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Journal of Hydrology 228 (2000) 215–227

Journal of Hydrology

www.elsevier.com/locate/jhydrol

Understanding runoff processes using a watershed model—a case study in the Western Ghats in South India

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Received 6 January 1997; accepted 16 December 1999

Abstract

The wet tropical Western Ghat Mountain ranges in South India present an interesting combination of meteorological and physical characteristics. The results of a watershed model analysis carried out to understand the catchment response and the relative importance of different runoff processes in the region are reported in this paper. A lumped parameter model simulating saturated source area runoff, lateral flow through pipes and the saturated zone groundwater flow, has been developed assuming that source area runoff is the only quickflow component. The model has been calibrated on seven catchments using sufficiently long records of daily data. A wide range of tests has been used to show that the model performs reliably. The influence of catchment characteristics on the relative importance of the flow components and the catchment response has been studied. The model simulations have been interpreted to infer that the pipeflow contributions augment the contributions of source area runoff to stream quickflow. Suggestions for further research in the area are given, based on the inferences drawn. © 2000 Elsevier Science B.V. All rights reserved.

Keywords: Wet mountainous catchments; Variable source area theory; Lumped parameter model; Pipe quickflow; Catchment characteristics; Dynamic contributing volumes; Rainfall influence

1. Introduction

A watershed model is a mathematical representation of the catchment processes capable of simulating streamflow and other outputs of the catchment system, corresponding to any given values of the inputs, mainly precipitation. Hence, the model is normally utilised either for generating streamflow or to determine how runoff is affected by factors such as afforestation (e.g. Aston and Dunin, 1980; Eeles and Blackie, 1993), urbanisation (Smith and Bedient, 1981) or rainfall augmentation (Lumb and Linsley, 1971). As shown by several researchers, however, it is possible to utilise the model as an investigative tool also for learning about catchment response and inferring about the runoff processes in the catchment. For example, Betson (1964) inferred the existence of partial source areas of runoff by his regression model. Freeze (1972) made deductions about soil parameters using a subsurface flow model. Smith and Hebbert (1983) use an unsaturated vertical flow model to infer the influence of soil depth and anisotropy on source areas and runoff. Ward (1984), comparing streamflow predicted by his catchment model with observed flows, suggests physical processes to which the differences between the two are linked. McCord et al. (1991) employ their model

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PII: S0022-1694(00)00141-4

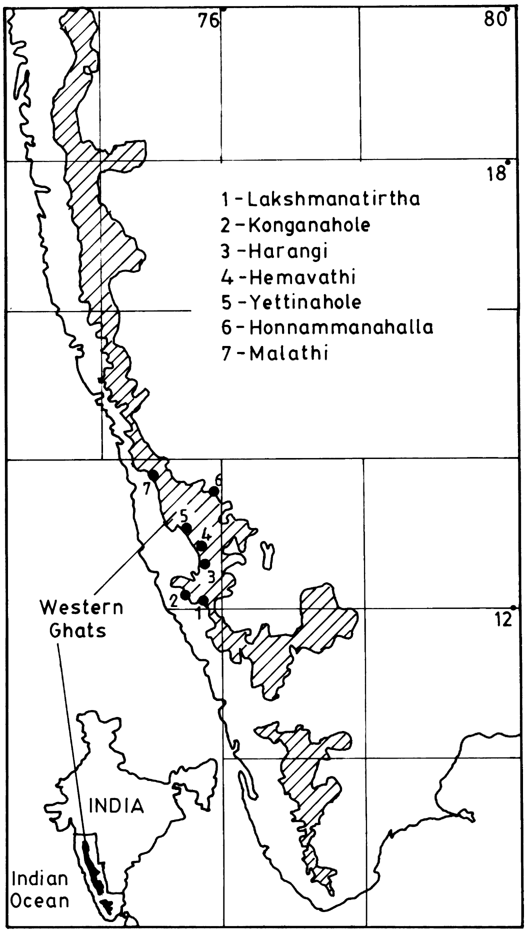

Fig. 1. Location details of the Western Ghats (Sahyadri ranges).

to determine the cause of the anisotropic behaviour and the impact of geology and topography on the flow through sand dunes. The present work, using such an approach, applies a model to analyse the nature of the catchment response in the mountainous region of the Western Ghats (*Ghat* means mountain in Kannada, the regional language), in South India. This region supplies more than 80% of the surface waters of Peninsular India. Annual rainfall in the region exceeds 2500 mm everywhere. But rainfall intensities are most of the time very low and durations are large, despite the region being in the tropics. The soil is deep and has a good structure. Studies on runoff processes in such conditions have not been reported. The present work forms a part of a more detailed research programme undertaken with the intention of learning about the streamflow generation mechanisms in the region. This paper reports results of application of a watershed model developed in accordance with the commonly accepted theories of runoff production in wet mountainous regions, considered worth presenting although the model used is likely to require modification.

2. The study area

The Western Ghats, locally called '*Sahyadri Ranges*' form an unbroken relief dominating the west coast of the Indian peninsula, for almost 600 km, extending between north latitudes of 8 and 21° (Fig. 1).

The area selected for the present study lies between north latitudes 11°30′ and 14°30′, along the Western Ghats. Morphologically, this region can be divided into three zones: (i) the escarpment of the Ghats, which consists of numerous high altitude peaks (maximum elevation 1800 m above MSL), characterised by rounded crests; (ii) the foot of the escarpments on the west, towards which the Ghats descend very fast, characterised by very deep and steep valleys; and (iii) the backslope of the Ghats extending about 50 km into the South Indian plateau, forming the hilly hinterland characterised by numerous peaks of intermediate level. The Western Ghat ranges form a barrier to the monsoon winds originating in the Indian ocean and moving north-east. Hence rainfall in the region is very heavy during the south-west monsoon, which lasts between June and October. Annual rainfall exceeds 6000 mm all along the escarpments, with the wettest areas in the region recording about 7800 mm. Rainfall magnitude decreases steadily towards east, to a minimum of 1200 mm in areas bordering the Ghats. More than 90% of the annual rainfall occurs during the four monsoon months, with an average number of 120–140 rainy days per year. During the monsoon, a major portion of the rainfall is contributed by four to five spells each lasting 8–10 days. During such spells, daily values are very high. However, intensities are relatively moderate and rainfall occurs during most part of the day (Putty, 1994). For example,15-minute intensities seldom exceed 80 mm/h and contribute about 2% of the annual rainfall, while hourly intensities of 60 mm/h contribute less than 1% of the annual rainfall.

Geologically, the study area consists exclusively of Precambrian formations with gneiss and intrusive granites forming the important rock types. The combination of such old rocks and heavy but low intensity rainfall has resulted in a well-developed soil mantle characterising most of the slopes of the Western Ghats. Soil thickness in the region varies between about 3 m on grassed slopes and about 20 m on well-vegetated slopes. Soils in the surface layer are usually sandy loams, characterised by very high infiltration rates, even on the rounded crests of the hills. Forest vegetation in the Western Ghats can be classified into three types: (i) thick evergreen to semi-evergreen forests occupying vast stretches of the steep Appalachian slopes; (ii) the evergreen montane forests confined to the valleys and locally called *Shola*; and (iii) pastures, covering extensive areas on the rounded crests of the escarpment of the Ghats. Large areas of forest in the hinterland have been converted into cardamom and coffee plantations. Yet, the whole of the study area is a region characterised by very high infiltration rates (Putty,1994; Ranganna et al., 1991) and very little surface runoff.

Rainfall in the area being aplenty, numerous perennial streams flow through the Western Ghats in small meandering channels (except in head reaches) with wide valley floors, where paddy is grown. Streams expand their channel during rains and occupy the whole of the valley floors, during floods. Preliminary investigations in the region (Putty, 1994; Putty and Prasad, 1994a) indicate that the mechanism of stream flow generation in the area is well explained by the theory of variable source areas (Dunne and Black, 1970; Hewlett and Troendle, 1975), according to which the storm period direct runoff in the stream is primarily contributed by surface runoff from the saturated source areas of the watershed, augmented by subsurface lateral flow in the near-surface layers of the soil mantle from contributing areas riparian to the stream. A survey of the region during rainy season shows that the wide valley floors which get saturated often during monsoon form potential source areas, and pipe formations, locally called *Jala* (Putty and Prasad, 1994b), supply substantial quantities of subsurface flow. Field investigations also indicate that delayed groundwater discharge also forms a very important part of streamflow in these regions. However, the relative importance of the various runoff mechanisms and the nature and variation of the source areas can only be understood through an intensive study of runoff processes. Such knowledge would be of help in choosing the hydrological design procedures and be of importance in planning watershed management strategies. This is particularly so since planning being done presently in the region (Central Water Commission, 1986; Jain and Ramasastri, 1992; Mallikarjuna et al., 1992; Karnataka Power Corporation, 1994) is completely based on the assumption of predominance of infiltration excess overland flow, which is the mechanism widely believed to be active in the humid tropical areas (WMO, 1983), under which climatic group the Sahyadri ranges may be classified.

A watershed modelling study can be the first step towards the goal of understanding runoff processes. Ward (1984) and others have shown how the analysis of model results can suggest the course of further research. The present study aims at applying a model developed in accordance with hypotheses formulated on the basis of field observations, on a few typical catchments in the region, and to discuss the runoff components and the mechanisms of streamflow generation in the light of the model simulations. It is hoped that the results of the present study will help bring to light some important aspects of the hydrology of the region, which suggest revision of the hydrological design procedures and a change in the approach of the watershed managers, who presently associate soil erosion even on grassed slopes with Hortonian overland flow.

3. Selection of the model

The Western Ghats form an area of hectic activity as far as water resources development is concerned. Hence, streamflow records pertaining to many small catchments of practical importance are available. Further, long and reliable records of rainfall are easily available. However, data is all in terms of daily values and little information is available concerning the hydrological parameters of the soil mantle. Given the purpose and these data limitations, the best choice would be a lumped parameter conceptual model, capable of simulating the various components of streamflow. Such a model incorporating algorithms

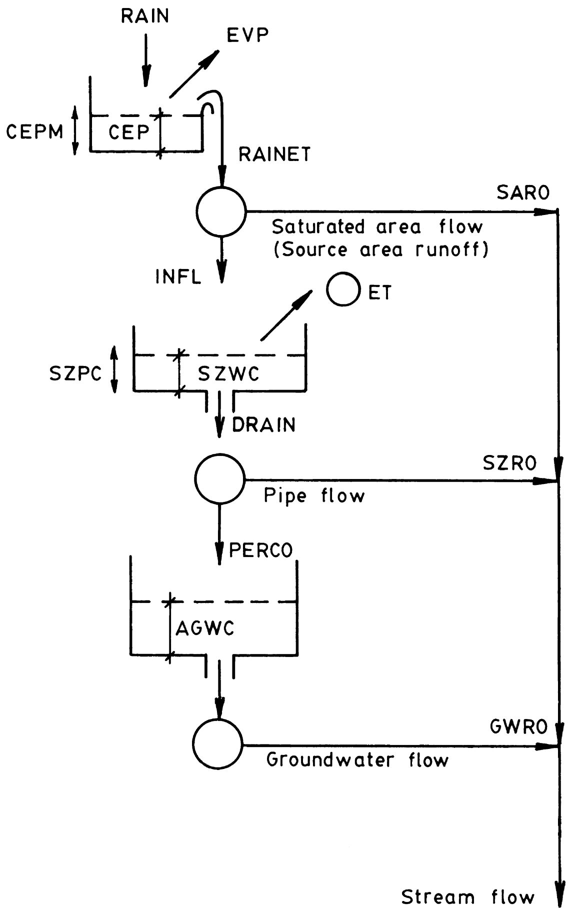

Fig. 2. A schematic representation of the model SAHYADRI.

and assumptions that are compatible with the principles of hillslope hydrology, explained by the variable source area theory, has been developed and used in the present study. This model, called SAHYADRI, is a modified version of the variable source area model developed by Moore et al. (1983). The structure of SAHYADRI is explained below.

4. The model structure

SAHYADRI considers a day's runoff to be made up of three components, the saturated source area runoff (also called quickflow), the soil zone lateral seepage or flow through pipes and macropores (called lateral flow) and the saturated soil zone discharge (called groundwater flow). Field observations at numerous road cuttings (near valley bottoms) showed that even during heavy rainfall events, lateral flow through the soil occurred only through pipes and not through the soil matrix. For this reason, lateral flow is referred to as pipeflow hereafter. It was also observed that areas contiguous to the river, especially where pipes open on to the surface, become saturated and overland flow occurs from there. Hortonian overland flow is not considered in the model, since infiltration rates almost always exceed rainfall intensities in the region, and infiltration excess overland flow is negligibly small (Putty, 1994). Instead, in accordance with the variable source area theory, saturated areas are assumed to develop in the neighbourhood of the stream and all the rainfall over the saturated area becomes direct runoff. The runoff processes are assumed to occur in three conceptual zones—the interception store, the unsaturated soil store and the saturated groundwater store, as shown in the schematic diagram presented in Fig. 2. Rainfall (*RAIN*) in excess of the interception store capacity (*CEPM*) reaches the ground as throughfall (*RAINET*). Throughfall on the saturated portion of the catchment (*SAF*) reaches the stream immediately as source area runoff (*SARO*). Hence

$$RAINET = RAIN - CEP \quad (1)$$

where *CEP* is the interception storage, which equals *CEPM* when *RAIN* is greater than *CEPM*, and

$$SARO = RAINET \cdot SAF \quad (2)$$

It is assumed that the quickflow in the stream, which is that part of a day's rainfall which reaches the catchment outlet the same day, is contributed by the source area runoff alone. Pipeflow runoff is assumed to be slower, and to reach the gauge site over a span of a few days. The source (saturated) area starts developing next to the stream. As rainfall continues over the catchment, and infiltrates into pipes, parts of the pipes near the valley bottom become full due to direct infiltration as well as inflow from upslope. Areas riparian to the channels get saturated as a result, leading to expansion of the source area up the slope. The extent of the source area is therefore a function of net infiltrated water, which is represented by the soil moisture and groundwater stores. Since only a part of the soil moisture (at lower elevations) is in the saturated state, a weighting

Table 1
Parameters of SAHYADRI

1. CEPM:	Interception store capacity
2. SAK:	Source area coefficient
3. SZWK:	Soil zone weighting coefficient for source area
4. SZE:	Source area exponent
5. SZWP:	Soil zone wilting point
6. SZFC:	Soil zone field capacity
7. SZPC:	Soil zone pore capacity
8. SZRK:	Soil zone storage recession coefficient
9. SZROK:	Pipeflow runoff coefficient
10. GZK:	Groundwater zone coefficient
11. GZE:	Groundwater zone exponent

coefficient is to be applied to the soil zone water content. The source area (*SAF*) is modelled as an exponential function of the storage in the soil zone (*SZWC*) and in the groundwater zone (*GZWC*), using the expression

$$SAF = SAK \exp[(SZWK.SZWC + GZWC)/SAE] \quad (3)$$

where *SZWK* is the soil zone weighting coefficient and *SAK* and *SAE* the coefficient and exponent, respectively.

The evaporative demand on the storage in the soil zone is

$$EVPT = EVP - CEP \quad (4)$$

where *EVP* is the potential rate of evapotranspiration and *CEP* the interception.

Transpiration (*ET*) from the soil zone is a function of *EVPT* and the storage available in the zone (*SZWC*), which is supplied by infiltration ($INFL = RAINET - SARO$). *ET* is calculated as

$$ET = EVPT \cdot (SZWC - WP)/(SZPC - WP) \quad (5)$$

where *WP* is the wilting point and *SZPC* is a parameter of the soil zone representing its water holding capacity. The actual evapotranspiration (*AET*) is then the sum of *CEP* and *ET*.

The soil zone storage begins to get depleted due to drainage, when the storage exceeds the field capacity (*FC*). The rate of drainage (*DRAIN*) is taken to be the outflow of a linear reservoir, given by

$$DRAIN = SZRK \cdot (SZWC - FC) \quad (6)$$

where *SZRK* is the soil zone recession coefficient. A constant proportion (*SZROK*, the pipeflow runoff coefficient) of the draining water is assumed to become pipeflow (*SZRO*). A non-linear model for *DRAIN* was found to offer no particular advantage (Putty and Prasad, 1992), and in the interests of keeping the number of model parameters low, the linear model was adopted. The remaining part (*PERCO*) percolates down into the groundwater zone.

The groundwater flow (*GWRO*), which is assumed to form the delayed component of streamflow, is modelled as outflow from a non-linear store as

$$GWRO = GZK \cdot (GZWC)^{GZE} \quad (7)$$

where *GZWC* is the water content in the zone and the parameters *GZK* and *GZE* are, respectively, termed the coefficient and exponent of the zone.

The daily water balance of each zone is maintained separately and the total runoff for any day is calculated by summing the three components. It can be noted that the model takes daily values of rainfall and potential evapotranspiration as the input variables. In case records of daily values of evapotranspiration are not available, values calculated empirically as averages over longer duration may also be used.

Table 2
Catchment details[a]

Catchment/gauge site	Area (km^2)	RF (mm)	RO (mm)	No. RG	Forest (%)	Valley (%)	RR (%)
1 HonnammanaHalla/Attigundi	4.5	1447	895	1	20	5	16.3
2 YettinaHole/Harle	27	3044	2099	4	23	13	6.6
3 KonganaHole/Nadagundi	83	2461	1639	4	26	40	2.2
4 Lakshmanathirtha/Kanur	179	2428	1667	4	38	20	1.4
5 Malathi/Kalmane	266	5660	4701	5	28	18	0.5
6 Harangi/Hudgur	420	2866	1879	6	30	18	2.6
7 Hemavathi	600	2888	1959	6	30	28	0.9

[a] RF: monsoon rainfall, RO: monsoon runoff, RG: rain gauges, RR: relief ratio (maximum altitude difference/distance between the points).

Table 3
Suggested range of values for physically based parameters of SAHYADRI and for the crop factors (CF)

Land-use	Soil-type	*CEPM* (mm)	Soil thick (cm)	*SZFC* (%)	*SZWP* (%)	*CF*
Evergreen forest (dense)	Sandy clay organic	4.5–5.5	150–200	25–30	10–12	1.20
Deciduous/open forest (plantations)	Sandy clay	4.0–5.0	125–175	25–30	10–12	1.00
Scrubby	Gravelly sandy loam	2.5–3.5	50–100	15–20	10–12	0.85
Grassed	Gravelly sandy loam	1.8–2.0	50	10–15	10–12	0.85
Paddy (valley)	Gravelly sandy loam	1.8–2.0	50	20–25	10–12	1.10

The model parameters, a total of 11, are listed in Table 1. Of these, the three concerning the land use and soil characteristics, viz., *CEPM*, *FC* and *WP*, are, at least in principle, physically based and can be determined from a knowledge of the catchment characteristics. Hence, the number of parameters required to be optimised is eight, which is quite reasonable (Beven et al., 1984). With this set of parameters, the trial and error hydrograph matching technique of optimisation itself should suffice. An objective function like the coefficient of efficiency (Aitken, 1983) may also be used as a guide for proceeding with the optimisation.

5. Calibration of the model

The model SAHYADRI has been calibrated on seven catchments, varying in size from 4.5 to 600 km^2, in the Western Ghat regions of the State of Karnataka. The details concerning these catchments are furnished in Table 2. In each case, data for 5 years, corresponding to the season of the south west monsoon (roughly June to September), each consisting of about 120 rain days have been utilised for the study. Outside this season, there is virtually no rainfall, and streamflow becomes too small to be measured with reasonable accuracy. The dry season is therefore not considered. Initial values of the soil zone and groundwater stores used in the model are chosen on an average basis and errors in these values will cease to matter after the first few days because of the very great increase in these stores once rains start. The physically based parameters are determined using the land use data presented in Table 2 and the approximate values suggested in Table 3, for each land use type. The potential evapotranspiration values are input as weekly average daily values, in accordance with the information made available by the Water Resources Development Organisation of the State of Karnataka and Mohan and Prasad (1987) and using crop factors, presented in Table 3, for the different land use types. Calibration of the parameters for the present study was carried out by the trial and error procedure adopting the split record technique. In each case, records of 3 years, showing the greatest, the least and an average value for the difference between seasonal rainfall and measured runoff, were used for calibration and the remaining length of data was used for validation. The trial and error method is considered adequate for the purpose of this paper, which is to analyse the importance of different runoff components. The goodness of the fit of the model was tested by inspection of the scatter diagrams, visual comparison of the hydrographs of estimated and observed runoffs, and by calculating the following three statistics:

1. coefficient of efficiency, defined by

   $$R_E^2 = 1 - \left[\sum (RO - ROE)^2 / \sum (RO - ROM)^2\right]$$

   where *ROE* is the runoff estimated corresponding to a day for which *RO* is the measured runoff and *ROM* is the mean of *RO*;
2. coefficient of determination, R_D^2 which is the square of the correlation coefficient between estimated and observed runoff values; and
3. the residual mass curve coefficient R_R^2, which is the square of the correlation coefficient between the ordinates of the residual mass curves of the estimated and observed runoff.

While R_E^2 is a measure of the overall performance of the model, R_D^2 and R_R^2 provide information concerning the systematic errors (Aitken, 1983) in the model.

Table 4
Optimised values of the parameters of SAHYADRI (*SZWK* = 1.0 for all the catchments)

Parameters	*CEPM*	*SAK*	*SZE*	*SZFC*	*SZWP*	*SZPC*	*SZRK*	*SZROK*	*GZK*	*GZE*
1. HonnammanaHalla	2.00	0.020	400	120	100	360	0.70	0.05	0.0055	1.15
2. YettinaHole	2.50	0.045	400	300	140	500	0.70	0.1	0.0250	1.00
3. KonganaHole	2.50	0.015	300	250	100	400	0.60	0.3	0.0100	1.20
4. Lakshmanatirtha	2.50	0.015	310	250	100	300	0.70	0.3	0.0120	1.20
5. Malathi	2.50	0.085	310	250	100	300	0.70	0.2	0.0120	1.25
6. Harangi	2.50	0.038	350	250	120	300	0.70	0.1	0.0050	1.10
7. Hemavathi	2.50	0.035	350	250	100	300	0.70	0.4	0.0080	1.25

In the present study, these statistics were calculated corresponding to both daily values and weekly sums, and for the individual years separately. The results are presented and discussed below.

6. Model results and simulation

Since soils are deep and very porous in these catchments, groundwater storage is large and plays an important role in runoff generation. Hence *SZWK* is assumed to be unity. Three other parameters, namely *CEPM*, *SZFC* and *SZWP* were given suitable values. The number of parameters to be optimised is thus seven, which is considered reasonable (Beven et al., 1984). The calibrated values of all parameters are shown in Table 4 and the performance statistics in Table 5. The model-estimated means and standard deviations are close to observed ones and the R_E^2 values are high (Table 5). The magnitudes of R_D^2 and R_R^2 suggest the absence of systematic errors. The simulated and observed hydrographs, groundwater runoff, rainfall hyetograph and saturated area as a fraction of catchment area are shown in Fig. 3(a) and (b) for two streams, namely Konganahole (lowest R_E^2) and Malathi (highest R_E^2) for one of the years. These are typical of other catchments and other years also. The statistics of Table 5 and the hydrographs indicate that the model performs well. Using the model as an analytical tool, two aspects of catchment behaviour, which provide information concerning runoff processes and hint at the course of further research that may be taken towards the goal of understanding runoff mechanisms, are discussed below.

6.1. Runoff components

The simulated values of the runoff components, averaged over the length of the data, are shown in Table 6. Groundwater runoff contributes between 30 and 80% of the total runoff. The values of *GZK* and *GZE* from Table 4 suggest that the daily groundwater runoff is of the order of 0.5–1.2% of the groundwater storage, which is reasonable considering that almost

Table 5
Results of the tests of goodness of fit: annual values averaged over the record length[a]

Catchment	Daily prediction							Weekly sums		
	m_o	m_e	s_o	s_e	R_E^2	R_D^2	R_R^2	R_E^2	R_D^2	R_R^2
HonnammanaHalla	7.51	7.33	3.71	3.54	0.75	0.77	0.94	0.85	0.93	0.95
YettinaHole	14.7	15.6	17.8	15.0	0.72	0.76	0.94	0.85	0.90	0.96
KonganaHole	8.9	9.3	11.4	9.3	0.61	0.63	0.95	0.79	0.81	0.96
Lakshmanatirtha	13.4	13.9	14.1	12.0	0.81	0.83	0.94	0.86	0.88	0.94
Malathi	36.1	37.9	39.2	35.6	0.86	0.87	0.87	0.94	0.95	0.96
Harangi	13.4	13.7	13.9	10.4	0.74	0.76	0.94	0.87	0.89	0.95
Hemavathi	15.7	16.2	18.5	15.2	0.81	0.86	0.97	0.91	0.93	0.98

[a] *m*: mean runoff, *s*: standard deviation: for observed (*o*) and estimated values (*e*).

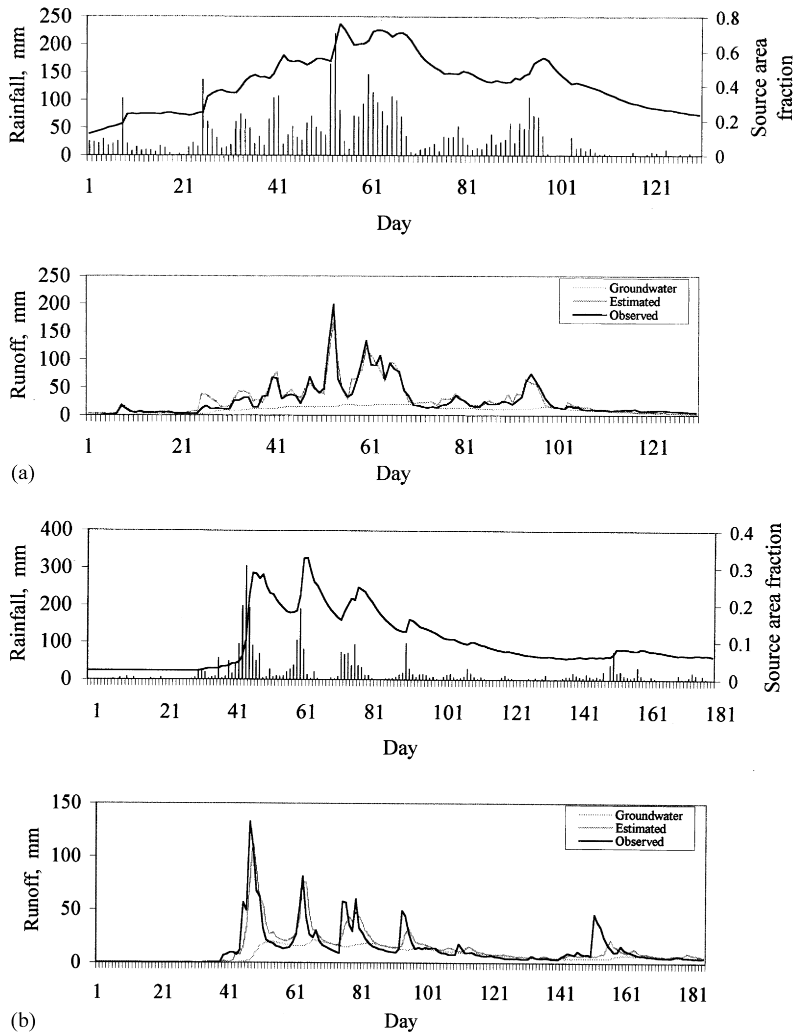

Fig. 3. Typical hydrographs and temporal variations in the source area: (a) Malathi; and (b) Konganahole.

the entire rainfall infiltrates into the ground. Other factors which also point to a substantial groundwater runoff component are the very slow catchment response and the failure of surface runoff models such as the curve number method in simulating runoff from Western Ghat catchments (Putty and Prasad, 1994a).

In order to find possible dependence of the different runoff components on catchment characteristics, correlations of the source area runoff, pipe flow and groundwater runoff as proportions of total runoff against catchment rainfall, percent forest area, percent valley area, percent relief ratio and catchment area were analysed. The respective coefficients of determination are shown in Table 7. Only source area runoff and rainfall, groundwater runoff and rainfall, and groundwater runoff and relief ratio are significantly correlated. Since almost all the rainfall infiltrates into the ground over the unsaturated part of the catchment, irrespective of whether the land cover is forest, plantation or grass, the runoff components are independent of catchment area as well as forest area. The three significant correlations are plotted in Fig. 4 together with the best fit lines. Groundwater contribution

Table 6
Runoff components estimated by SAHYADRI[a]

Catchment	*RF* (mm)	*SARO* (mm)	*SZRO* (mm)	*GWRO* (mm)	*ROE* (mm)	*GWRO*/*ROE* (%)	*ROE*/*RF* (%)	*EVPT* (mm)	*RO* (mm)	*ROE*/*RO* (%)
HonnammanaHalla	1447	124	54	704	882	79.8	61.0	220	895	98.5
YettinaHole	3044	839	164	1216	2219	54.8	72.9	400	2099	105.7
KonganaHole	2461	225	465	1002	1692	59.2	70.0	465	1639	103.2
Lakshmanatirtha	2429	211	488	1000	1669	58.9	68.7	438	1667	100.2
Malathi	5660	3065	395	1470	4931	29.8	87.1	462	4701	104.9
Harangi	3177	1263	128	631	2023	31.2	63.7	442	1929	104.9
Hemavathi	2888	453	687	889	2029	43.8	70.3	455	1959	103.6

[a] *RF*: rainfall; *ROE*: estimated total runoff; *RO*: observed runoff.

Table 7
Coefficient of determination between runoff components and catchment characteristics[a]

%	Relief ratio (%)	Valley (%)	Catchment area (km^2)	Forest (%)	Rainfall (mm)
Source area runoff	0.111132	0.037308	0.027439	0.004392	*0.895453*
Pipeflow runoff	0.383753	0.331593	0.5366	0.396251	0.023208
Groundwater runoff	*0.585244*	0.055165	0.473669	0.155167	*0.616838*

[a] Italicised values significant at 5% level; others not significantly different from zero.

decreases with increasing rainfall because more rainfall is drawn away as source area runoff. Groundwater contribution increases with the relief ratio. This conforms to the principles of the variable source area theory (Dunne, 1978; Anderson and Burt, 1990), according to which the chances of development of saturated source areas are more on the flatter areas. Against expectation, however, the simulated magnitude of source area runoff is not related to the extent of the valley bottoms (Table 7), which would ordinarily be assumed to form the potential source areas of quickflow. A probable explanation for the above emerges if the extent of the source areas as simulated by the model is analysed as below.

6.2. The extent of the source areas

The extent of saturated areas in the catchments could not be mapped due to infrastructure limitations. But the valley floors are usually planted with rice, and the experience of the farmers is that during prolonged rainfall events, the whole of the valley floors as well as small widths across narrow upland valleys get saturated. The Konganahole catchment map is shown in Fig. 5, with the valley floors marked using survey of India toposheets. These valley floors form 40% of the total catchment area. The maximum extent of the source area (as a fraction of the catchment area) simulated by the model and the extent of the valley bottoms in the catchment are compared in Table 8.

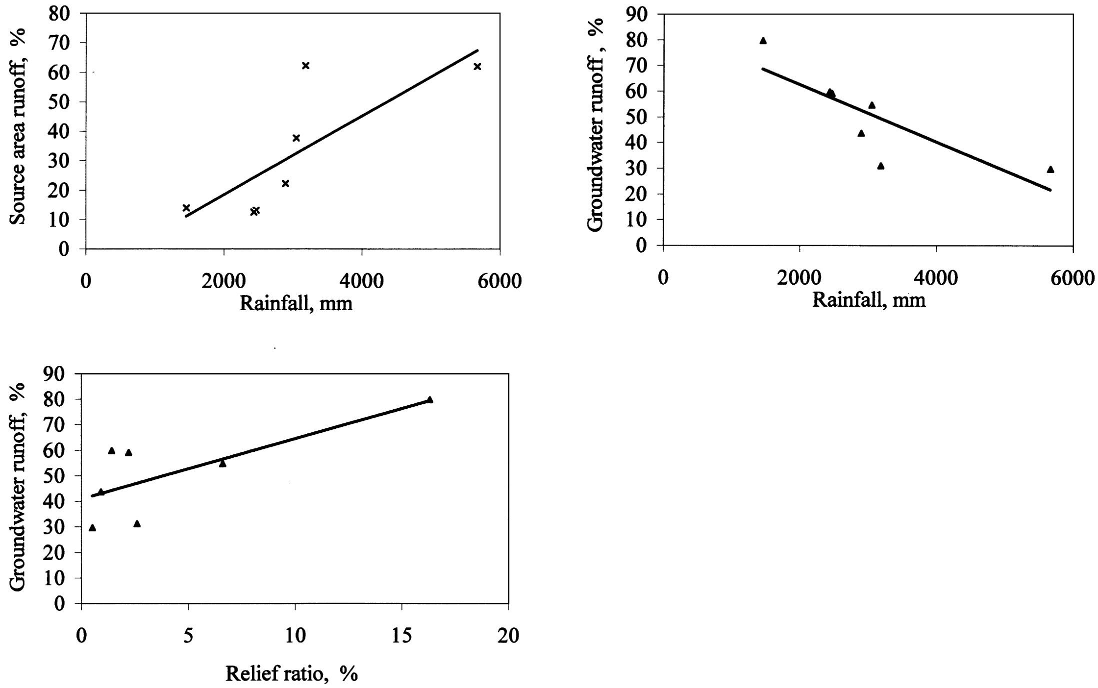

Fig. 4. Influence of catchment characteristics on runoff components.

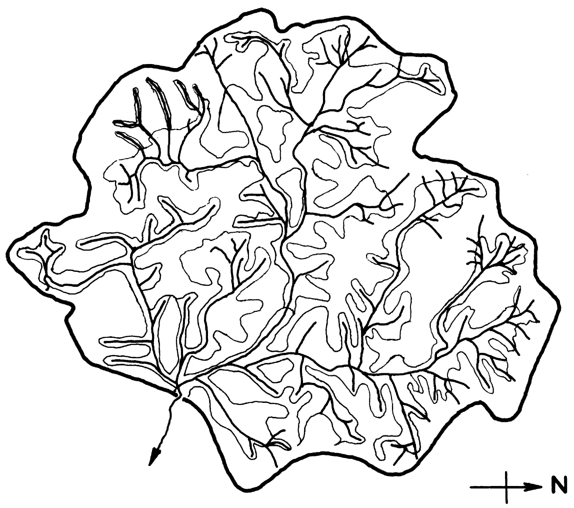

Fig. 5. Konganahole catchment showing extent of valley floors.

Table 8
Maximum values of source area simulated by SAHYADRI[a]

Catchment	*SA*	*ROE*	*RO*	*Valley*
HonnammanaHalla	31.2	21.7	22.3	5.0
YettinaHole	65.3	50.2	58.4	13.0
KonganaHole	28.7	88.6	67.9	40.0
Lakshmanatirtha	27.4	57.2	51.2	20.0
Malathi	86.8	141.8	128.6	18.0
Harangi	69.3	29.4	34.2	18.0
Hemavathi	45.3	172.0	133.0	28.0

[a] *SA*: source area (%); *Valley*: area covered by valley floors (%).

The simulated source areas are much larger than the flat valley portions, although source area runoff is not the major contributor to streamflow in five of the seven catchments. Three possibilities which might account for this unexpected behaviour are: (i) contributions of infiltration excess overland flow being substantial during periods of high flood; (ii) saturated source areas getting developed on slopes, in addition to those covering the valley floors; and (iii) pipeflow being itself a contributor to quickflow.

The case of saturated source areas spreading to cover very large portions of the catchment, often the complete area, has been reported by Bonell and Gilmour (1978) from Australia. In the region studied by them, rainfall is very intense with daily depths often exceeding 25 cm. In contrast, even though daily depths of rainfall do exceed 20 cm on a few days in some of the present catchments, rainfall is never very intense in the Western Ghats. Analysis of rainfall intensities in the region has shown (Putty, 1994) that on days when rainfall exceeds 10 cm, it rains during more than 21 h of the day, on an average. Groundwater levels were monitored (Putty, 1994) at several points in the catchments, and it was found that outside the valley floors water table is below the surface, indicating that saturated areas do not extend beyond the valley floor. With low rainfall intensities and deep soils on the slopes, expansion of saturated areas much beyond the valley floor is improbable in the Sahyadris. Infiltration capacities measured on cultivated and grassed slopes (Putty, 1994) vary between 5 and 300 mm/h. Comparison with the 15-minute rainfall intensities at the heaviest rain recording station in the region shows that less than 3% of the rainfall has chances of generating overland flow on such slopes. Infiltration capacities on forested slopes are far higher than rainfall intensities. Actual average infiltration rates being higher than infiltration capacities, Hortonian overland flow is not a process to reckon with. The only remaining explanation for the large source areas simulated by the model is therefore that in addition to saturation excess overland flow, quickflow also arrives subsurface (which, in the absence of observable matrix flow, can only be pipeflow). This can happen by the formation of what Jones (1979) called ‘dynamic contributing volumes’, which are saturated soil masses far removed from the stream but draining into pipes leading to the stream. Field surveys indicate that most of the subsurface flow in the Western Ghats arrives through pipenets (Putty and Prasad, 1994b) and the results of the present analysis (which can be broadly considered a method of sophisticated flow separation) show that contributions of pipeflow to stream-quickflow must be substantial. The results imply that (i) runoff processes in the region are best explained by Jones’s (1979)extended form of the variable source area theory propounded by Hewlett and Hibbert (1967) and Dunne and Black (1970), and (ii) variable source area models, when applied in regions similar to the Western Ghats, need to incorporate a quickflow component through pipes draining subsurface saturated zones in addition to flow from contributing areas riparian to the channels. That quickflow may also arrive through pipes is also suggested by the dominant influence of rainfall magnitude on catchment response. Rainfall magnitude, which also determines the amount of water entering the soil mantle in a catchment, has a profound influence on the depth of the soil, the development of subsurface pathways like pipes. Greater amounts of infiltration result in higher densities of pipenet, since water entering into the soil has to find its own pathways to get drained out. This leads to quicker and greater contributions of subsurface flow to the stream. Further, rainfall magnitude also controls the variations in the surface saturated zones. Higher magnitudes of rainfall, which mean more number of rainy hours in the Western Ghats, result in saturated zones being sustained for longer periods (Fig. 3) and contributions of surface runoff being greater. Hence, it can be concluded that in wet mountainous areas like the Sahyadris dominated by pipeflow, the catchment response is shaped more by the subsurface flow pattern, than by surface flow lengths and drainage densities, in contrast to other regions. Incidentally, the drainage densities of the catchments of HonnammanaHalla, Yettinahole, Malathi and Harangi, which exhibit different catchment responses, are all nearly the same and lie between 1.5 and 1.8 km^{-1}.

7. Summary and conclusions

The results of the study have established that the three-component watershed model SAHYADRI, developed in accordance with the postulations of the theory of variable source areas forms a useful first step in understanding the response characteristics of the catchments in the Western Ghat regions of South India, although the need to add a fourth component is indicated. The model simulations have shown that groundwater flow forms a dominant component of runoff and the catchment response is strongly dependent on the rainfall magnitude. Two major implications of the study are that (i) flow through pipes from dynamic subsurface saturated zones may contribute substantial quantities of quickflow, and (ii) field work necessary for further research must concentrate on pipeflow responses and the influence of rainfall on the nature of pipenets. A modified model incorporating quickflow through pipes is now under development at the National Institute of Engineering. Field work on the lines stated above is also being undertaken.

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