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APPLICATION OF SHE MODEL TO KOLAR SUBBASIN OF RIVER NARMADA

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ACKNOWLEDGMENT

The present report describes modelling work carried under a project signed between Govt. of India and Commission of European Cummunities. The author was one of the six NIH scientists identified to work on this project. The modelling efforts include collection of data from various agencies in India, and modelling of the basin using SHE model.

It would not have been possible to complete this work without assistance and advice of a number of people. The data collection work was carried out by the author with help and support of a number of colleagues from NIH. Particular thanks are due to Dr S M Seth, Mr R D Singh, and Mr V K Lohani. Officers of MP Irrigation Department, and officers of various other agencies like Narmada Valley Development Agency, MP Ground Water Survey, Narmada Control Authority and CWC provided data and various details useful in this study. Their help is gratefully acknowledged.

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ABSTRACT

Kolar sub basin of Narmada basin, India is one of the six subbasin chosen for modelling using the SHE model. A part of this basin with a catchment area of 828 sq. km. upto the Satrana Gauge-Discharge site was modelled in this study.

A SHE setup for this basin was prepared using the grid size of 2 km * 2 km. The data for the period 1983-88 was used in modelling. Hourly rainfall data at four SRRG stations was used. The period 1983-85 was chosen for model calibration and 1986-88 for validation.

The results of the modelling are presented in this report. The simulation of volume of monthly discharges as well as the basin response during the high flow period was very good. The simulation of base flow has scope for some improvements. To obtain further improvement in the results, it is necessary to carry out a field investigation to update and extend the data base as the values of a number of parameters are not directly available.

A detailed sensitivity analysis was carried out by changing several model parameters - one at a time. It was found that the basin response is significantly effected by the variation in soil hydraulic properties. Further, the Strickler coefficient is very important in determining the basin response during high flow periods.

1.0 INTRODUCTION

The mathematical modelling of hydrologic system is a powerful tool for both the research hydrologists and the practicing water resources engineers involved in planning, development and management of water resources, Clarke(1973). Due to ever increasing cost of water resources development, there has been increasing demand for better approach to hydrological modeling of late also concerned with the effects of land use changes on hydrologic regime, implications of existing and proposed irrigation schemes and several problems arising from conjunctive use of water, Anderson and Burt(1985). Conventional hydrological models are often inappropriate for such problems and a new generation of hydrological models is needed. Attention is, therefore, being focused on physically based distributed catchment models which have the potential to overcome many of the deficiencies associated with the traditional approaches, Beven(1985). It is in the light of these facts that three European Organizations, viz., the Danish Hydraulic Institute, the British Institute of Hydrology and the French consulting company SOGREAH have jointly developed the European Hydrological System- Systeme Hydrologique Europeen (SHE) model.

A financial agreement entitled "Hydrological computerized modelling system (SHE)", ALA 86/19, was signed in June/July 1987 between the Commission of European Communities (CEC) and the Government of India, on a project to transfer the SHE model to NIH, India, by the above organizations and to apply this model to selected focus basins in India. The Narmada basin was chosen for model application. The Kolar subbasin was one of the focus basins chosen for application of SHE model.

1.1 SCOPE OF PRESENT REPORT

The present report describes the modelling of Kolar basin using the SHE model. It starts with the brief details of the model. A brief description of the study area is given followed by data availability and processing, and calibration and model validation for Kolar basin. The results of a sensitivity analysis carried to determine the sensitivity of various model parameters have also been discussed.

2.0 BRIEF DESCRIPTION OF SHE

The SHE is a deterministic, distributed and physically based modeling system. It has been jointly developed by the Danish Hydraulic Institute (Denmark), the Institute of Hydrology (UK) and SOGREAH (France). The partial differential equations describing the processes of overland and channel flow, saturated and unsaturated zone are solved by finite difference methods. In addition, different methods are used for description of interception, evapotranspiration and snowmelt. The unsaturated zone computations are made in one-dimensional columns, Abbott et al (1986a, 1986b). The structure of the model is illustrated in Fig. 2.1.

In the SHE model, a separate sub-model component is solved for each hydrological process with a master component controlling the running of each of these as well as data exchange among them. The linkage of one-dimensional unsaturated zone and two-dimensional saturated zone is achieved through a coupling component. Similarly, the exchange of water between river and aquifer is achieved with the help of an exchange component.

The SHE model also allows the user to make a choice among the components which he wants to invoke. In case it is decided to skip execution of particular component, a corresponding dummy component is called which sets and

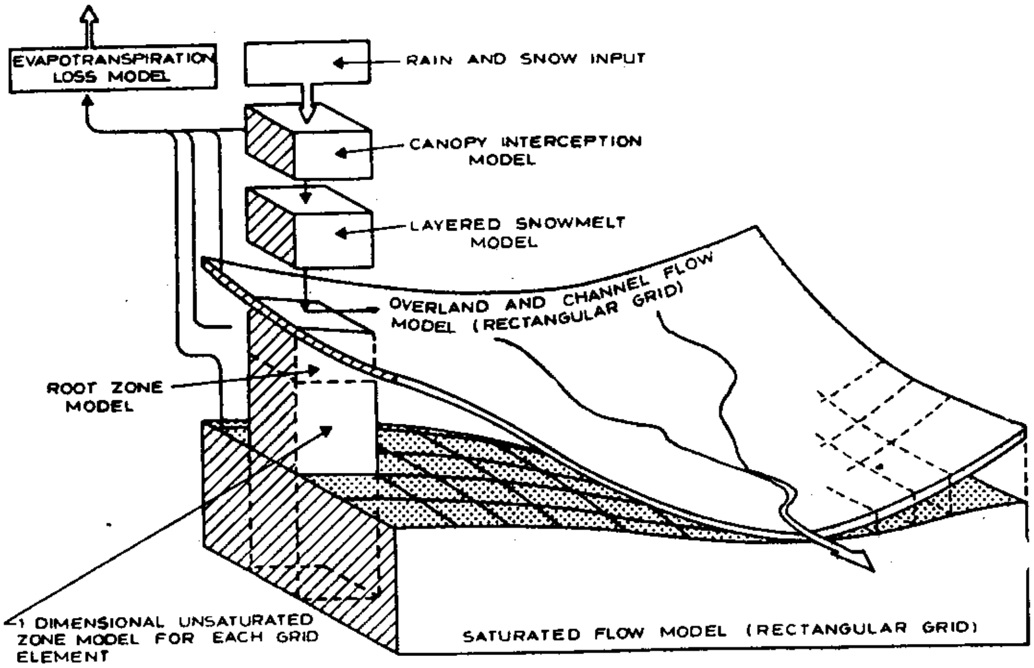


Fig. 2.1 Structure of the European Hydrologic System

transfers default boundary conditions. This permits greater application-flexibilities since the same code can be used for modeling a single unsaturated zone column alone as well as a large basins with manifestations of all component processes.

A brief description of various components follows.

2.1 SNOWMELT (SM) COMPONENT

This Component models the snow pack thickness as affected by precipitation and melting and also the rate of deliveries of meltwater from the snowpack to the soil surface. The model is structured so that the total heat flux to the snowpack is calculated either by Degree-Day or by Energy Budget method, the amount of melting by this flux is calculated and finally the meltwater is routed through the snowpack.

2.2 OVERLAND AND CHANNEL (OC) FLOW COMPONENT

The generation of overland flow takes place in three conditions: a) when precipitation input is greater than infiltration capacity of soil in which case it is termed as Hortonian Flow, b) when top soil layer is saturated in which case even as low intensity rainfall produces flow called saturation excess flow, and c) when subsurface flow is forced up to the surface where it flows as overland flow. The surface runoff is routed in the down-gradient towards the river system. During the journey, whose route is determined by the topography and surface resistance, the quantity of water undergoes changes because of evaporation infiltration and additional rainfall.

The water reaching river system is routed in the downstream direction. In the model, it is assumed that the rivers runs parallel to grid boundaries. The routing of surface runoff as well as streamflow is done using the St. Venant Equations. In the simplified form, these equations can be described as :

$$\partial A/\partial t + \partial Q/\partial x = 0 \qquad (2.1)$$

$$\partial Q/\partial t + \partial(U^2 A)/\partial x + gA(\partial h/\partial x - S_o) + gAS_f = 0 \qquad (2.2)$$

where

$A = A(x,t)$ is wetted cross section area,
$U = U(x,t)$ is uniform velocity.

The finite difference scheme is solved using an implicit finite difference scheme. An efficient numerical scheme is used to obtain solution.

2.3 UNSATURATED ZONE (UZ) COMPONENT

This component is used for computation of soil moisture changes in the unsaturated zone. The upper part of this zone loses water due to soil evaporation and root extraction. In the lower part of unsaturated zone, moisture changes take place due to fluctuations in water table. The UZ columns are modeled by one-dimensional Richards' equation:

$$C\partial\Psi/\partial t = \partial/\partial z\ (K\partial\Psi/\partial z) + \partial K/\partial z - S \qquad (2.3)$$

where,
$C = \partial\theta/\partial\Psi$ = slope of soil water retention curve,
θ = volumetric soil moisture content,
Ψ = pressure head,
K = Unsaturated hydraulic conductivity,
S = Root extraction sink term.

This equation is non-linear in nature and requires knowledge of physical properties of soil for obtaining a solution. Two important parameters of soil physical property are K(θ) and (θ) The hydraulic conductivity K(θ) decreases sharply as the moisture content decreases from saturation. This happens because as saturation decreases, more pores get filled with air, less area becomes available for flow and also the flow path becomes more tortuous. In SHE, the relationship between $K_r(\theta)$ and θ is described using Averjanov's (1950) formula according to which

$$K_r(\theta) = ((\theta - \theta_r) / (\theta_s - \theta_r))**n \tag{2.4}$$

where,
θ = actual moisture content,
θ_s = saturated moisture content,
θ_r = residual moisture content,
n = Averjanov's exponent, varying with soil type.

In the SHE model, a fully implicit formulation has been adopted to solve the Richards' equation. The space derivatives are represented by their finite difference analogs at time level n+1. The values of C(θ) and K(θ) are referred to at time level n+½. These are evaluated in an iterative procedure.

2.4 SATURATED ZONE (SZ) COMPONENT

In SHE model, this component is used to simulate the saturated zone of ground water. The present version is capable of handling unconfined heterogeneous aquifer. For these types of aquifers, applying the Dupit assumption of horizontal flow, the partial differential equation describing the flow is

$$\partial/\partial x_i \ (K_{ij} \ H \, \partial h/\partial x_j) = S \, \partial h/\partial t + R \qquad (2.5)$$

where H is the saturated thickness of the aquifer, h represents the position of water table, K_{ij} is the hydraulic conductivity tensor, S is the storage coefficient, t is time and R is local volume flux per unit area. The solution of this equation is obtained using a finite difference approximation.

2.5 PROGRAMMING ASPECTS

In the SHE programme, separate set of routines are available for modeling of different components of the hydrologic cycle. The main programme called FRAME, is responsible for calling initialization routine, reading the input data and determining the time step size. It also calls different subroutines in proper order and ensures data transfer among them. In case it is decided to omit a particular component, a dummy is called instead. The advantage of this modules programming is that whenever a new version of any component is developed it can replace its older version without affecting any other component. Each component reads its input data from separate files.

2.6 DATA REQUIREMENTS

A large number of parameters describing the physical characteristics of the catchment on a spatially distributed basis is required in addition to the hydrological and meteorological time series for successful running of the SHE Model.

The data required for a typical SHE Model application may be obtained from field measurements and from such measurements supplemented by the available scientific literature. For example, the soil hydraulic properties which are required for a SHE application may not be available in Indian context and field and/or laboratory measurements will have to be carried out in such cases to determine the required parameters. The data and parameters required for a typical SHE application can be divided in two categories - fixed data and time series data.

The fixed or time invarying data for each grid square (or channel link) for the SHE model consists of

a) Ground surface elevation,
b) Impermeable bed elevation,
c) distribution codes for rainfall and meteorological stations,
d) distribution codes for soil and vegetation types,

e) soil hydraulic properties,

f) river channel geometry and conveyance properties,

g) surface roughness characteristics,

h) surface detention storage.

The time series data consists of the following

a) precipitation data series,

b) potential evaporation data series,

c) temperature data series,

d) variation of root zone depth and leaf area index with time,

e) initial phreatic surface level,

For further details, reference is made to DHI(1988).

2.7 DATA PREPARATION

Application of SHE Model requires provison of a large amount of parametric and other input data organized in several data files. With each component, one data file is attached. The naming of the files is usually given in a way which identifies the specific catchment followed by three letters indicating the component:

KOLAR.FRD	Frame data file,
KOLAR.SZD	Saturated zone data file,
KOLAR.UZD	Unsaturated zone data file,
KOLAR.OCD	Overland and channel flow data file,
KOLAR.ETD	Evapotranspiration data file,
KOLAR.SMD	Snowmelt data file,
KOLAR.PRD	Precipitation data file.

Since the model requires a huge amount of spatially distributed data, it is a very time consuming and tedious process to prepare the input files for SHE in the particular format required. Moreover, the data are often available on maps of different scale. It is, therefore, convenient to provide the data on the scales available and then automatically set up the spatially distributed data on the scale which has been selected for the numerical computation. In order to facilitate the data preparation, a preprocessor, SHE Array Formatting Routine (SHE.AF), may be used.

2.8 THE SHE ARRAY FORMATTER (SHE.AF)

The SHE.AF reads a series of data files containing various arrays of spatially distributed data and transforms these data to an appropriate format. It also requires a set of existing SHE input files which are read and updated again with appropriate new data arrays. The entire data preparation can be finalized within short time for grid systems comprising several thousands squares using SHE.AF.

2.9 RUNNING SHE PROGRAMME

After preparation of the required SHE datafiles, the SHE simulation can be started. The user is prompted to give the catchment name. Using this catchment name, a file is opened which contains the names of data files for different components. These data files are then read in and the input is obtained.

Two output files are created in a SHE run.

The SHE output printfile contains various results, warnings and error messages. It is recommended that in the initial phase of a SHE application, the initial conditions may be written on the print file for checking up of data.

The results of a SHE run are stored in a result file which is a binary file. The results may be retrieved from this file by applying the output retrieval routine, SHE.OR.

2.10 PRESENTATION OF INPUT AND OUTPUT DATA

The SHE Graphical Display Routine SHE.GD can be applied either for display of SHE results which are retrieved by applying the SHE.OR, or for display of indata to the SHE. A number of options are available.

For detailed description of various programmes and input data preparation, reference is made to the model documentation, DHI(1988).

3.0 GENERAL DESCRIPTION OF KOLAR RIVER BASIN

The Kolar subbasin is located in the latitude range of 22° 40′ to 23° 08′ and longitude 77° 01′ to 77° 29′. The Kolar river originates in the Vindhyachal mountain range at an elevation of 550 m above mean sea level (msl) in the district Sehore of Madhya Pradesh (M P) state. The river, during its 100 km course first flows towards east and then towards south before joining the river Narmada near a place named Neelkanth. During its course, the Kolar river drains an area of about 1350 sq. km. In the present study only the catchment area of 820 sq. km. up to Satrana gauge-discharge site has been modeled. The entire basin lies in two districts, Sehore and Raisen. The index map of the basin showing the locations of gauge-discharge stations, rain gauging sites and other hydraulic structures is given in Fig. 3.1.

In the basin, a dam is nearing completion near the village Lawakheri. This Kolar dam will be used to provide drinking water to the city of Bhopal which lies at a distance of 30 km towards north. The water stored in the dam will also be used for irrigation. For this purpose, a barrage is being constructed in the basin near Jholiapur from where two canals will take off. Construction of these lined canals is in progress and they will be operational soon.

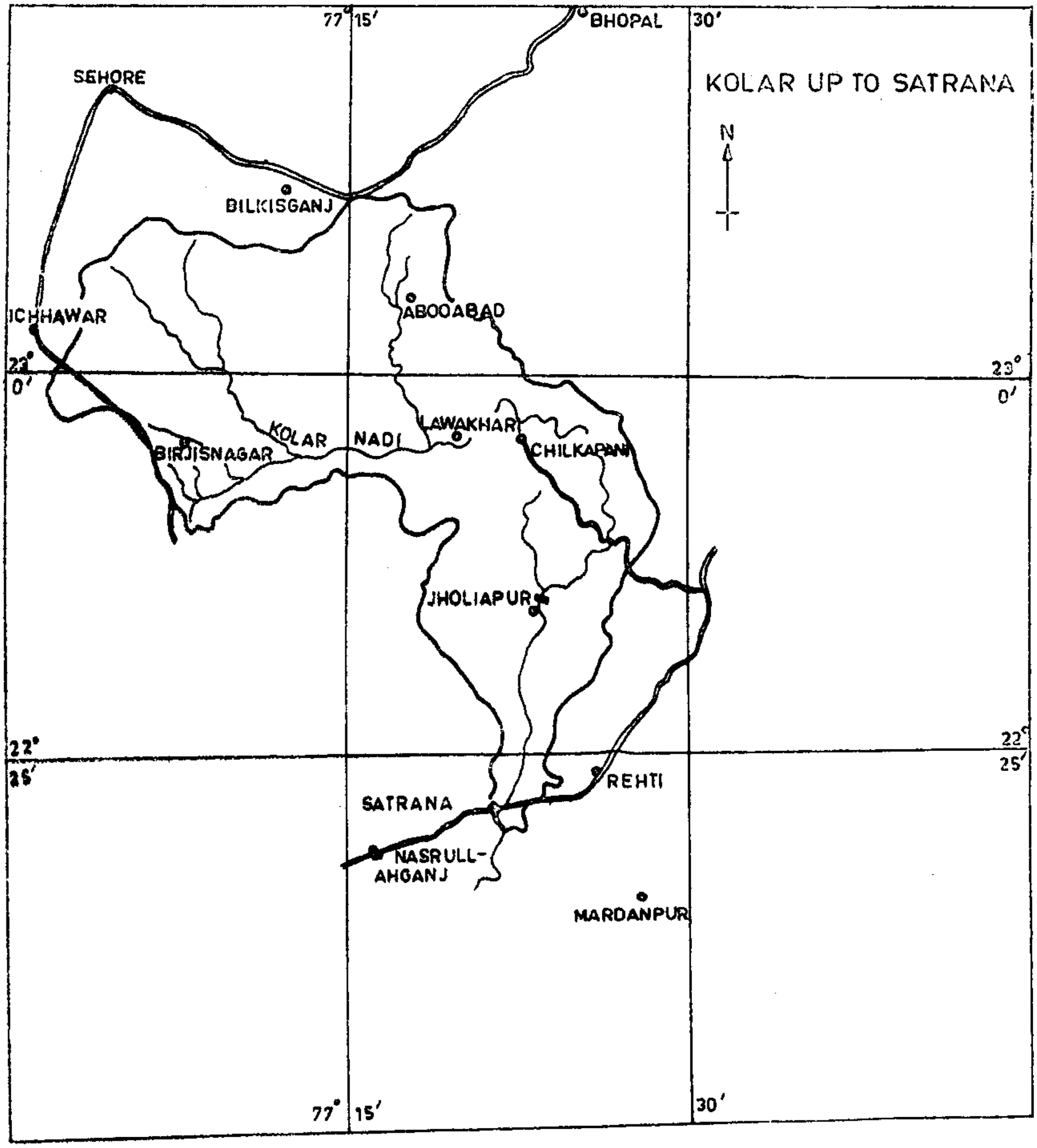


Fig. 3.1 : The Kolar basin upto Satrana gauging site. Also shown are the locations of hydrometeorological sites and important towns.

3.1 HYDROLOGY OF KOLAR BASIN

Topographically, the Kolar basin can be divided into two distinct zones. The upper four-fifth part of the basin and lower one-fifth part. The upper four-fifth part having elevations ranging from 600 m to 350 m is predominantly covered by deciduous forest (dense and open). The boundaries of catchment are mild sloped at the northern end of the basin. The river debauches to plains from this area upstream of Jholiapur through ramp shaped southward sloping topography. The soils are skeleton to shallow in depth except near channels where they are relatively deep. The rock outcrops are easily visible at many places. In this area, the rocks are weathered and deep fissures can be seen. The channel beds are rocky or graveled. The thin soils get saturated even during low intensity rains and water moves through the fissures rapidly. Agricultural activity is carried out in relatively large areas in the north western part (adjacent to Ichhawar) and in small pockets elsewhere in which the main crops are wheat and grams. The general response of this upper part of basin to rain appears to be quick.

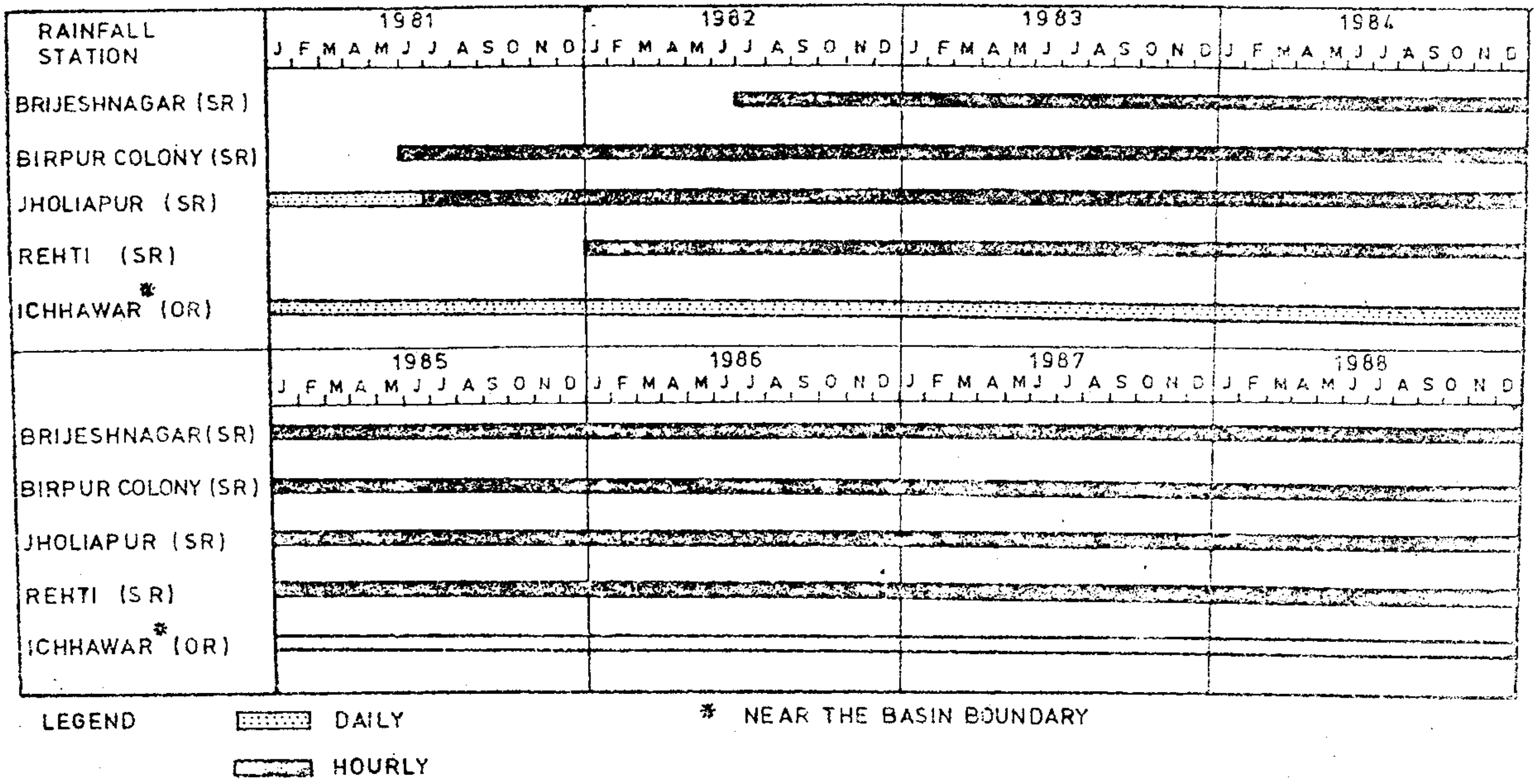
The lower part of the basin consisting of flat bottomed valley narrowing towards the outlet and having elevations ranging from about 350 m to 300 m is predominantly cultivable area. The soils are deep in the area and have flat slopes. The places where agricultural activity is carried out have bunded fields in which water is impounded during the monsoon period. The response of this area to input rainfall is likely to be quite slow. Part of this area comes under the command of Kolar dam.

3.2 DATA AVAILABILITY

The topographic map of the Kolar basin was prepared using the Survey of India toposheets of scale 1:50,000. This map formed the base map for setting up of computational grid points, river network and topographic elevations.

The availability of rainfall data for Kolar basin at the time of carrying out the present study is shown in Table 3.1. The Satrana gauging site located at the outlet of this basin was established in 1983. The gauge-discharge measurements are made at a bridge on Rehti-Nasrullaganj road where an automatic gauge recorder (AGR) has been installed. The flow velocity is measured using current meter. At the Satrana gauging site, hourly gauge observations and daily discharge measurements were available for the monsoon months during 1983-88. The cross section of the river at the gauging station was also available. The hourly river stages and rating curve was also available for Lawakheri G-D site for the period 1981-86. The flow velocity at this site is measured using floats and because of this, the discharge estimates are highly uncertain.

Table 3.1 : AVAILABILITY OF RAINFALL DATA FOR THE KOLAR BASIN



The soil and land use maps on scale 1:250,000 were obtained from the Narmada Valley Development Authority (NVDA). However, the hydraulic properties of the soils were not directly available, and were derived from secondary sources. The soil depth was assumed to be dependent on the land use and slopes. The ground water levels are observed by the M.P. State Ground Water Board at selected permanent observation wells two/three times a year. However in case of Kolar, only one well lies inside the basin. There are several wells in the downstream area lying near the periphery of the basin. The information about ground water level was used as general guideline about the position of water table before and after the monsoon season. The pan evaporation data for a station named Powerkheda which is located near the basin was available from 1983 onwards (weekly during 1983-87 and daily during 1987-88) and used.

4.0 DATA PROCESSING AND PREPARATION

A grid network was drawn on the topographic map to establish the computational points. The basic network was drawn for square grids of size 500 m * 500 m. The ground elevation at the grid points were read in. Similarly the grid maps were prepared for land use and soil type on 1:250,000 scale maps. The land use was classified in six categories - dense forest on uplands, dense forest on slopes, open forest, agriculture on uplands and agriculture on low lands and waste land. If more than one land use category was falling in any one square, the dominant land use type was assumed to represent that grid square.

The hourly rainfall data at Rehti, Jholiapur, Birpur and Brijeshnagar was used for this study. Using the gauge discharge data at Satrana site for the monsoon months rating curves were developed and used to convert hourly discharge values corresponding to hourly stages. Two different rating curves were used -- one for the years 1983 - 1985 and other for 1986 - 1988.

The pan evaporation data at Powerkheda was processed and presented in the format required for the SHE model. The model also requires information about variation of leaf-area-index with time for different land uses. This information was derived using the literature available e.g., ICAR(1987), discussions with Agriculture Wing of NVDA, M.P.

Agriculture Dept. and field visits. The curves developed for this study are shown in Fig. 4.1. Similarly, the development of root zone with time is also required for different land uses. This was also derived using the information from above sources. The hydraulic properties of soils were derived using the information about neighbouring basins, Versey and Singh(1982), Hodnett and Bell(1985), and other related literature, e.g., Kauraw et al (1983), and the retention curve adopted is shown in Fig. 4.2.

4.1 WATER BALANCE

The water balance calculations for the Kolar basin were done on a lumped basis. The rainfall, river flow at the outlet and the evaporation data was used in this analysis. The runoff coefficients were determined for the Kolar basin on monthly basis, cumulative for the monsoon season and for the entire monsoon season.

The results of the water balance calculations are given in Table 4.1. No inconsistency was detected in the data based on this analysis as the runoff coefficients were found to be within the acceptable range.

4.2 SHE SETUP FOR KOLAR BASIN

As mentioned above, the computational grids were initially drawn of 500 m * 500 m size. Since, the computational requirements for a set up on this size of

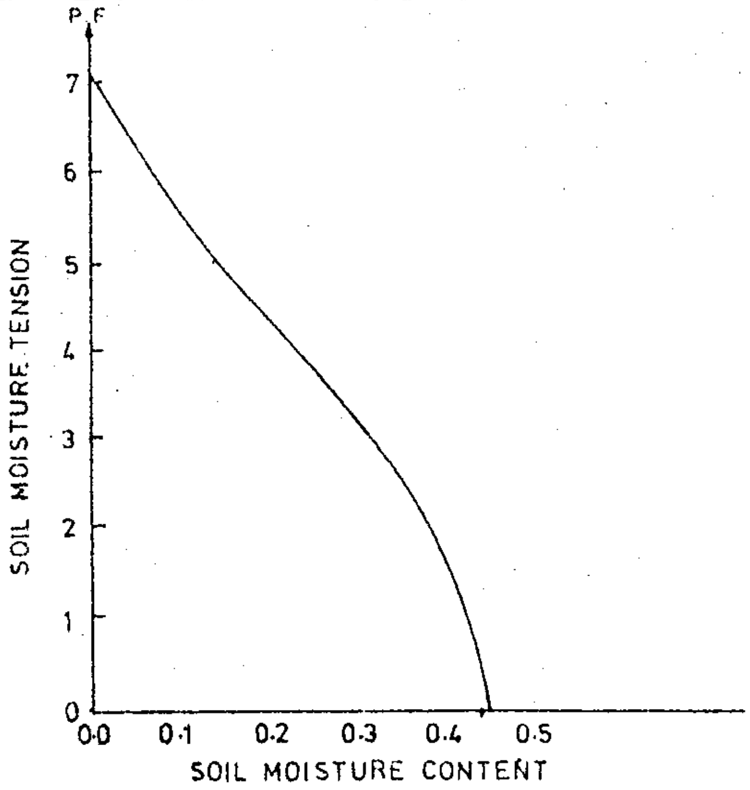


Fig. 4.1 : Soil moisture retention curve used for all soil types in the simulations. Based on data from ICAR

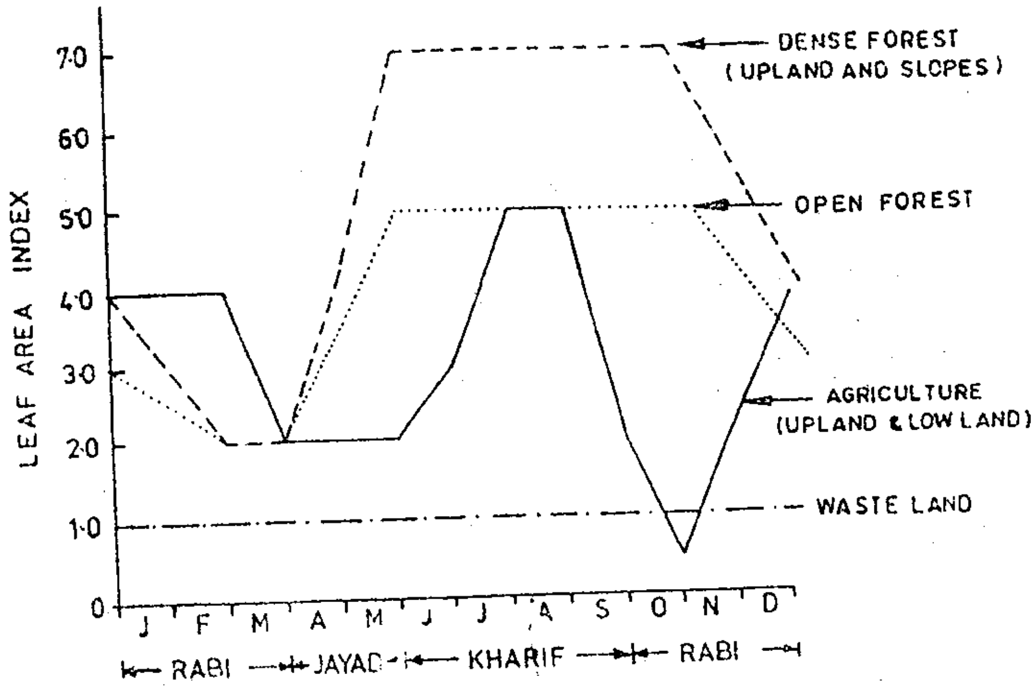


Fig. 4.2 : Time variation of leaf area index for the six landuse types used in the simulations.

TABLE 4.1
Water Balance for Kolar Basin

1983 All figures are in mm

Month	Monthly rainfall at				Mean rain-fall P	Flow at Satrana Q	Pot. Evap.	Q/P	ΣQ/ ΣP
	Rehti 0.04*	Jholiapr 0.18*	Birpur 0.40*	Brjngr 0.38*					
Jan	-1	-1	8	12			47		
Feb	-1	-1	0	0			82		
Mar	-1	-1	0	0			148		
Apr	-1	-1	0	0			232		
May	0	0	22	44	24		380		
Jun	0	29	1	0	7	0	247		
Jul	269	470	213	214	270	29	134	0.12	
Aug	407	612	617	443	548	361	89	0.76	0.54
Sep	331	357	308	487	382	248	92	0.63	0.57
Oct	0	27	11	0	10	37	118	3.9	0.60
Nov	0	0	0	0	0		102		
Dec	0	0	0	0	0		74		

Note : a) -1 indicates that data is not available.
b) * these are Thiessen weights for the station.

1984 All figures are in mm

Month	Monthly rainfall at				Mean rain-fall P	Flow at Satrana Q	Pot. Evap.	Q/P	ΣQ/ ΣP
	Rehti 0.04*	Jholiapr 0.18*	Birpur 0.40*	Brjngr 0.38*					
Jan	0	53	7	0	14		50		
Feb	0	0	11	2	3		87		
Mar	0	0	0	0	0		158		
Apr	0	0	0	0	0		247		
May	0	0	0	0	0		405		
Jun	66	120	163	136	141	10	230	0.07	
Jul	195	181	97	163	141	20	141	0.14	0.16
Aug	828	938	943	698	851	592	98	0.70	0.55
Sep	48	21	22	34	27	53	85	1.96	0.58
Oct	0	10	5	1	4	23	112	5.8	0.60
Nov	0	0	0	0	0		92		
Dec	0	0	0	0	0		67		

1985

All figures are in mm

Month	Monthly rainfall at				Mean rain-fall P	Flow at Satrana Q	Pot. Evap.	Q/P	ΣQ/ ΣP
	Rehti 0.04*	Jholiapr 0.18*	Birpur 0.40*	Brjngr 0.38*					
Jan	0	0	0	0	0		85		
Feb	0	0	0	0	0		90		
Mar	0	0	0	0	0		126		
Apr	0	0	2	2	1		216		
May	0	0	6	4	4		322		
Jun	72	151	117	163	139		260		
Jul	294	323	302	263	293	76	121	0.26	
Aug	398	388	389	381	386	218	89	0.56	0.52
Sep	90	176	165	210	181	60	149	0.33	0.53
Oct	123	128	92	143	118	40	85	0.34	0.50
Nov	0	0	0	0	0		69		
Dec	0	0	0	0	0		62		

Note : a) -1 indicates that data is not available.
b) * these are Thiessen weights for the station.

1986

All figures are in mm

Month	Monthly rainfall at				Mean rain-fall P	Flow at Satrana Q	Pot. Evap.	Q/P	ΣQ/ ΣP
	Rehti 0.04*	Jholiapr 0.18*	Birpur 0.40*	Brjngr 0.38*					
Jan	0	0	0	0	0		70		
Feb	0	0	37	15	20		67		
Mar	0	0	1	0	0		124		
Apr	0	0	0	0	0		224		
May	0	0	13	4	7		245		
Jun	176	176	162	265	201	0	113	0.96	0.79
Jul	1069	787	1047	953	958	918	90	0.76	0.78
Aug	360	345	269	310	302	230	79	0.58	0.77
Sep	168	56	58	55	60	35	90		0.79
Oct	5	0	0	0	0	24	110		
Nov	0	0	0	0	0		75		
Dec	0	0	0	0	0		60		

1987

All figures are in mm

Month	Monthly rainfall at				Mean rainfall P	Flow at Satrana Q	Pot. Evap.	Q/P	$\Sigma Q/\Sigma P$
	Rehti 0.04*	Jholiapr 0.18*	Birpur 0.40*	Brjngr 0.38*					
Jan	0	0	45	0	18		52		
Feb	0	0	30	16	18		65		
Mar	0	0	5	9	5		96		
Apr	0	0	0	0	0		200		
May	0	0	18	0	7		212		
Jun	43	159	96	89	105		179		
Jul	142	152	239	77	160	42	146	0.26	
Aug	506	639	515	425	509	30	79	0.1	0.11
Sep	78	77	55	48	58	201	105	3.5	0.38
Oct	0	51	62	63	58	64	88	1.1	0.43
Nov	0	0	0	0	0	17	78		0.45
Dec	0	0	18	16	13		81		

Note : a) -1 indicates that data is not available.
b) * these are Thiessen weights for the station.

1988

All figures are in mm

Month	Monthly rainfall at				Mean rainfall P	Flow at Satrana Q	Pot. Evap.	Q/P	$\Sigma Q/\Sigma P$
	Rehti 0.04*	Jholiapr 0.18*	Birpur 0.40*	Brjngr 0.38*					
Jan	0	0	17	14	12		88		
Feb	0	0	0	0	0		100		
Mar	0	0	0	0	0		172		
Apr	0	0	11	13	9		202		
May	0	0	16	0	6		270		
Jun	112	209	168	221	195	5	173	0.02	
Jul	462	494	551	432	494	154	55	0.31	0.23
Aug	403	434	308	277	327	189	48	0.58	0.34
Sep	88	96	85	97	92	45	89	0.49	0.36
Oct	28	30	39	42	38	40	98	1.05	0.37
Nov	0	0	3	3	1		91		
Dec	0	0	0	0	0		73		

grid are enormous, later on the set up for grid size of 1 km * 1 km and 2 km * 2 km were made. These representations are shown in Fig. 4.3 and 4.4. In the model, the rivers can run only along the grid boundaries, hence their course was approximated by straight lines. The river network representations for grid sizes of 1 km and 2 km are shown in Fig 4.5 and 4.6. For Kolar, the number of grids and the number of river links representing the catchment and the river system is shown in Table 4.2.

For the purpose of setting up land use and soil depth, a grid map was prepared in which codes were assigned to different grids and corresponding parameters were specified. The initial position of water table was specified in similar way. Since the UZ calculations consume significant CPU time, these calculations are not made for all grids. A classification scheme is followed to group the grids whose response is likely to be same and then the computations are made for one grid in each group. The SHE array formatting routine was then used to prepare the model set up according to the format required by the different model components.

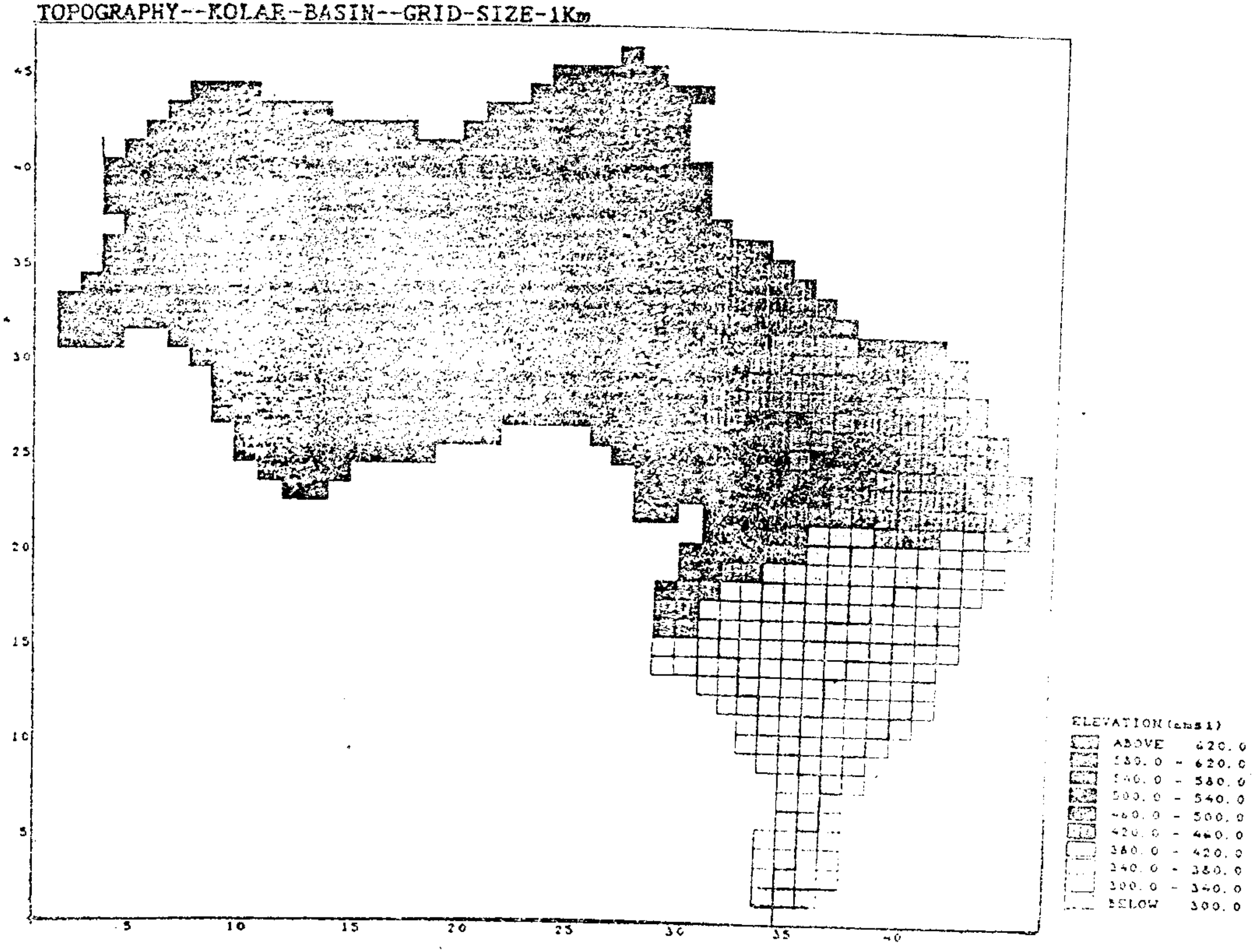


Fig. 4.3 : Topographic representation of Kolar basin using grid sizes of 1 km x 1 km.

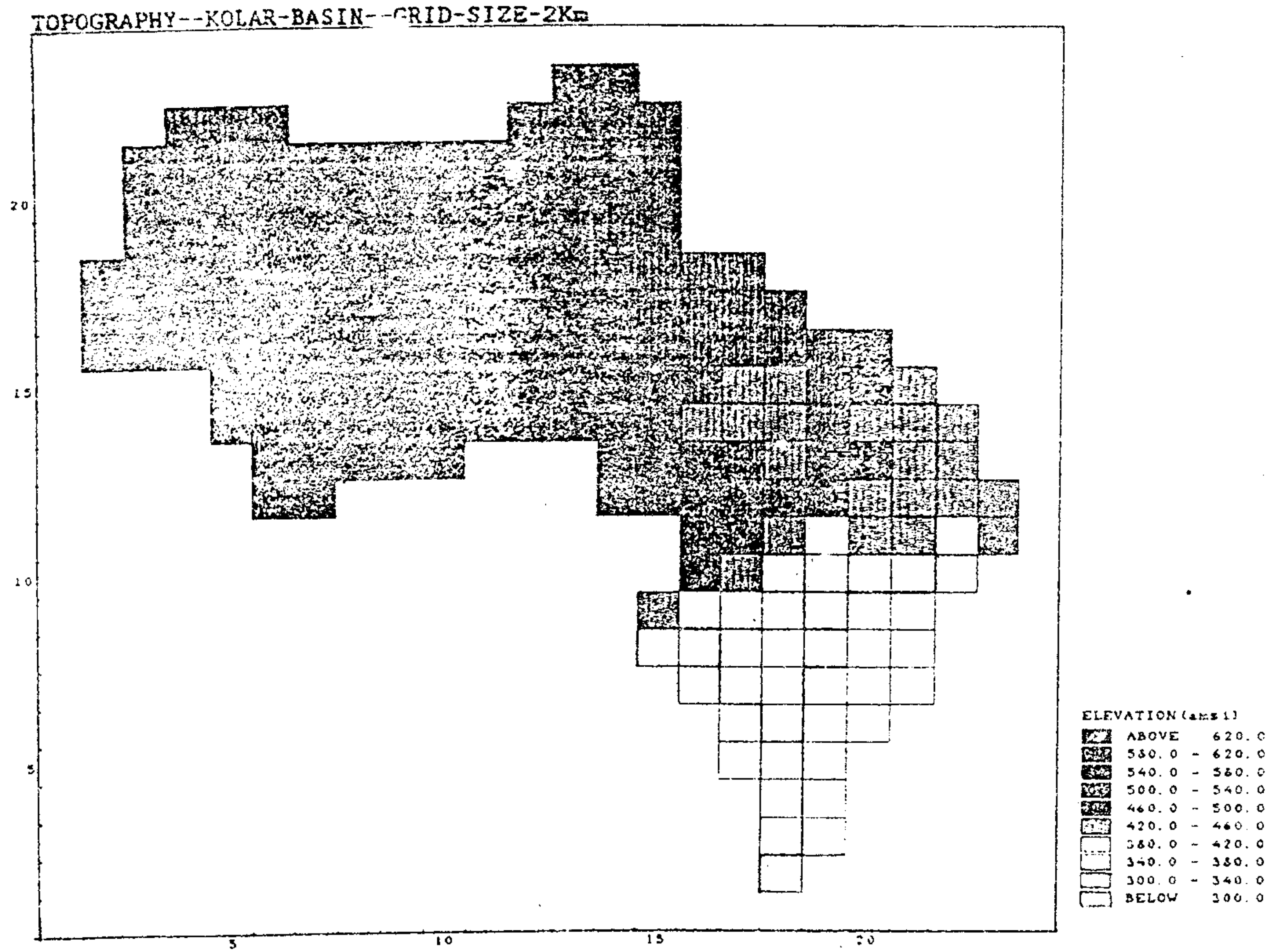


Fig. 4.4 : Topographic representation of Kolar basin using grid sizes of 2 km x 2 km

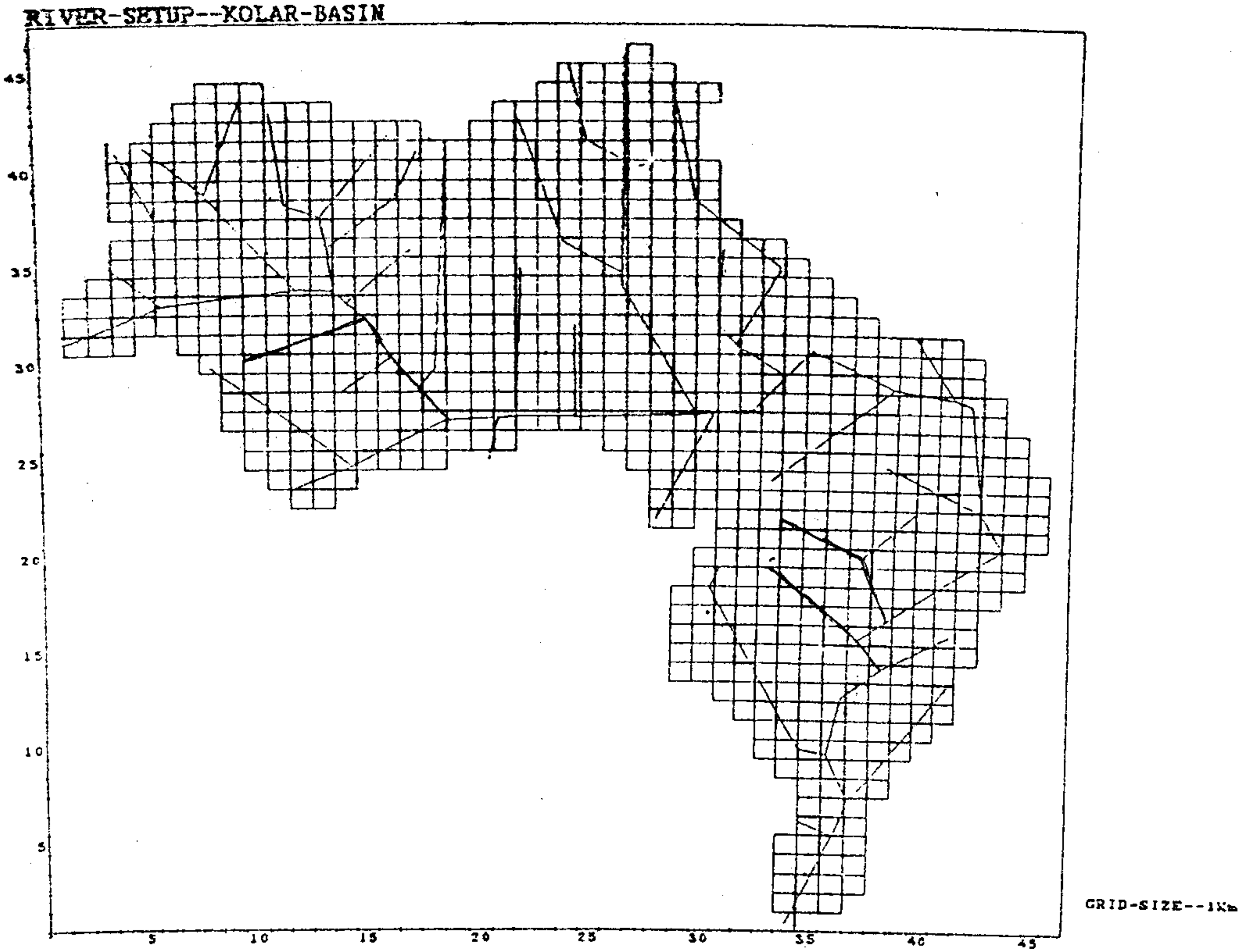


Fig. 4.5 : Derivation of model channel network from straight line approximations to the mapped network: Kolar basin at grid scale 1 km x 1 km.

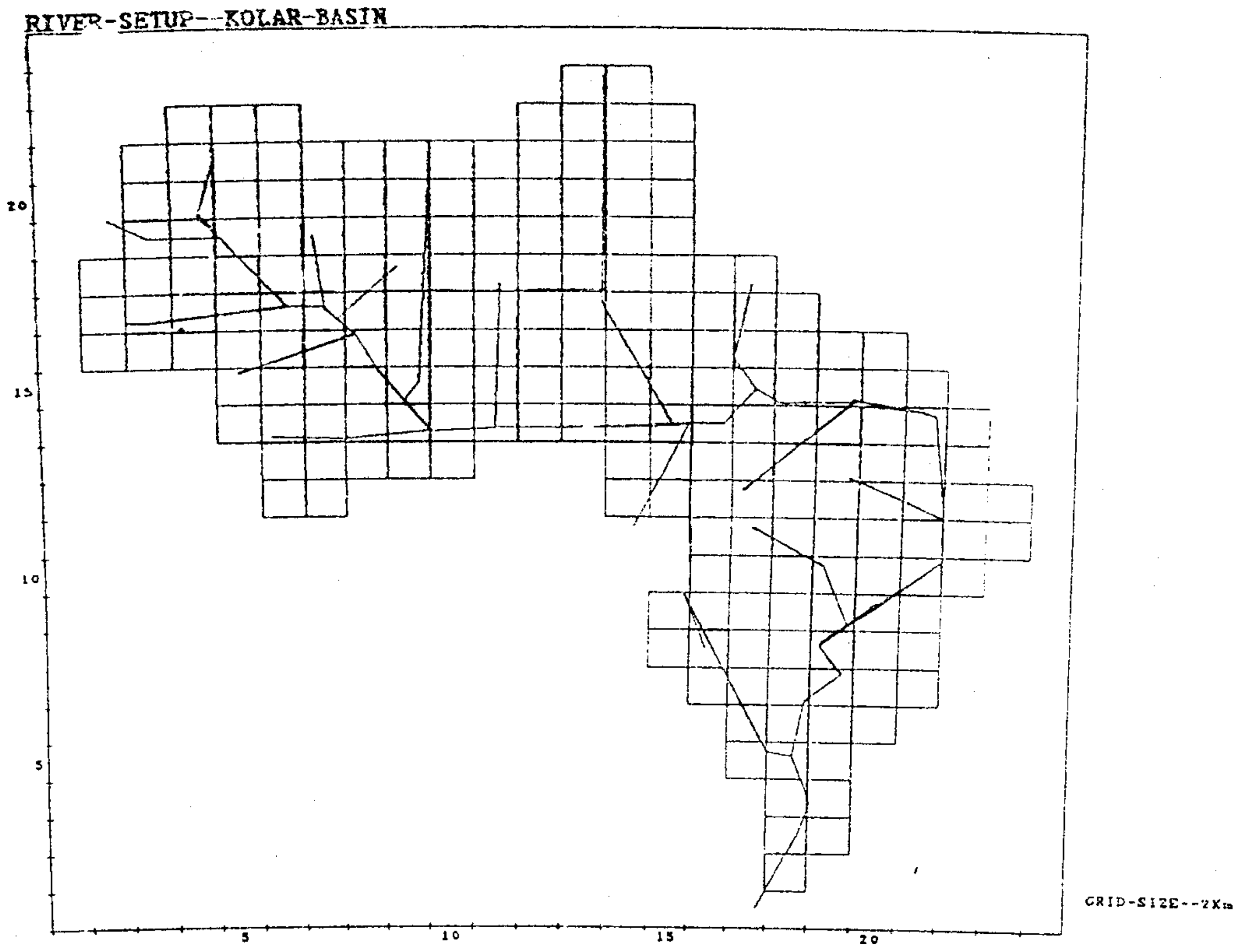


Fig. 4.6.: Derivation of model channel network from straight line approximations to the mapped network: Kolar basin at grid scale 2 km x 2 km.

Table 4.2

Grid and Channel Dimensions for the Kolar Basin

for Different Grid Scales

Grid square size km*km	Represented basin area km*km	Number of grid squares representing the basin	Number of river links representing the river system	Ratio of number of links to number of squares
0.5 * 0.5	821	3285	781	0.24
1.0 * 1.0	828	828	387	0.47
2.0 * 2.0	832	208	107	0.51

5.0 CALIBRATION OF SHE FOR KOLAR BASIN

As the discharge observations at the basin outlet were available for the period 1983-88, it was decided to use the data for the period 1983-85 for calibration and 1986-88 for validation. The model was calibrated by comparing the simulated values of monthly runoff volumes, monsoon peaks, baseflow and phreatic surface levels with the corresponding observed values.

An overview of associated literature and past experience with the model brings out following parameters which must be correctly tuned during the calibration phase : Strickler roughness coefficient for overland and channel flow, soil hydraulic conductivities in saturated and unsaturated zones, representation of cracks in soil and surface detention storage. It may be mentioned that SHE being a physically based model, theoretically it should not require any variation in the parameters during calibration for the given basin. However, in practice variation in parameter values is required because :

a) the measured values of several parameters at different locations in the basin are not available particularly in the Indian context.

b) some degree of lumping is done even in a fully distributed model, which makes this tuning necessary.

In general it has been observed that the Strickler coefficient has strong influence on hydrograph peaks, unsaturated zone hydraulic conductivities mainly affect the infiltration and thereby the volume of discharge hydrograph, the detention storage and soil cracks modelling affects the hydrograph peaks and infiltration during the initial period of monsoon rains and the saturated zone conductivities affect the baseflow.

The calibration strategy adopted was to first match the volume of observed and simulated hydrographs at the basin outlet. Once an acceptable match was obtained, the next step was to match the shape of the two hydrographs as close as possible. It was also the attempt to ensure that the response of the phreatic surface also follows the observed behaviour.

The range of values within which the parameters were allowed to vary was decided based upon information gathered from literature, e. g., Refsgaard and Hansen(1982), Li & Simons(1982), Decoursey(1982), and Engman(1986), and field visits. The Strickler coefficient for overland flow was varied between 1 & 10, the saturated soil conductivity in the unsaturated zone was allowed to vary between 0.01 to 0.8, and the saturated soil conductivity in the saturated zone was varied between 1 & 20.

The calibration started with initial parameter values taken based on these sources. The comparison of observed and simulated volumes of runoff was reasonable. The timings of peaks were acceptable but the magnitudes were not. In particular, the first few peaks during the monsoon were being over simulated. The response of the phreatic surface was also unsatisfactory at some locations in the basin.

It was at this stage that soil cracking consideration was introduced in the model. Modifications were made in the code which permitted improved modeling of the response of the basin to precipitation in presence of soil cracks. This was achieved by specifying a fraction of input rain which directly goes to the bottom of the root zone rather than contributing to overland flow. The cracks vanish when the cumulative rainfall exceeds a specified threshold. This along with a surface detention storage led to better matching of monthly discharge volumes and initial hydrograph peaks. Whenever a variation of parameters values was required to obtain a better fit, the strategy followed was first to take two runs with extreme values to bracket the feasible zone. Then the concerned parameter was systematically varied to obtain the best fit. This manual optimization worked very well in all cases.

The magnitudes of the observed and simulated peaks were matched by changing the Strickler roughness coefficient for overland flows. The conductivities in saturated and unsaturated subsurface zone were varied to simulate ground water response according to the observations as well as to match the base flow.

Proceeding in this fashion, the representative values of the parameters mentioned earlier were found.

In the final run, good fit was obtained for monthly volumes and peak values but the simulation of base flow had some room for improvement. However, the error involved is small compared with the overall volumes. The final parameter values adopted are given in Table 5.1. The observed and simulated hydrographs for a year (1983) falling in the calibration period have been plotted in Fig. 5.1. A comparison of volume and peaks of observed and simulated discharge is shown in Table 5.2.

5.1 VALIDATION OF MODEL

As mentioned earlier, the data for period 1986-88 was used to validate the model. This strategy of splitting the sample in two parts and using one part for calibration and the other for validation is a standard approach in hydrology and has been used in numerous studies, Flemings(1975).

During the validation run, the model set up and parameters were kept exactly same as during the calibration runs. In this run the initial condition was kept same as in

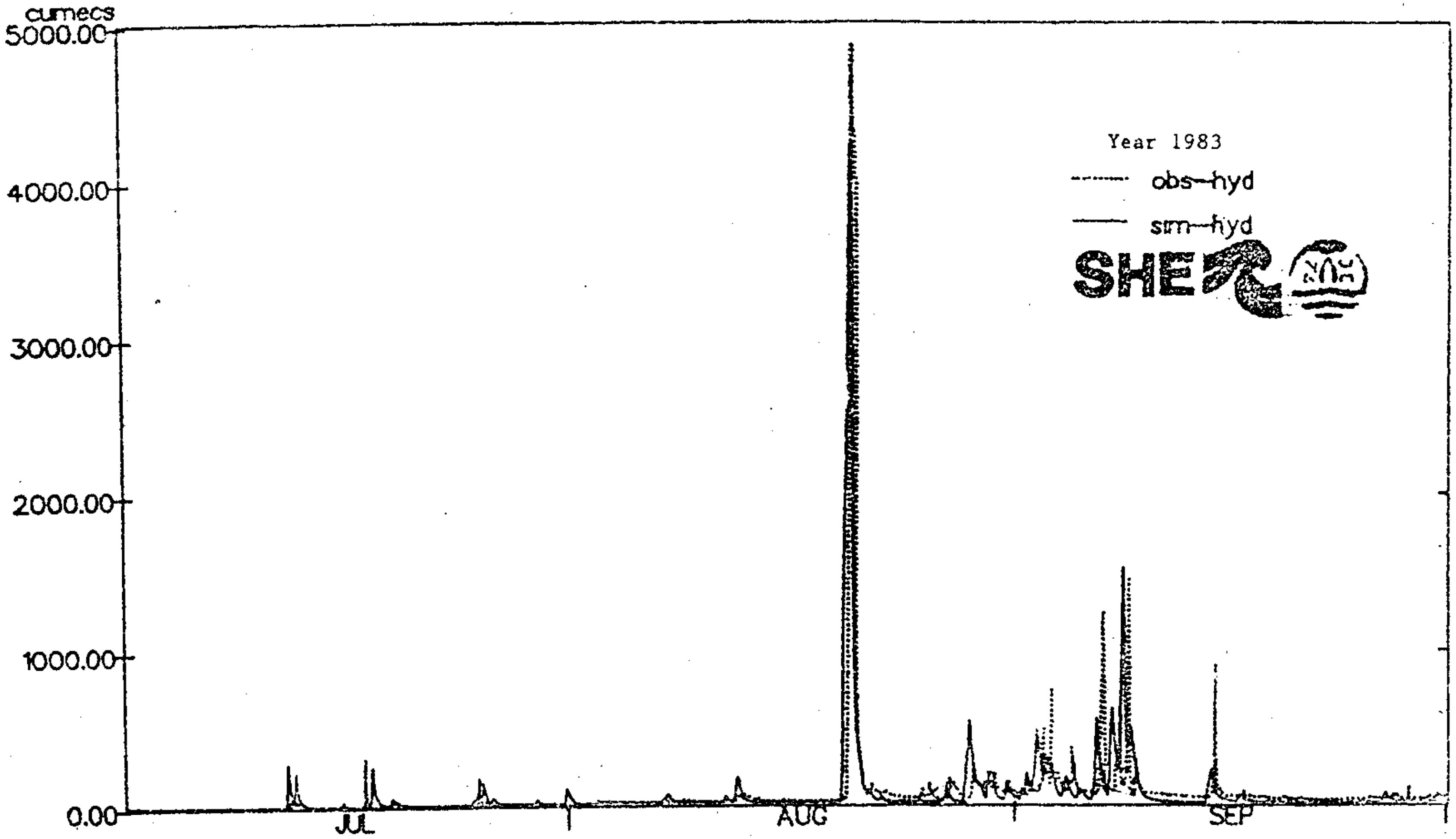


Fig. 5.1 : Comparison of simulated and observed hydrographs at the Satrana gauging site for calibration run

Table 5.1

Soil and vegetation parameters and distribution used in simulations

Land use	Proportion of basin covered %	Soil type	Saturated soil conductivity m/day		Soil Depth m	Root zone depth m	Initial Phreatic level depth m
			Unsat zone	Sat zone			
Agriculture - Low land	13	Deep clay	0.04 0.16	10.0 Root zone 10.0 Below roots	15	0.6	10.0
Agriculture - Upland	14	Deep clay	0.04 0.16	10.0 Root zone 10.0 Below roots	3	0.6	2.5
Dense Forest - Upland	34	Medium Deep clay	0.02 0.08	10.0 Root zone 10.0 Below roots	4	1.5	3.5
Dense Forest - on slopes	24	Medium Deep clay	0.02 0.08	10.0 Root zone 10.0 Below roots	6	2.0	4.5
Open Forest	13	Medium Deep clay	0.02 0.08	10.0 Root zone 10.0 Below roots	2	1.0	1.8
Wasteland	2	Shallow clay clay	0.02 0.08	10.0 Root zone 10.0 Below roots	2	0.5	1.8

Table 5.2

Comparison of Volumes and Peaks of Observed and Simulated Discharges for Calibration Period

Year	Mon	Obs mm	Sim mm
1983	6	0	6
1983	7	29	42
1983	8	361	330
1983	9	248	231
1983	10	37	13
	Sum	675	621
Peak(m3/s)		4900	4216
1984	6	10	5
1984	7	20	6
1984	8	592	602
1984	9	53	5
1984	10	23	6
	Sum	698	624
Peak(m3/s)		3100	2088
1985	6	0	10
1985	7	76	119
1985	8	218	230
1985	9	60	80
1985	10	40	47
	Sum	394	485
Peak(m3/s)		1392	1889

calibration runs and a continuous run for three years was taken. Table 5.3 gives observed and simulated discharge volumes and peaks for the validation period. The observed and simulated hydrographs for a year (1986) falling in the validation period have been plotted in Fig. 5.2. An analysis of the results shows that the volumes of discharge matches with the observations very well. The matching of the peaks, however, was not that good. Further, the general trend of ground water response is also simulated reasonably well. This suggests that the calibrated model is a reasonable representation of the Kolar basin within the constraints of data availability.

Table 5.3

Comparison of Volumes and Peaks of Observed and Simulated Discharges for Validation Period

Year	Mon	Obs mm	Sim mm
1986	6	0	23
1986	7	625	687
1986	8	218	182
1986	9	36	11
1986	10	22	8
	Sum	901	911
Peak(m3/s)		2428	3965
1987	6	21	6
1987	7	30	22
1987	8	201	275
1987	9	61	17
1987	10	18	6
	sum	331	326
Peak(m3/s)		2029	1628
1988	6	6	17
1988	7	148	218
1988	8	182	127
1988	9	43	22
1988	10	39	16
	Sum	418	400
Peak(m3/s)		775	1732

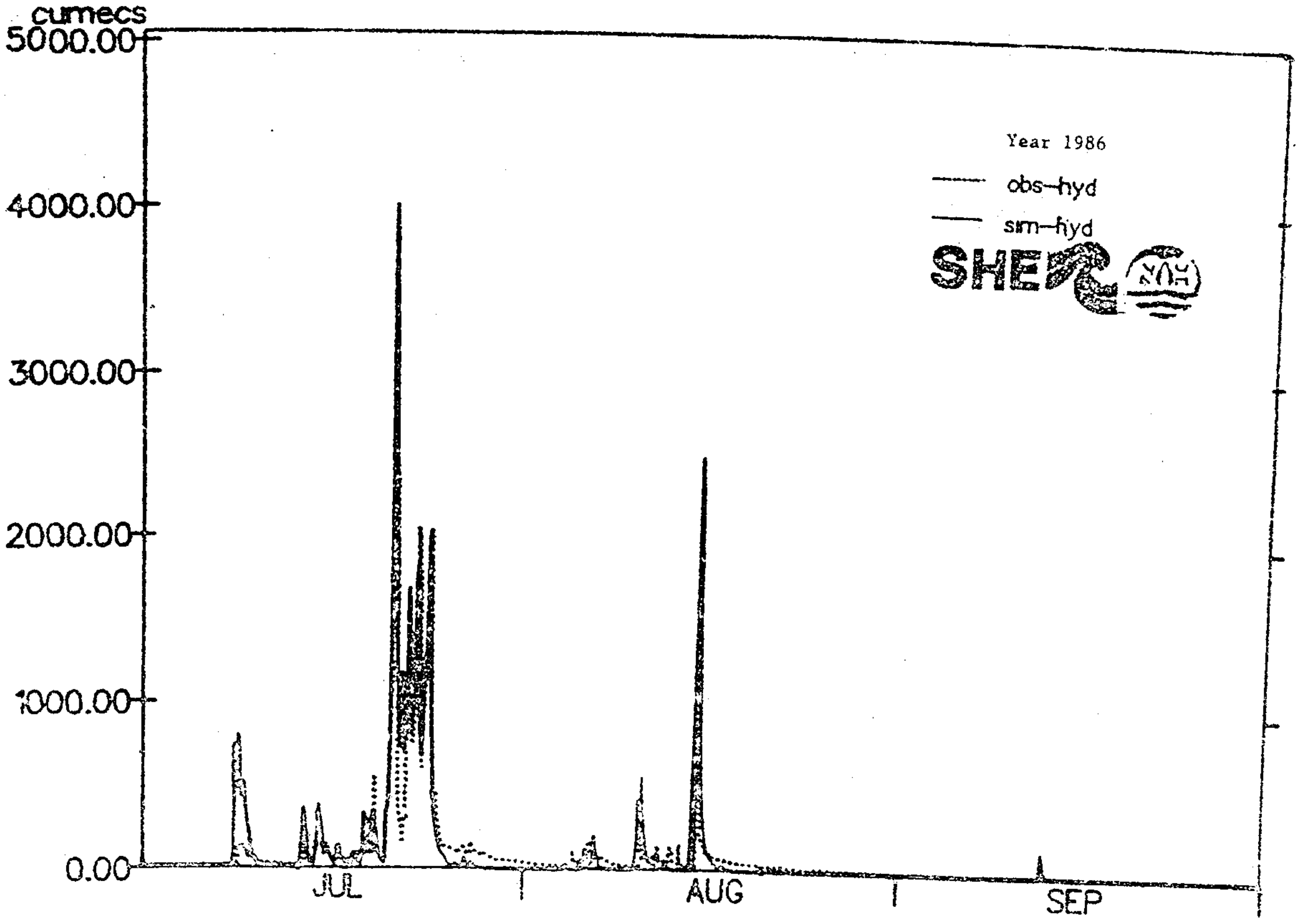


Fig. 5.2 : Comparison of simulated and observed hydrographs at the Satrana gauging site for the validation run

6.0 SENSITIVITY ANALYSIS

In order to examine the sensitivity of simulation results with respect to the important calibration parameters, a sensitivity analysis was performed. This type of analysis is very helpful in identifying the parameters for which additional field measurements are useful and the accuracy with which these measurements should be carried out, Rogers et al(1985) and Bathurst(1986). In each of the sensitivity runs, just one parameter was changed and the response of the basin in the new situation was simulated. This response was then compared with the results of best simulation run referred to as the reference run in the remaining discussion. During the sensitivity analysis, some runs were also taken after varying the parameters of interest in a typical model application such as land use, and grid size to study the influence of these changes on the simulated basin response. The ability of the model to examine what happens to basin response if there is a change in basin characteristics (the 'what if ?' approach) is a very useful feature of SHE type models which is not always available in simpler models.

Following sensitivity runs were taken :

a) By doubling the Strickler coefficient for overland flows.

b) By doubling the saturated soil conductivities in UZ.

c) By doubling the saturated soil conductivities in SZ.

d) Without using the soil-cracks modeling.

e) Using mean areal rainfall(MAR) instead of distributed rainfall as input.

f) Using 1.1*MAR as input.

g) By changing land use for grids lying in dense forest area to agriculture.

h) By representing the catchment using grids of 1Km * 1Km.

A discussion of the results of these runs follows.

a) The Strickler roughness coefficient for overland flows was made twice as big as the calibrated value of 5. This implies that for model representation, the basin was more smooth and gives more flashy response.

A comparison with the reference run shows that the new volume of discharge at the outlet is greater and the new peaks are also higher. This happens because the smoother surface allows water to move more rapidly. Consequently, the opportunities for infiltration and evaporation are less. An examination of the new simulated hydrograph, the hydrograph from the reference run and the observed hydrograph shows that the extent of increase in the peak is as much as 20% in 1983 and 1985. This suggests that the response of the basin during high floods is very sensitive to this coefficient. A correct estimate of this parameter is therefore essential for properly simulating the basin response during the periods of high flows because the peak discharge appears to be quite sensitive to this parameter. However, the total volume appears to be insensitive to this parameter; the changes were less than 4%.

b) The saturated soil conductivities in the unsaturated zone were doubled everywhere. The volume of discharge then simulated was about 10% less than the reference simulation run but the peaks were higher in two out of the three years. The reduction in the simulated discharge volume is because higher soil conductivity allow more infiltration leaving behind less water for overland flow. The increase in peaks takes place because the saturated zone reaches to the surface quickly particularly in the zones of thin soils and this leads to more flashiness in the overland flow response. The hydrograph peak showed small increase of 5% in 1983, 14% in 1985 but decreased by 5% in 1984.

c) The saturated zone conductivity was doubled for all grid squares. In this case, the volume of simulated discharge was lower than that for the reference run during the first two years and was higher during the third year. The variation was about 2%. The volume was low during the first two years because the higher conductivity allowed more water to enter the ground and less was available as surface flow. However, in the third year, due to higher antecedent recharge, the water table at the beginning of monsoon was closer to ground and consequently the recharge was less. The new peak was higher (25 and 20%) in the first and third year because the higher conductivity led to quick movement of water in SZ and the higher baseflow coincided with higher surface flow. In the second year, there were two big peaks and between these two, the second one was higher. The second peak was very much affected by the saturation caused by the storm of first peak. But when the conductivity was increased, the ground was relatively less saturated when the storm which produced the second peak arrived. The hydrograph peak appears to be quite sensitive to this parameter but the volume is insensitive.

The results of these runs demonstrate the sensitivity of the results to the soil parameters. A correct tuning of these parameters is required for not only simulating the response of the subsurface zone properly but also for better match of overland flows. This observation is in agreement with the recent realization that correct modeling of subsurface response of a basin is crucial even for surface water modeling. A particular strength of SHE type models is integration of surface and subsurface modeling.

d) In order to see the effect of soil-crack modeling on the simulation, one run was taken without the soil-crack modeling, i.e., representing the basin as if no cracks develop in the soil. A comparison of the results reveal that the volume of discharge increased by 3 to 7% and the peaks were higher by 1 to 13% as compared with the reference run. It can be seen that in the situation without soil cracks, more water is available at the surface and less is absorbed by soil. Consequently more water flows as overland flow and eventually as channel flow.

The soil-crack modeling led to marked improvement in simulation of the basin response during initial monsoon rains. Hence it is important to have a good estimate of related parameters for those basins where the cracks are formed on the ground surface.

e) A SHE run for the Kolar basin was taken in which the mean areal rainfall was input for all grid squares instead of the distributed rainfall. The volume of simulated discharge was about 2% less but the peaks were higher by 2 to 36% as compared with the reference run. This behaviour was observed because the intensity of input rainfall was less for the basin when the mean rainfall is used. This led to increased losses through evaporation and infiltration. The peaks were higher because during the period of peak flows, the entire catchment area contributed to the discharge at the outlet. In case of distributed rainfall, depending upon the spatial rainfall pattern, not all parts of the catchment might contribute to a peak. A comparison of the volumes for individual months shows that the match improved for few months and worsened for few others. These results show that it is necessary to have correct representation of spatial distribution of rainfall. To attain this, there should be an adequate network of raingauging stations in the basin and these should be uniformly distributed over the whole catchment. There should be enough self recording stations in the network so that the temporal distribution of rainfall is also correct.

f) The input rainfall was set 10% higher than the mean areal rainfall. The idea behind this was to examine as to how errors in rainfall measurement might affect the simulated basin response. A sharp increase in the volume of discharge (12 to 24%) and peaks (15 to 57%) as compared with the reference run was observed showing the sensitive nature of this parameter. This indicates that even a small error in measurement of rainfall can produce a significant change in the simulated output. It also implies that calibration based on erroneous rainfall data may result in significantly erroneous values in the calibrated parameters.

g) In order to demonstrate a very useful capability of the physically based models, the land use in all squares in the dense forest area was changed to agriculture. The depth of root zone as well the leaf-area-index for crops is far less than the same for trees. A comparison of the results of this run with the reference run showed that the discharge volume as well as peaks were higher in the changed situation. The increase in volume was small (less than 4% but was significant in peak (2 to 21%). This occurs because the loss of water through transpiration is less during the dry season and when the monsoon arrives, the soil is relatively more moist supporting a greater runoff.

h) A very pertinent question when using a SHE type model is how the catchment response changes with change in the scale of discretization or, in other words, with changes in the grid size. To investigate this, a simulation run was taken by representing the catchment by 1 Km * 1 Km grids. All other conditions including the parameters were kept same as in 2 Km * 2 Km setup. The volume of the simulated discharge was larger (of the order of 5-7%) in this case. The peak was 19% higher in 1983 and 10% in 1985 but was 5% smaller in 1984. An examination of sub-surface conditions shows that the water table is relatively deeper in this case as compared with the reference run.

While making the model set up for grid sizes of 1 km and 2 km, attempt was made to keep the ratio of number of links to the number of grid squares same (0.47 for grids of 1 km and 0.51 for grids of 2 km). However, since the grid areas and link lengths are different in the two cases, it implies that in the case of grid size of 1 km, on an average, the catchment area of a link (or river) of 1 km length is 2.14 sq. km while in case of grid size of 2 km, it is 3.89 sq. km. This indicates that the overland flow is relatively less dominant and hence there is less infiltration opportunity in the first case. this lead to higher simulated discharge volume in case of grid size of 1 km.

A comparison of simulated and observed peaks and volumes of discharge for the above sensitivity runs is given in Table 6.1.

It must be kept in mind that the results of the above sensitivity analysis give only some qualitative idea of the sensitivity of each parameter. Further to determine sensitivity of a parameter, only those events should be examined in which the process related with the parameter being analysed has important role. For example, consider a case in which sensitivity of overland flow parameters is being studied. If the data for those events has been used which do not have significant overland flows, the misleading conclusion that these parameters are insensitive may be arrived at. Moreover, in reality, the changes like land use changes involve more than one parameter and therefore any detailed study related with the effect of such changes should take in to account the new values of all such parameters.

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Table 6.1
Comparison of Volumes and Peaks of Observed and Simulated
Discharges for Sensitivity Runs

Year	Mon	Obs mm	Sim mm	Koc mm	Ksz mm	Kuz mm	CRK mm	MAR mm	1.1MAR mm	LU mm	K1 mm
1983	6	0	5.5	5.5	0.6	5.4	5.3	5.5	5.5	5.5	9.8
% change relative to sim				0.0	88.5	1.1	2.9	0.7	0.7	0.7	79.5
1983	7	29	41.8	45.0	40.6	34.3	59.3	9.0	15.3	46.0	40.0
% change relative to sim				7.5	2.9	18.0	41.7	78.5	64.2	9.9	4.4
1983	8	361	330.0	342.0	340.7	300.0	350.0	344.0	401.3	342.0	342.0
% change relative to sim				3.6	3.2	9.1	6.1	4.2	21.6	3.6	3.6
1983	9	248	230.8	231.0	226.0	204.0	222.0	239.0	278.0	232.0	235.0
% change relative to sim				0.1	2.1	11.6	3.8	3.6	20.5	0.5	1.8
1983	10	37	13.0	12.0	1.7	21.0	9.5	12.2	14.0	14.5	21.5
% change relative to sim				7.6	86.9	61.5	26.9	6.1	7.6	11.5	65.4
	Sum	675	621.1	635.5	609.6	564.7	646.1	609.7	714.1	640.0	648.3
% change relative to sim				2.3	1.8	9.1	4.0	1.8	15.0	3.0	4.4
Peak(m3/s)		4900	4216	5070	5281	4688	5289	5022	5632	4767	5010
% change relative to sim				20.3	25.3	5.0	25.4	19.1	33.6	13.1	18.8
1984	6	10	5.0	5.1	1.6	5.0	7.2	4.7	5.0	4.5	5.2
% change relative to sim				2.0	68.0	0.0	44.0	6.1	0.0	10.0	4.0
1984	7	20	6.3	6.6	3.9	5.8	11.8	4.7	5.0	6.0	6.0
% change relative to sim				4.8	38.1	7.9	87.3	25.4	20.6	4.8	4.8
1984	8	592	602.3	612.0	609.0	525.0	617.8	539.0	678.0	616.0	609.0
% change relative to sim				1.6	1.1	12.8	2.6	10.5	12.6	2.3	1.1
1984	9	53	5.4	5.1	1.3	9.6	3.7	6.0	6.5	5.3	5.1
% change relative to sim				5.6	75.9	77.8	31.5	11.1	20.4	1.8	5.6
1984	10	23	5.8	5.3	1.4	10.0	3.7	6.0	6.7	6.0	4.6
% change relative to sim				8.6	81.5	72.4	36.2	3.4	15.5	3.4	20.7
	Sum	698	624.0	634.1	617.2	555.4	644.2	560. 4	701.2	637.8	629.9
% change relative to sim				1.5	1.2	11.1	3.1	10.3	12.2	2.1	0.8
Peak(m3/s)		3100	2088	2113	2114	1991	2115	2137	2392	2121	1990
% change relative to sim				1.2	1.2	4.6	1.3	2.3	14.6	1.6	4.7
1985	6	0	10.1	12.0	10.2	11.0	23.0	7.8	12.0	12.0	11.8
% change relative to sim				18.8	1.0	8.9	127.7	22.8	38.6	38.6	15.8
1985	7	76	118.5	127.0	125.4	116.0	134.0	124.0	145.0	129.0	128.0
% change relative to sim				7.2	5.8	2.1	13.1	4.6	22.4	8.9	8.0
1985	8	218	230.0	232.0	231.0	196.0	232.0	222.0	252.0	234.0	236.0
% change relative to sim				0.9	0.4	14.8	0.9	3.5	9.6	1.7	2.6
1985	9	60	80.3	82.0	81.0	67.0	80.5	82.0	100.0	81.0	83.0
% change relative to sim				2.1	0.9	16.6	0.2	2.1	24.9	0.9	3.4
1985	10	40	46.5	49.5	47.6	40.0	48.0	41.6	51.4	49.0	50.3
% change relative to sim				6.4	2.4	14.0	3.2	10.5	10.5	5.4	8.2
	Sum	394	485.4	502.5	495.2	430.0	517.5	477.4	604.0	505.0	519.0
% change relative to sim				3.5	2.0	11.4	6.6	1.6	24.4	4.0	6.9
Peak(m3/s)		1392	1889	2255	2273	2154	2126	2572	2962	2289	2072
% change relative to sim				19.4	20.3	14.0	12.5	36.2	56.8	21.2	9.7

Note : Obs - Observed, Sim - Simulated, Koc - Doubling Strickler Coeff.
Ksz - Doubling SZ conductivity, CRK - Without modelling cracks,
MAR - using mean areal RF, 1.1MAR - Using 1.1 Mean areal RF,
K1 - Using grid size of 1*1 Km, Kuz - Doubling UZ conductivity,
LU - Changing land use from dense forest to agriculture,

8.0 CONCLUSIONS

Based on the above study, the following conclusions can be made :

a) The SHE model has been successfully used for modeling of Kolar basin within data availability constraints. The simulating response of the basin shows good matches with the observed volume and peaks of discharge and phreatic surface level. There is, however, scope of improvement in simulating the response of the catchment during the lean flow periods.

b) The modelling of subsurface response also requires further efforts, both in terms of model improvements as well as input data.

c) For the basins where prolonged hot weather precedes the rainy season and cracks develop on the soil surface, it is very important that these soil cracks are properly accounted for.

d) Based on the sensitivity analysis, it can be concluded that besides the soil parameters, the surface and channel roughness should be correctly represented for obtaining good match between the observed and simulated response.

e) In case of Kolar, additional field measurements are necessary to reduce the uncertainty associated with the parameters of soil hydraulic properties to improve the simulation. One or two more rainfall stations in the northern part of the catchment, which is not covered very well by the four stations available, may improve the accuracy of the results.

f) In the present simulation, no spatial variation was considered for Strickler roughness coefficient, detention storage, and soil-cracks. Future simulation studies should take into account such variation as a function of land use.

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