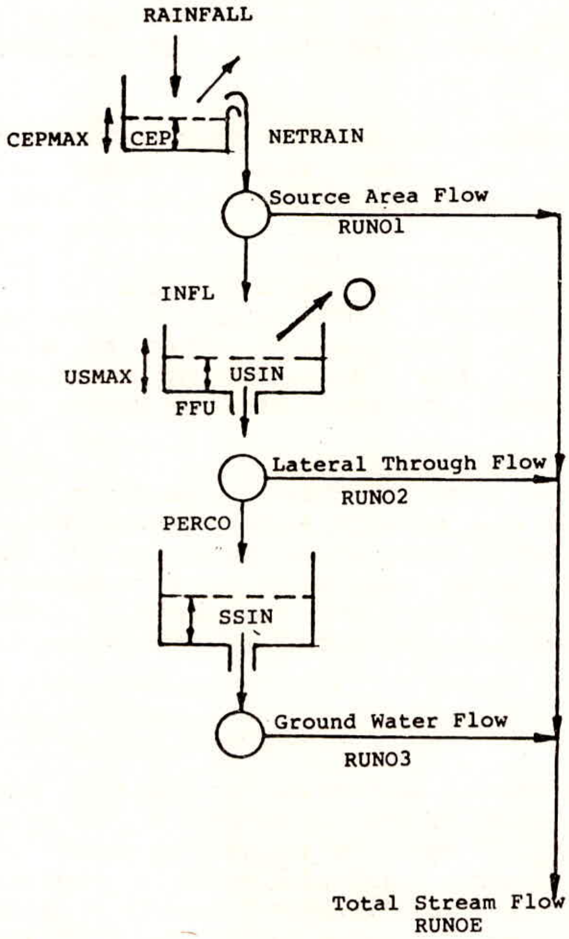

Table 1. Mathematical formulation

Interception:
CEP = RAIN   RAIN < CEPMAX
CEP = CEDMAX   RAIN > CEPMAX

Throughfall:
NETRAIN = RAIN - CEP

Source area runoff:
RUNO1= PB * NETRAIN
PB = PBI + PC * EXP [(K1*USIN +K2*SSIN)*KC/CMMAX]

Infiltration:
INFL = (1- PB) * NETRAIN

Drainage:
FFU = FU * (USIN/UST)**KU

Lateral throughflow:
RunO2 = FFU * K3

Vertical Drainage:
PERCO = FFU * (1 - K2)

Evapotranspiration:
AET = EVP *(USIN - USWP)/(USMAX-USWP)
EVPT = CEP + AET ; EVPT < PEVP
= PEVP ; EVPT >PEVP

GW discharge:
RUNO3 = FS *(SSIN)**KS

Total discharge:
RUNOE = RUNO1+RUNO2+RUNO3

RAIN	: daily rainfall (mm)
NETRAIN	: throughfall (mm)
PB	: source area extent
INFL	: daily infiltration (mm)
FFU	: daily drainage from upper zone store (mm)
PERCO	: daily vertical percolation (mm)
USIN	: upper soil zone moisture store (mm)
SSIN	: ground water zone moisture store (mm)
EVP	: evoporation (mm/day)
EVPT	: evopotranspiration
PEVP	: potential Evpt.(mm/day)

soil zone. Flow occuring out of this storage is taken as equal to the unsaturated hydraulic conductivity of the soil, determined as a function of the water content. This quantity of outflow is divided between two components - the vertical percolation into the ground water table and the lateral through flow in a constant proportion. The delayed ground water discharge is estimated as a nonlinear recession function. Evaporation is allowed at the potential rate from the interception store and actual evapotranspiration from the soil zone is calculated as a linear function of the available moisture and the potential rate.

The mathematical formulation of the model is given in Table 1 and its schematic representation is shown in Figure 1. Table 2 gives the description of the parameters and their calibration procedure.

Expressions adopted, in the present study for calculation of unsaturated hydraulic conductivity, the ground water recharge and its discharge are the same as those used by Moore et al., 1990. These authors give a detailed description of the expressions and hence the same is not repeated here. However, the concept of field capacity is introduced in the present model as a modification to the original model. Accordingly, the depletion of the soil zone storage is limited to the field capacity, as described by Beven et al., 1984. The function adopted for estimating actual evapotranspiration, in the present model, is that used by Beven and Kirkby, 1979.

The model being presented takes a major deviation from the original in estimating the extent of the dynamic source area. While the original model estimates the source area as a function of the upper zone water content alone, the model suggested here considers it as a function of both the upper and lower zone storages. The parameters included in this component are empirical as are those in the original version.

CATCHMENTS SELECTED FOR THE STUDY

The two catchments, in Western Ghats, selected for testing the performance of the model are of contrasting characteristics, in many respects. The Yettinahole catchment (27 km^2) lying in the heart of the Ghats consists of moderately sloping hillocks with a maximum elevation of 1298 m. The river flows a distance of nearly 7.5 km upto the gauging site (980 m). The complete area is in the vicinity of the human settlement. While a quarter of the area is under coffee plantations, another 10% forms unirrigated farm land. Paddy is cultivated in the valley portion, where the ground water table can be found very near the surface and a number of springs, called 'Jala', could be detected even during extended dry periods. While the hill slopes near the ridges are covered by pasture forming the 'Gomala' (grazing field), the minor hillocks have scrub forest They respectively occupy about 14% and 8% of the total area. The remaining area is under semievergreen open forest. The mean annual rainfall for the area is around 3050 mm, with quite a few days each year recording more than 150 mm. Soils under the forests and coffee plantations is sandy clay loam with coarse sand. Soils under pasture is clay-loam with coarse sand. The average soil depth for the catchment is worked out to be about 1200 mm.

The Honnammananahalla catchment (4.51 km^2) lying on the steep western slopes of Bababudangiri ranges, a little away from the main ranges of Western Ghats, is completely protected from human interference. The stream falls through a height of about 550 m (1893 m - 1350 m, MSL) in a short distance of about 3 km. More than 75% of the area is under pasture, which goes dry by November implying very low evapotranspiration. The remaining area, surrounding the valleys, is under dense moist decidious vegetation. Soil in the region is considered to be silty clay loam and silty clay with fine sand. The average depth is worked out to be around 800 mm. The soil mantle is highly porous, but has a lower hydraulic conductivity. The average annual rainfall is around 1500 mm. It is seldom that one can find a day recording more than 100 mm, although it rains every day during the South West monsoon.

CALIBRATION OF THE MODEL

The model has 10 parameters, in addition to those estimating the source area, as listed in Table 2. Of these the first five parameters may be approximately determined from topographical, land use and soil survey (Bourgeon, 1989) data. The remaining five parameters can be atleast in principle, determined by simple field measurements (Beven et al, 1984) or by optimisation. In the present analysis rainfall and runoff records of a length of 4 years in case of Honnamananahalla (1985-1988) and of 5 years (1985-1989) in case of Yettinahole have been used to test the performance of the model in simulating streamflow during the monsoon months. First three years' data were made use of for calibration. The remaining length of the records was used to validate the model so developed. The initial values of the parameters, which were not measured on field, have been taken equal to those given by Moore et.al., 1983. The final values were arrived at by trial and error so that the simulated hydrograph matches with the observed hydrograph.

PERFORMANCE OF THE MODEL

The performance of the model has been studied by carrying out various statistical tests of goodness of fit. In addition to the commonly adopted tests of coefficient of efficiency, visual comparison of the estimated and observed hydrographs and graphical comparison of these data, two of the tests mentioned by Aitken, 1973, have been carried out to detect presence of systematic errors. In addition the model efficiency has been compared with that of a linear regression model developed for the purpose. This multilinear regression model, earlier used to establish rainfall-runoff relationships for some larger catchments in Western Ghats (Ravi et al., 1986), uses the 10-day reciprocal antecedent precipitation index (Linsley et al. 1949) and time of the year as additional parameters.

Table 2. Parameters, their description, calibration procedure and optimised values for Yettinahole and Honnamana Halla

Sl. No.	PARA-METER	DESCRIPTION	CALIBRATION PROCEDURE	Optimised values	
1	K1	Coefficients		3.0	3.0
2	K2	used in estimation		1.0	1.0
3	CMMAX	of the extent	Optimisation	2500	2500
4	PC	of the saturated		0.006	0.005
5	KC	source area		6.0	6.0
6	CEPMAX	Maximum interception (mm/day)	from land use data	3.0	2.5
7	PBI	initial value of source area	topo sheets/ site mapping	0.025	0.025
8	UST	Soil (root) zone thickness (mm)	Soil survey data	1200	800
9	USFC	Soil zone field capacity (mm)	Soil survey data	300	100
10	USWP	Wilting Point (mm)	Soil survey data	140	95
11	FU	Soil water conductivity coefficient (Moore et al; 1983) (mm/day)	Optimisation	1.7	4.0
12	KU	Soil water conductivity exponant (Moore et al; 1983)	Field internal drainage test	10.0	8.0
13	K3	Ratio of lateral flow to total drainage	Optimisation	0.15	0.05
14	FS	Ground water recession coeff.	Short duration discharge	0.025	0.008
15	KS	Ground water discharge exponant	measurements & regression analysis	1.0	1.15

The coefficients of efficiency, determined for individual years, corresponding to the two models are presented in Table 3. It may be observed that the model presented performs fairly well in case of both the catchments. While its efficiency is only marginally better than that of the regression model in case of Yettinahole, the improvement in case of the small Honnammanahalla catchment is notable. The goodness of the model can be further understood by noting that Prakash, 1991, has reported 25-day yield simulation efficiencies between 35% and 50% in case of Yettinahole and 24% and 40% in case of Honnammanahalla, for the curve number method of runoff generation. Figures 2 and 3 show the graphical and hydrograph comparison of estimated and actual values of flow. They further show that the model fares well. Results of the two tests carried out to detect systematic errors are more revealing. While the residual mass-curves for the estimated and observed daily flow match fairly well, the residual mass curve coefficients are all above 80% in both cases. This should go to prove that the efficiency of the model has been penalised because of presence of random errors in data.

CATCHMENT RESPONSE TO RAINFALL INPUT

Assuming that the model presented is capable of simulating the catchment response to rainfall input satisfactorily, it would be of interest to take note of some of the features of the output. There is reason to believe that features common to the two catchments would, to some extent, typify the catchments in Western Ghats. Table 4 shows the magnitudes of rainfall, evapotranspiration loss, the three components and the total flow as estimated by the model and the observed flow corresponding to each year. It can be observed that in case of each of the catchments the delayed flow component dominates stream discharge. About 54% of the total flow in case of Yettinahole and as much as 86% in case of the other is simulated as ground water discharge. This may look to be grossly in error. However, one would appreciate this as `fact' if it is noted that the output of Honnammanahalla on the day of highest recorded rainfall of 143 mm was only a mere 18 mm. The maximum value of source area predicted is 12.6%. The corresponding total flow simulated is 29.2 mm, whereas the recorded value for the day is 32.6 mm.

The maximum extent of source area predicted in the case of Yettinahole is 60% of the total area. The corresponding values of estimated and actual discharge are 132 mm and 164 mm respectively. A value of 60% for source area looks odd at the first sight. But as noted by Bonnell and Gilmour, 1978 and explained by Ward, 1984, such a phenomenon is not rare in steadily sloping catchments in exceptionally wet areas.

CONCLUSION

Results and discussion presented here go to prove that the model is suitable for being used to simulate hydrological processes in catchments in Western Ghats. The model provides scope for further

Table 3. Coefficients of efficiency for the physically based model compared with those for the regression model.

		Yettina Hole		Honnammana Halla	
Year	Period	Modified Kentucky	regression model	Modified Kentucky	regression model
1985	Daily	0.677	0.746	0.699	0.269
	F.night	0.901	0.843	0.881	0.323
1986	Daily	0.868	0.871	0.777	0.512
	F.night	0.865	0.871	0.888	0.617
1987	Daily	0.645	0.696	0.736	0.326
	F.night	0.715	0.761	0.836	0.403
1988	Daily	0.647	0.605	0.822	0.843
	F.night	0.969	0.775	0.891	0.903
1989	Daily	0.654	0.714	-	-
	F.night	0.813	0.857	-	-

Table 4. Accumulated values of rainfall (RA), runoff (RO) and of simulated source area runoff (RO1), lateral flow (RO2), ground water runoff (RO3), total runoff (ROE) and Evapotranspiration (ET).

Sl.No.	Variable	Y. Halla	H. Halla
1	RA	15307.0	6414
2	RO	10046.0	4047
3	RO1	3032.0	305
4	RO2	1171.0	213
5	RO3	5429.0	3226
6	ROE	9633.0	3743
7	ET	2419.0	1018
8	RO3/ROE	0.563	0.862

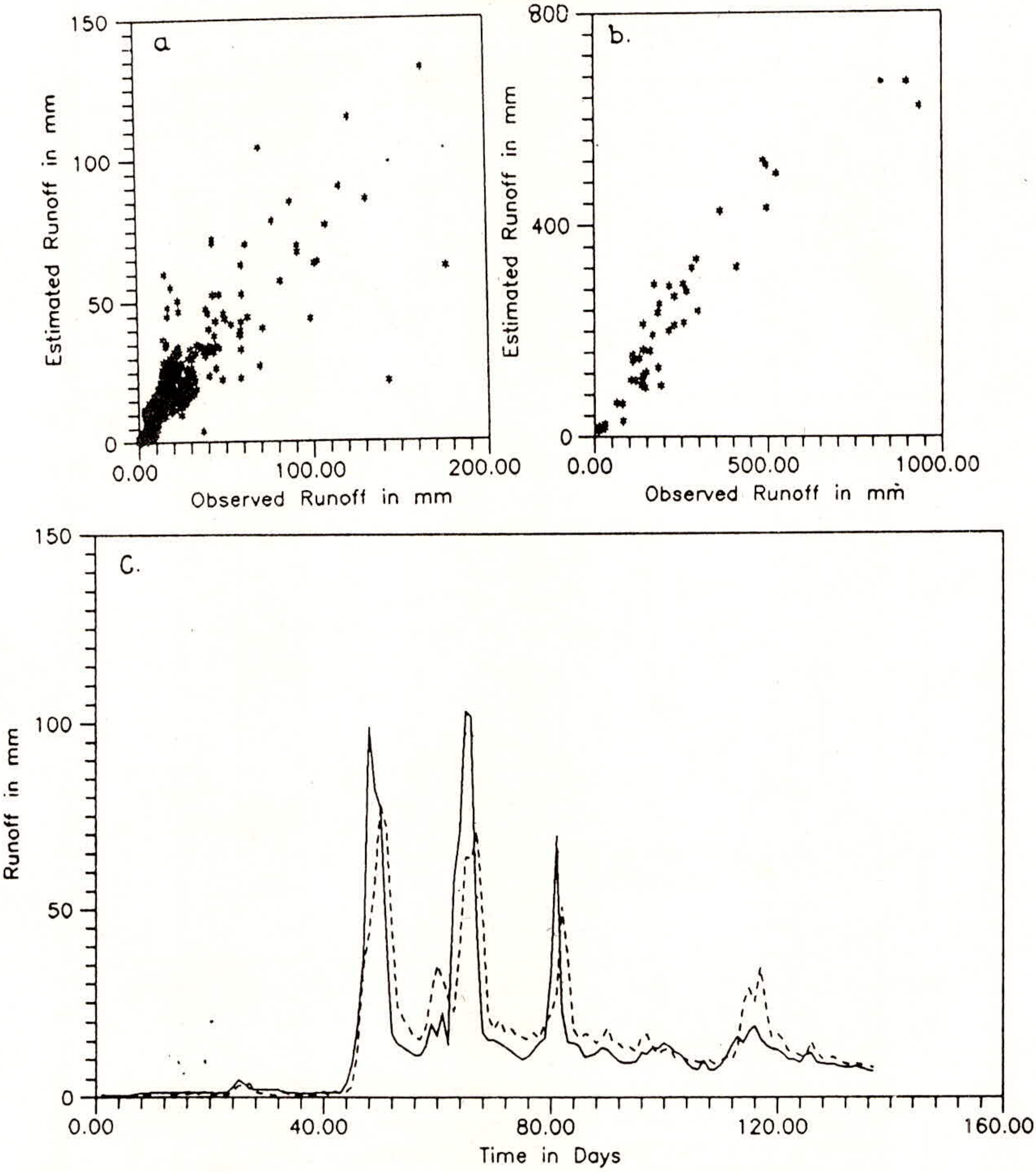

Fig.2.Yettinahole: Runoff estimated by the model compared with the observed values; (a) Daily runoff, (b) Fortnightly Yeild and (c) Hydrographs for the year 1988

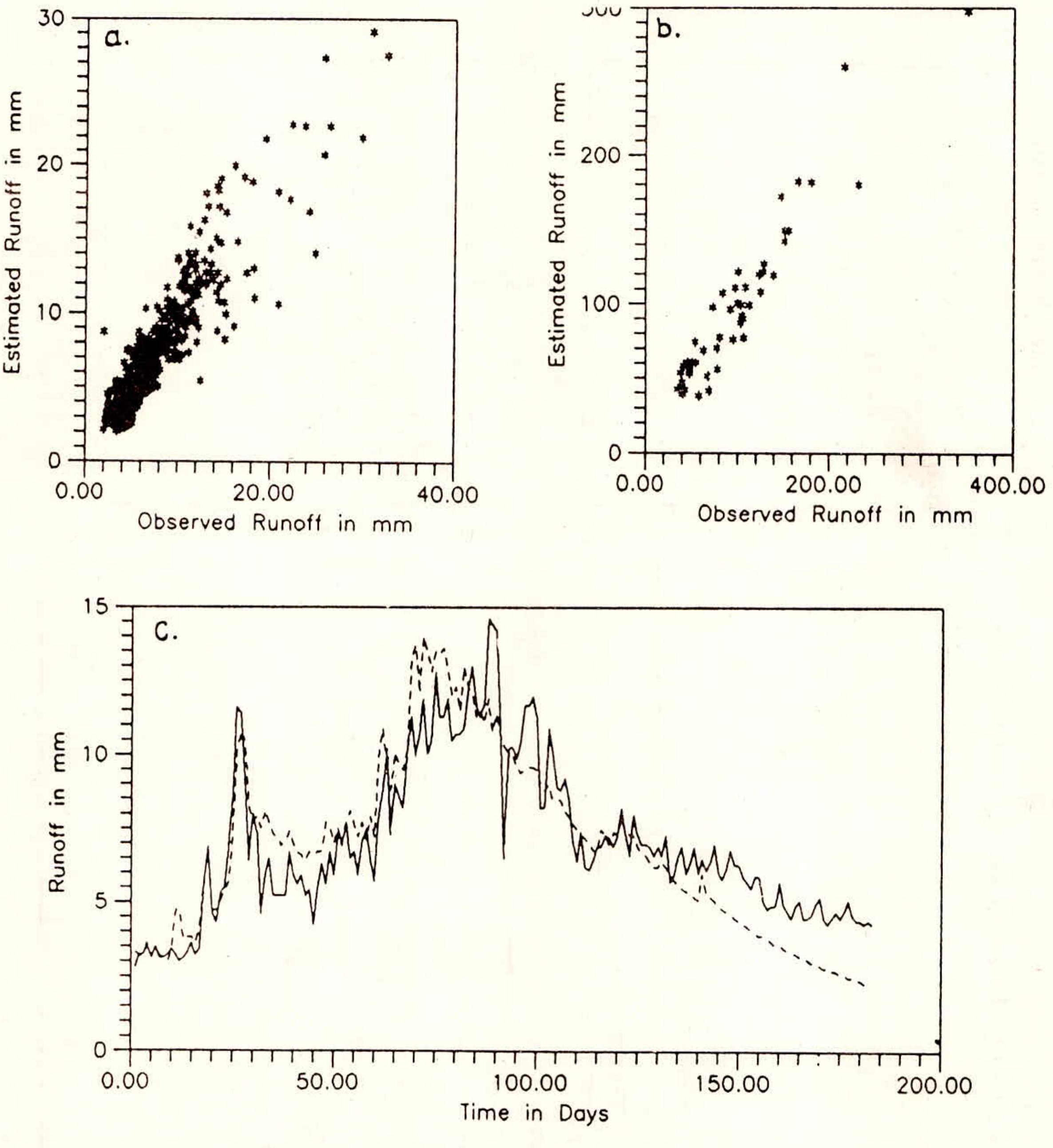

Fig.3. Honnammanahalla : Runoff estimated by the model compared with the observed values; (a) Daily runoff, (b) Fortnightly yield, and (c) Hydrographs for the year 1988

development in order to make it completely physically based so that it would then be applicable to ungauged catchments. Research in this direction is under progress.

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