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APPLICATION OF SHE MODEL TO BETI SUB BASIN OF RIVER MACHHU

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PREFACE

With increasing population and improved standard of living rising demand of water for irrigation, drinking as well as other domestic purposes, industrial use and hydropower generation etc. has drawn attention towards optimal utilisation of water resources the world over. The rapid growth in water resources development activity calls for proper assessment and optimal planning of water resources. The conventional rainfall-runoff models are in appropriate to deal with many hydrological problems, especially those related to the impact of man's activities, landuse changes, conjunctive use of surface and ground water, soil moisture conditions and water quality etc. These problems have focussed attention towards development and application of physically based hydrological models to deal with constantly changing hydrological environment. These models have physical basis and allow for spatial variations within a catchment.

The Systeme Hydrologique European (SHE) modelling system jointly developed by the Institutes of three countries, namely Denmark, France and U.K. has been transferred to National Institute of Hydrology under a collaborative project. The SHE has capability to provide detailed and to a large extent physically correct description of water flow processes because of its general formulation and physical basis. This model will be applicable to almost any kind of hydrological problem, although further development is still needed to realise this notion. The flexible model structure combined with the distributed nature and physical interpretation of the hydrological processes, is expected to provide significant advantages over existing hydrological models in dealing with various hydrological problems.

The present study involves use of available data of Beti sub-basin and deals with data processing and preparation, evaluation of model parameters, assessment of uncertainty in input quantities, carrying out simulation runs including calibration, validation and sensitivity analysis and interpreting the results. The study has been carried out by Mr. Rakesh Kumar, Scientist 'C' under the guidance of Dr. S M Seth, Scientist 'F' and Mr. K.S. Ramasastri, Scientist 'F'.

Satish Chandra

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ABSTRACT

The Systeme Hydrologique European (SHE) is a deterministic, distributed and physically based hydrological modelling system in the sense that the hydrological processes of water movement are modelled either by finite difference representations of partial differential equations of mass, momentum or energy conservation or by empirical equations derived from independent experimental research. Spatial distribution of catchment parameters, rainfall input and hydrological response is achieved in the horizontal by an orthogonal grid network and in the vertical by a column of horizontal layers at each grid square. The river channels are superimposed on the boundaries of the grid squares.

In the SHE, basic processes of land phase of hydrological cycle are modelled in seperate components viz, interception, by Rutter's accounting procedure; evaporation, by Penman-Monteith equation or by an approach developed by Kristensen and Jensen (1975), overland and channel flow by, simplifications of St. Venant equations; saturated zone flow by, two dimensional Boussinesq equation and snowmelt by, an energy budget method or degree day method.

The present study deals with application of the SHE model to the Beti sub-basin of river Machhu. The computational grid network and channel system was set up for the basin, forming the basis for spatial distribution of topographic elevation, soil types, landuse and rainfall stations. The study has been carried out for a grid size of 2 km x 2 km. As actual values of soil and vegetation parameters were not available, the model parameters in respect of them were evaluated on the basis of information derived from available current literature pertaining to neighbouring areas. The report describes, salient features of the SHE model, data availability, its processing, calibration and validation as well as sensitivity analysis carried out in the study.

1.0 INTRODUCTION

Water is a basic input for agriculture, industries, drinking as well as other domestic purposes and hydro power generation etc.To meet demands of growing population, there has been considerable development of water resources in the country, since independence.As the demands for water and costs of water resource development have increased, so there has been an increasing demand for a new approach to hydrological modelling to help optimise project planning. There are many practical hydrological problems which are becoming increasingly pressing. These problems are arising from the adverse impacts of man's activities on the hydrological cycle and consequently on water resources. Surface and ground water resources are being polluted by fertilizers and pesticides associated with intensive agricultural practices. Transport of contaminants from waste disposal sites and the more recently publicized effects of acid rain represent further threats to water quality. In the developing world, major water resource projects are detrimentally affected by large-scale deforestation under increasing population pressure, which is causing significant changes to the high and low flow regimes of rivers. Deforestation is also leading to massive soil erosion, the products of which are causing the rapid siltation of reservoirs. It is therefore all the more imperative that development options, and particularly their environmental impact, should be evaluated more rigorously to ensure the optimum exploitation of water resources.

A large number of hydrological models exist.However,many of the models function in basically the same way. For instance, atleast twenty different rainfall runoff models of the lumped ,conceptual type exist. A model represents the physical/chemical/biological characteristics of the catchment and simulates the natural hydrological processes. It is not an end in itself but is a tool in a larger process which is usually a decision problem. A model aids in making decisions, particularly where data or information are scarce or there are large numbers of options to choose from. It is not a replacement for field observations. Its value lies in its ability, when correctly chosen and adjusted, to extract the maximum amount of information from the available data, so as to aid in decision making process.

In classifying hydrological models the following terms are widely used :

A deterministic model is one in which no uncertainties in prediction are admitted, so that two equal sets of input always yield the same output if run through the model under identical conditions. The model has no component with stochastic behaviour, i.e. the variables are free from random variation and have no distribution in probability.

A stochastic model has some component of random character, having a distribution in probability through time. Identical inputs may result in different outputs if run through the model under identical conditions.

A lumped model isa model where the catchment is regarded as one unit. The inputs, variables and parameters represent average values for the entire catchment.

A black box model is a model developed without any consideration of the physical processes in the catchment. The model is merely based on analyses of concurrent input and output time series.

A conceptual model is based on some consideration of the physical processes in the catchment. In a conceptual model physically sound structures and equations are used together with semi-empirical ones. However, the physical significance is not so clear that the parameters can be assessed from direct measurements. Instead, it is necessary to estimate the parameters from calibration, applying concurrent input and output time series. A conceptual model, which is usually a lumped-type model, is often called a grey box model.

A fully physically based model describes the system using the basic equations governing the flows of energy and water. For catchment models,a fully physically based model in practice also has to be a fully distributed model. This type of model, also called a white box model, thus consists of a set of linked partial differential equations together with parameters which, in principle, have direct physical significance and can be evaluated by independent measurements.

It is considered that the further development or enhancement of the conventional hydrological models can not provide a sound scientific basis for tackling many of the problems concerned with the effects of land-use change related to agricultural and forestry practices, hazards of pollution and toxic waste disposal and general problems arising from conjunctive uses of water. These lumped parameter, rainfall-runoff models depend essentially on the availability of sufficiently long meteorological and hydrological records for their calibration and such records are not always available. Their calibration also involves a significant element of curve fitting, thus making any physical interpretation of the fitted parameter values extremely difficult. Under these circumstances, prediction of the effects of land-use changes on the hydrological regime of a catchment, particularly where only part of the catchment is affected, can not be undertaken with any confidence.Because of their inherent structure these models also make very little use of contour, soil and vegetation maps, or of the increasing body of information in such areas as soil physics and plant physiology. Similarly, much historical information frequently consulted during project planning, for example crop yields over specific periods, survival patterns of particular types of vegetation and characteristic events occurring during floods and droughts, is not used directly. A considerable improvement in project planning could therefore be derived from the integration of such information into the modelling process. In particular physically-based, distributed models can in principle overcome many of the above deficiencies through their use of parameters which have a physical interpretation and through their representation of spatial variability in the parameter values.

SHE Model Project at NIH - funded by CEC

The SHE model software has been transferred to the National Institute of Hydrology,Roorkee under a project financed by Agreement ALA 86/19 between the Commission of European Communities and the Government of India.The project was aimed to transfer the Systeme Hydrologique European - European Hydrological System (SHE) to the National Institute of Hydrology,Roorkee;and intended to increase India's capabilities for formulating water and land development strategies through numerical modelling.

Under the above project,the SHE model has been applied to following eight tributary basins

1. Narmada upto Manot (area 4980 sq km)
2. Hiran upto Patan (area 4064 sq km)
3. Sher upto Belkheri (area 1345 sq km)
4. Barna upto Bareli (area 1530 sq km)
5. Kolar upto Satrana (area 820 sq km)
6. Ganjal upto Chhidgaon (area 1730 sq km)
7. Hemavati upto Saklespur (area 600 sq km)
8. Beti upto Beti village (area 522 sq km)

Considerable efforts have been made in carrying out the assembling, review, processing and computerization of data for the eight basins. These basins have been modelled in connection with the comprehensive training of six NIH scientists at the Danish hydraulic Institute,denmark . Three scientists were trained for 4 months during the period May - September 1988, while a similar training has been given to another three scientists during the period August - December 1989. The ultimate aim of the training has been to bring the scientists to a level at which they can apply SHE in new water resources projects. The training programme comprised both theoretical and practical aspects of SHE applications. The theoretical aspects have been covered by lectures and tutorial exercises, while the practical experience has been gained through model set up and calibration on the focus basins.

2.0 THE SHE

2.1 General

The Systeme Hydrologique European-European Hydrological System (SHE) is an advanced, physically based, distributed catchment modelling system. It has been developed jointly by the Danish Hydraulic Institute, the British Institute of Hydrology, U.K. and SOGREAH (France) with the financial support of the Commission of the European Communities. Currently British responsibility for the SHE lies with the Natural Environment Research Council's Water Resource System Research Unit at the University of Newcastle upon Tyne (UON). In France the responsibility has been transferred from SOGREAH to Laboratorie d'Hydroulique de France (LHE).

The SHE was developed from the perception that conventional rainfall/runoff models are inappropriate to many hydrological problems, specially those related to the impact of man's activities of land use change and water quality. These problems can be solved only through the use of models which have a physical basis and allow for spatial variations within a catchment. The SHE is a physically based model in the sense that the hydrological process of water movement are modelled either by finite difference representations of the partial differential equations of mass, momentum and energy conservation or by empirical equations derived from independent experimental research. Spatial distribution of catchment parameters, rainfall input and hydrological response is achieved in the horizontal by an orthogonal grid network and in the vertical by a column of horizontal layers at each grid square. River channels are superimposed on the grid element boundaries. Parameters must be evaluated as appropriate for each grid element, river link and subsurface layer. Basic processes of the land phase of the hydrological cycle are modelled in separate components viz. interception by the Rutter accounting procedure; evapotranspiration, by the Penman-Monteith equation or by an approach developed by Kristensen and Jensen (1975); overland and channel flow by simplications of St.Venant equations; unsaturated zone flow, by one dimensional Richard's equation; saturated zone flow by the two dimensional Boussinesq equation and snowmelt, by an energy budget method. The SHE software is structured in such a manner that each hydrological process is allowed its own component and simultaneous operation of each component is controlled by a central frame component. For flexibility, the components can be modified or omitted i.e. replaced by dummy exchange components in any given application, depending on availability of data and hydrological conditions.

The SHE has a modular structure in order to incorporate improvements or additional components such as irrigation return flow, sediment yield and water quality etc. in future. Considerable operating flexibility is available through the ability to vary the level of sophistication of the calculation made to make use of as many or as few data as are available and also to incorporate data related to topography, vegetation and soil properties which are not usually incorporated in catchment models. The SHE does not require long term hydrometeorological data for its calibration and its distributed nature enables spatial variability in catchment inputs and outputs to be simulated. However, the large amount of data required by the model means that new operation methodologies must be evolved. Thus spatial scale effects or simply a lack of data may create significant uncertainties in the values of the catchment parameters used in simulation. These uncertainities give rise to corresponding uncertainties in the predictions. However, the SHE is able to quantify these uncertainties by carrying out sensitivity analysis for realistic ranges of the parameter values, even when there is a lack of data. Therefore, the SHE can act as a valuable 'decision support system'(Abbott et al.1986).

The SHE is designed as a practical system for application in a wide range of hydrological resource conditions. Its physical and spatially distributed basis gives it advantage over simpler regression and lumped models in simulating land use change impact, ungauged basins, spatial variability in catchment inputs and outputs, groundwater and soil moisture conditions, and water flows controlling the movements of pollutants and sediment.

In particular, the physical basis of the SHE suits it to predictions of the hydrological consequences of man-made changes in a catchment and for pollutant and sediment transport studies. However, the flexibility of the SHE also makes it possible for the one modelling system to perform predictions for a wide range of hydrological problems and at various levels of complexity. The logistics and benefits of the SHE, including a detailed review of potential areas of application, are discussed further by Abbott et al (1978) and additional information is supplied by Beven and O'Connel (1982) and Beven (1985). The schematic diagram of a catchment and a quasi three dimensional physically based distributed SHE model is shown in Fig. 1. Table-1 Summarises some of the possible fields of application of the SHE.

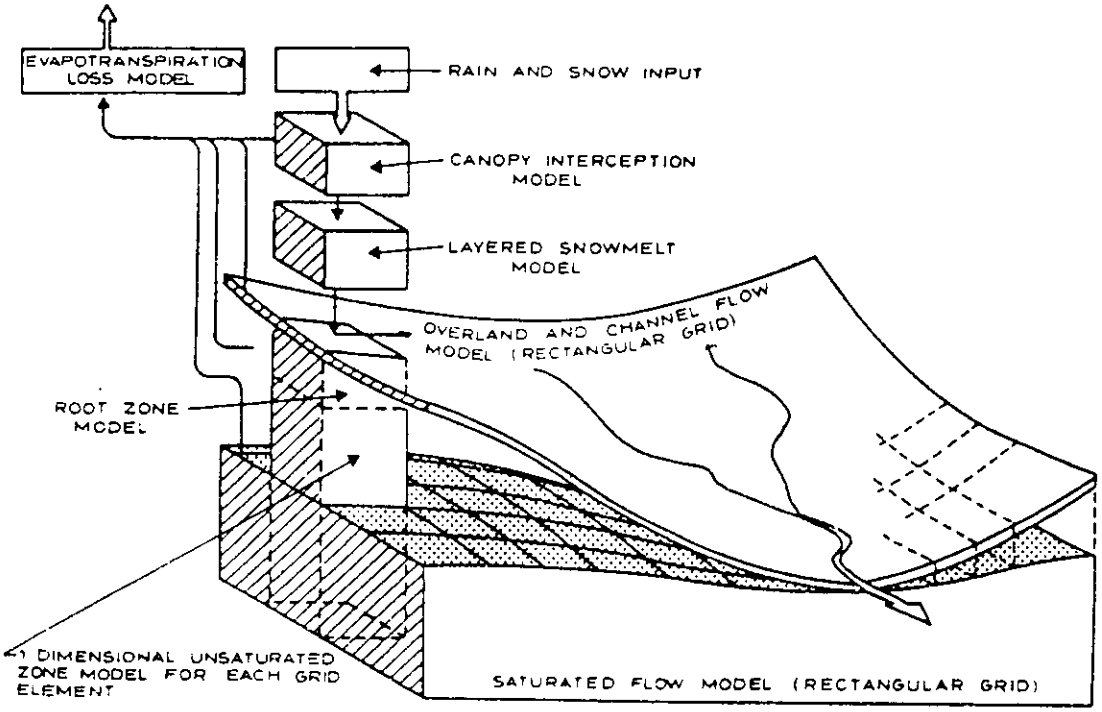


FIGURE 1 - STRUCTURE OF THE EUROPEAN HYDROLOGIC SYSTEM (SHE)

TABLE - 1

Possible fields of application for the SHE at different operation scales for some of the topics a water quality comonent would need to be added to the existing water quantity model:

Topics	Primary hydrological process	Possible scale of operation
Irrigation Scheme		
Irrigation water requirement	ET/UZ	field
Crop production	ET/UZ	Project
waterlogging	ET/UZ	field
Salinity/Irrigation management	UZ	field
Land-use Change		
Forest clearance	ET/UZ/SZ	Catchment
Agricultural practices		field/catchment
Urbanisation		catchment
Water developments Groundwater supply	SZ	catchment
Surface water supply	ET/UZ/SZ	catchment
Irrigation	UZ/SZ	Project/catchment
Streamflow depletion	SZ/OC	catchment
Surface water/groundwater interaction	ET/UZ/SZ	Project/catchment
Groundwater contamination Industrial and municipal waste disposal	UZ/SZ	field/catchment
Agricultural chemicals	UZ/SZ	field/project catchment
Erosion/sediment transfer	OC/UZ	Project/catch.
Flood prediction	OC/UZ	catchment

Note: ET= evapotranspiration. UZ=unsaturated zone. SZ=saturated OC=overland and channel flow

2.2 Typical Approaches for Modelling of Different Processes

In the SHE, major hydrological processes of water movement, are modelled in the following components:

1. FRAME (central control) component
2. Interception and evapotranspiration component
3. Overland and channel flow component
4. Unsaturated zone component
5. Saturated zone component
6. Snowmelt component

A detailed description of the above components is given by Abbott et al.(1986). The components of the SHE as discussed in NIH Case Study Report C S-29 are briefly reproduced hereunder.

2.2.1 FRAME (Central Control) Component

The FRAME component coordinates the parallel running of the other components by selecting their different time scales and organizing their data interchanges. Its functions include the following.

(i) Controlling the reading of the parameter sets and the initialization of all computations variables.
(ii) Controlling the sequence in which each component is called to perform its computations.
(iii) Controlling the exchange of data between components.
(iv) Controlling the mass balances between all components and within each component separately.

2.2.2 Interception and Evapotranspiration Component

This component uses meteorological input data and vegetation parameters to simulate the total evapotranspiration and net rainfall amounts resulting from the processes of

(i) interception of rainfall by the vegetation canopy;
(ii) drainage from the canopy;
(iii) evaporation from the canopy surface;
(iv) evaporation from the soil surface;
(v) uptake of water by plant roots and its transpiration.

Net rainfall, transpiration and soil evaporation rates are supplied to the unsaturated zone component, which in return provides information on soil moisture conditions in the root zone.

Because interception can significantly affect evapotranspiration, the two processes are modelled within the one overall component.

Interception

The interception component calculates net rainfall reaching the ground through the canopy, the amount of water stored on the canopy and evaporation from the canopy. Interception itself can be modelled by a modified Rutter model or based upon vegetation cover indices. The Rutter model (Rutter et al.,1971/72) is essentially an accounting procedure for canopy storage. From the canopy storage, which can vary during the growing season, e.g. as a function of the leaf area index, the intercepted water may either evaporate directly or drain to the soil surface according to a prescribed function. Consideration of interception loss is particularly important when dealing with forest areas.

Evapotranspiration

The evapotranspiration component calculates actual evapotranspiration and translates it into a loss term, describing uptake of water by plant roots and its transpiration in a response which is continuous as the canopy varies from a dry, through a partially wetted, to a fully wetted state. The loss term is then used in the calculation of soil moisture changes by the unsaturated zone component. The most complex and physically realistic model used in the SHE is the Penman - Monteith equation for actual evapotranspiration (Monteith, 1965) in which three approaches are used, giving flexibility and allowing the model to be adapted to whatever is known of local conditions. In the first two approaches, actual evapotranspiration at subpotential rates is assumed to be limited, at least in part, by vegetation factors, particularly the stomatal resistance to movement of water. In the third approach the limitation is assumed to be due only to the resistance of the unsaturated soil to water movement. The other model (Kristensen and Jensen, 1975) offered as option two, calculates actual evapotranspiration on the basis of potential rates which are required as input data and the actual soil moisture status in the root zone. The derivation of the equations has been based on comparisons with actual measurements.

The total actual evapotranspiration calculated for each grid square depends on how wet the canopy is and on the degree of ground coverage by the canopy. Extraction of moisture for transpiration from the root zone is distributed according to the vertical distribution of root mass in the root zone. Moisture for the soil evaporation is drawn from the top of the soil column.

2.2.3 Overland and Channel Flow Component

This component uses topographic, channel shape and flow resistance parameters to route surface water as overland and channel flow. The depth of surface water available as runoff is determined from the net rainfall and evaporation rates supplied by the interception/evapotranspiration component and from the soil infiltration rate determined by the unsaturated zone component. In addition there is an exchange between channel and aquifer to allow for seepage losses and ground water input.

Both the overland flow and channel flow are modelled by approximations of the St.Venant equations of continuity and momentum (inertia terms neglected). In the modelling of overland flow the slope of the water surface is assumed to be parallel to the ground slope (kinematic wave assumption), but for channel flow, a water surface slope term is included in the mathematical formulation so that backwater effects can be modelled. An equivalent roughness coefficient is used to characterize resistance to overland flow, while depth-dependent flow resistance functions are required for the river flow description.

2.2.4 Unsaturated Zone Component

This component determines the soil moisture content and tension, or pressure, distributions in the unsaturated zone. The zone extends from the ground surface to the phreatic surface. It is mostly nonuniform in its physical properties and the upper part, the root zone, exhibits considerable fluctuations in moisture content as a result of evapotranspiration and rainfall infiltration. Its lower boundary also varies through time, as the phreatic surface elevation changes. The component plays a crucial role in the SHE since all the other components draw upon the boundary data which it supplies.

Based on the assumption that there is flow in the vertical only, the solution is obtained with the one-dimensional Richards equation:

$$K \qquad C\frac{\partial\psi}{\partial t} = \frac{\partial}{\partial z}\left(K\frac{\partial\psi}{\partial z}\right) + \frac{\partial K}{\partial z} - S \qquad \ldots \quad (1)$$

where,

ψ = soil moisture tension or pressure head;
t = time;
z = vertical space coordinate (positive upwards);
$C = \frac{\partial\theta}{\partial\psi}$ = soil water capacity;
θ = volumetric water content;
$K(\theta,z)$ = hydraulic conductivity;
$S(z)$ = source/sink term for root extraction and soil evaporation.

Two functional relationships are needed to solve the equation. These are the relationship between unsaturated conductivity K and the volumetric moisture content θ and the relationship between soil tension and the volumetric moisture content. The latter, called the retention curve, is known to exhibit hysteresis effects in nature but is approximated for the moment by a single-valued relationship in the SHE. Equation 1 is solved by an implicit finite difference scheme.

Infiltration into the soil is determined by the upper boundary condition which may shift from flux-controlled conditions to soil-controlled (i.e. saturated) conditions and vice versa. The lower boundary is usually the phreatic surface and a mass balance calculation for the unsaturated zone determines the exchange with the saturated zone. A particularly difficult problem is the calculation of the change in the phreatic surface level. This requires linking the one-dimensional, vertical flow, unsaturated zone model with the two-dimensional, horizontal flow, saturated zone model. In particular the simulated soil moisture profile in the lower part of the unsaturated zone must remain compatible with the phreatic surface level computed by the saturated zone component. In the SHE, the approach used is based on the water balance of the total soil column, including the saturated zone. Upto four soil layers with different characteristics can currently be incorporated in a simulation. Allowance is also made for the disappearance of the unsaturated layer as the phreatic surface rises to the ground surface.

2.2.5 Saturated Zone Component

This component computes the phreatic surface level and the flows, assumed to be horizontal only, in the saturated zone. At present only single-layer, unconfined aquifers can be modelled.

However, the component is designed so that it can easily be expanded to account for confined and multilayer aquifers in the future. Otherwise allowance is made for spatial variations in aquifer permeability and the impermeable bed level. The component receives net percolation rates from the unsaturated zone calculations and supplies in return the phreatic surface level as a lower boundary condition for those calculations. Stream/aquifer interactions, ground water seepage at the ground surface and artificial pumping are also simulated.

The variation through time of the phreatic surface level at each square is modelled by the nonlinear Boussinesq equation. This combines Darcy's law and the mass conservation of two-dimensional laminar flow in an anisotropic, heterogeneous aquifer, to give :

$$S \frac{\partial h}{\partial t} = \frac{\partial}{\partial x} (KxH \frac{\partial h}{\partial x}) + \frac{\partial}{\partial y} (KyH \frac{\partial h}{\partial y}) + R \qquad \ldots(2)$$

where,

S(x,y) = specific yield;
h(x,y,t) = phreatic surface level;
Kx(x,y),Ky(x,y) = saturated hydraulic conductivities in the x and y directions respectively;
H(x,y,t) = saturated thickness;
t = time;
x,y = horizontal cartesian coordinates;
R(x,y,t) = instantaneous vertical recharge into the saturated zone.

This can be expressed by :

$$R = \Sigma q - \frac{\partial}{\partial t} \int_{h}^{gs} \theta \, dz \qquad \ldots(3)$$

where,

Σq = transpiration + soil evaporation + infiltration + stream/aquifer exchange + external boundary flows;
θ(z,t) = soil moisture content in the unsaturated zone;
gs = ground surface level.

Equation 2 is solved by a finite difference approximation using an alternating-direction, non-iterative implicit scheme. Allowance is made for both the complete disappearance of the saturated zone and the rise of the phreatic surface to the ground surface.

2.2.6 Snowmelt Component

This component uses snowpack and vegetation parameters, along with meteorological input data, to predict the transfer of moisture resulting from processes of :

i. snowfall addition to the snowpack;
ii. snowmelt from the snowpack;
iii. spatial variations in snowpack conditions;
iv. interception and evapotranspiration in the presence of a snowpack and at air temperatures below freezing.

Its aim is to model the snowpack thickness as it is affected by precipitation and melting and to model the rate of delivery of meltwater from the snowpack to the soil-surface. The component is structured so that first the total heat flux to the snowpack is calculated, then the amount of melting engendered by this flux is determined and finally the meltwater is routed through the snowpack. Thus both energy and mass fluxes within the snowpack are modelled.

Again, depending on the availability of data or on general requirements, two different calculation modes can be used to determine the total heat flux. The simplest is an adaptation of the degree-day method. Because of its empirical nature, this method is used only when available data are limited to air temperatures. At a more sophisticated level, the heat flux is determined from a budget of the energy inputs and outputs. The snowmelt resulting from the total heat flux is derived from an energy balance equation, in which due account is taken of the latent heat gained by movement of water into the snowpack.

2.3 Data Required for SHE Model Application

A description of data requirement for the SHE model application as described in NIH Case Study Report C S - 29 is reproduced hereunder.Application of a distributed, physically-based model such as the SHE requires the provision of large amounts of parametric and input data, some of which, like crop parameters, may be time dependent. Such data will not always be readily available and therefore options have been built into the system to allow components to degenerate to simpler modes of operation and thereby reducing the data requirements. It is stressed that parameter values are in principle measurable in the field and it is hoped that a general availability of models like SHE, which are able to utilize almost any hydrological information, will instigate more widespread measurements of the data required, if not on a routine basis, then at least as part of the application of the model to specific projects.

Parametric values and data input to the model can vary from grid square to grid square or from point to point in the vertical. However, in most cases the same input data and parametric values will be associated with an assembling of grid squares. Both input data and parametric values are assumed to be valid over the entire area associated with a grid point. An option for variable grid spacing both in the horizontal and vertical direction is included in the system. Thus a refined grid may be introduced around rivers, pumping fields and other such areas, characterized by a significant variation in natural or man-influenced hydrologic processes. The parameters and parametric functions required by the SHE at each grid square for the most comprehensive calculation modes are listed below:

FRAME Component

Model parameters

(i) Ground surface elevation

(ii) Impermeable bed elevation

(iii) Distribution codes for rainfall and meteorological source stations

(iv) Distribution codes for soil and vegetation types

Interception Component

Input data	(i)	Rainfall rate
Model parameters (for each crop type)	(i)	Drainage parameters
	(ii)	Canopy storage capacity (time varying)
	(iii)	Ground cover indices (time varying)

Evapotranspiration Component

Input data	(i)	Meteorological data
Model parameters (for each crop type)	(i)	Canopy resistance
	(ii)	Aerodynamic resistance
[For Kristensen and Jensen model only (iii) and (v) are required]	(iii)	Ground cover indices (time varying)
	(iv)	Ratio between actual and potential evapotranspiration as a function of soil moisture tension
	(v)	Root distribution with depth

Overland and Channel Flow Component

Input data	(i)	Specified flows or water levels at boundaries
	(ii)	Man-controlled diversions and discharges
	(iii)	Topography of overland flow plane and channel cross-sections

Model parameters	(i)	Strickler roughness coefficients for overland and river flows
	(ii)	Coefficients of discharge for weir formulae

Unsaturated Zone Component

Model Parameters (for each soil type)	(i)	Soil moisture tension/ content relationship
	(ii)	Unsaturated hydraulic conductivity as a function of moisture content

Saturated Zone Component

Input data	(i)	Impermeable bed elevations
	(ii)	Specified flows or potentials at boundaries
	(iii)	Pumping and recharge data
Model parameters	(i)	Porosities or specific yields
	(ii)	Saturated hydraulic conductivities

Snowmelt Component

Input data	(i)	Meteorological and precipitation data
Model parameters	(i)	Degree-day factor
	(ii)	Snow zero plane displacement
	(iii)	Snow roughness height.

The components interact with each other through a series of internal boundary conditions, either as flow or pressure conditions, which appear as a result of progress in time in the other components. No iteration between the components are performed but they are run in parallel. This means that time steps are taken which are based on 'old' information.

In principle the parameter values should not need to be calibrated, since they are based on physical measurements. However, in practice a certain amount of calibration is likely to be required. One reason for this is that measured values are often obtained at the point scale and may not be representative of the grid scale to which the model parameters are applied.

2.5 Studies Elsewhere using SHE Model

Physically based models of the individual components in SHE have been known for years. The uniqueness of SHE is, however, that it is one of the few models integrating all submodels into one system of the entire land based part of the hydrological cycle. In recent years, application of SHE has moved from purely research oriented studies to projects of practical significance. Examples include

(i) a study of the effects of land use changes on floods and sediment loads (Thailand),
(ii) a study of the environmental impact of the use of fertilizers (Denmark),
(iii) a water supply planning project for the city of Aarhus (Denmark),
(iv) a comparative study of different models to simulate runoff from medium size catchments (Zimbabwe and Denmark),
(v) a study of the effects of irrigation development (India)

[within the frame work of the project ALA 86/19].

Further developments are currently undertaken to promote its use as an operational tool for water resources and environmental studies.

3.0 STUDY AREA AND DATA AVAILABILITY

3.1 General

In the present study the SHE has been applied to the Beti sub-basin of river Machhu. The Machhu rises near Bhadla in the Rajkot district of Gujarat at an elevation of 275 m at north latitude $22^{\circ}11'$ and the east longitude $71^{\circ}6'$ and flows in a generally northerly direction for a total length of 140 km. to join the Rann of Kutch near village of Maliya. The Machhu river drains a total area of 2,515 sq.km.Out of which the Beti sub basin has an areal extent of 522 sq. kms.Location of beti sub basin in Machhu basin is shown in Fig.2 and Map of the Beti sub basin is illustrated in Fig.3.

The study area has semi-arid climate. The rainfall in this region varies from 400 mm along the Gulf of Kutch to a little over 600 mm along the Gulf of Cambay. About 96 percent of rainfall occurs during monsoon period from June to September. The average annual rainfall in the catchment based on WMR of 7 raingauge stations viz.,Rajkot, Wakaner, Jasdan, Machhu-I dam site, Chotila, Sardhar and Kuvadva for the period 1961-1980 works out to 512 mm. The difference between daily mean maximum and mean minimum temperature is however, the highest during the month of March. The wind velocity is high during the months of May to August. However, highest wind velocity is observed during the month of July.

3.2 Data Availability

A data assembly programme was carried out to provide hydrometeorological data and the information about the basin parameters such as soils, vegetation and topographic characteristics, needed to support the SHE simulations. In view of this a large number of data collecting agencies belonging to the Government of India and Gujarat State Government had to be approaoched. A part of data needed for this study was available at NIH and for the remaining part of the data visits were made to the data collecting agencies.

The SHE simulates all the major aspects of the land phase of the hydrological cycle. As a result, its application requires the evaluation of a large number of parameters and their spatial distributions along with the necessary time series data for calibration,validation and operation of the model.It was not expected that the full range of requirements would be satisfied by the available data but a list of data sources and recording instrumentation reported to be in use was drawn up. The data availability for the present study is given in Table 2.

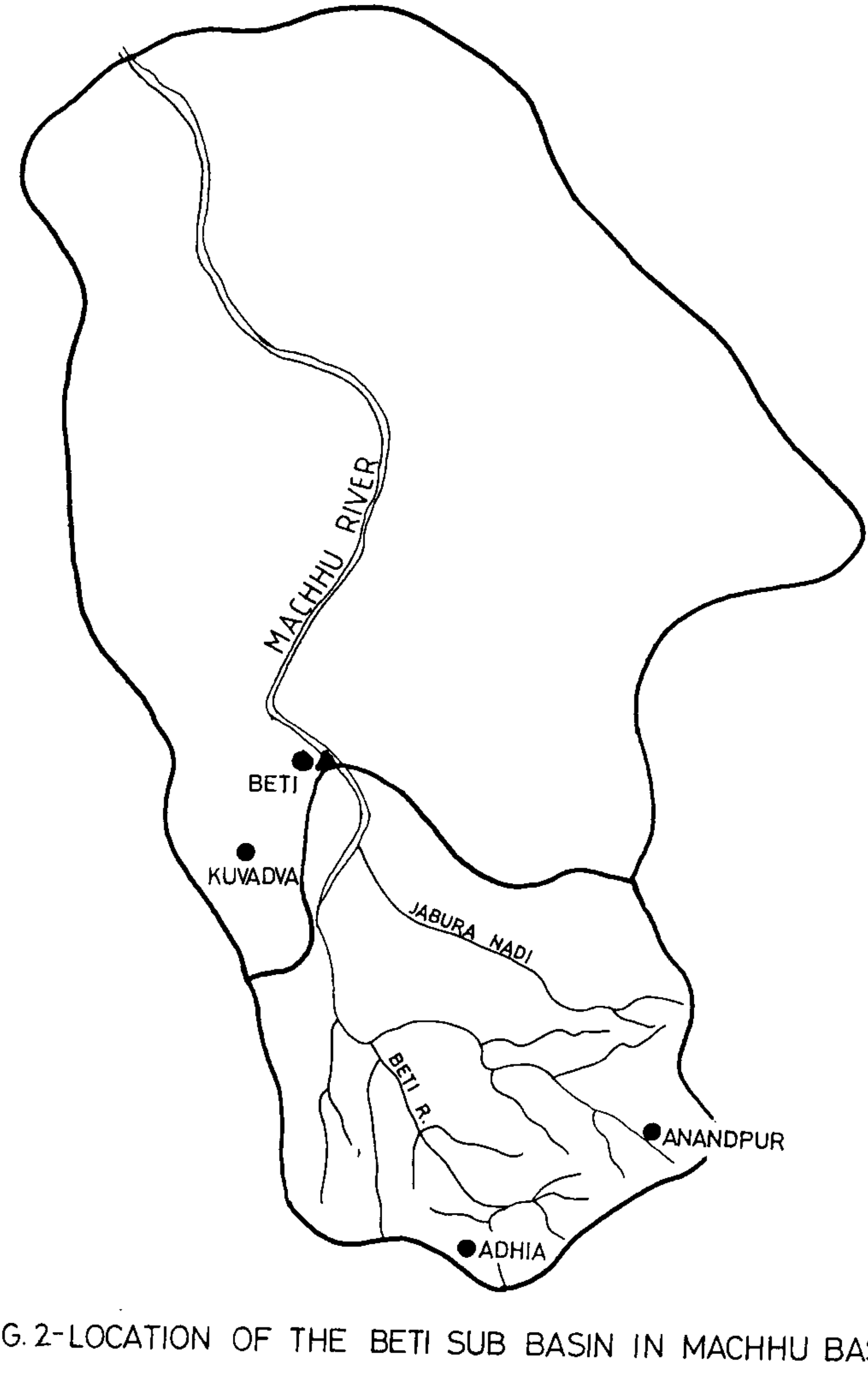


FIG. 2- LOCATION OF THE BETI SUB BASIN IN MACHHU BASIN

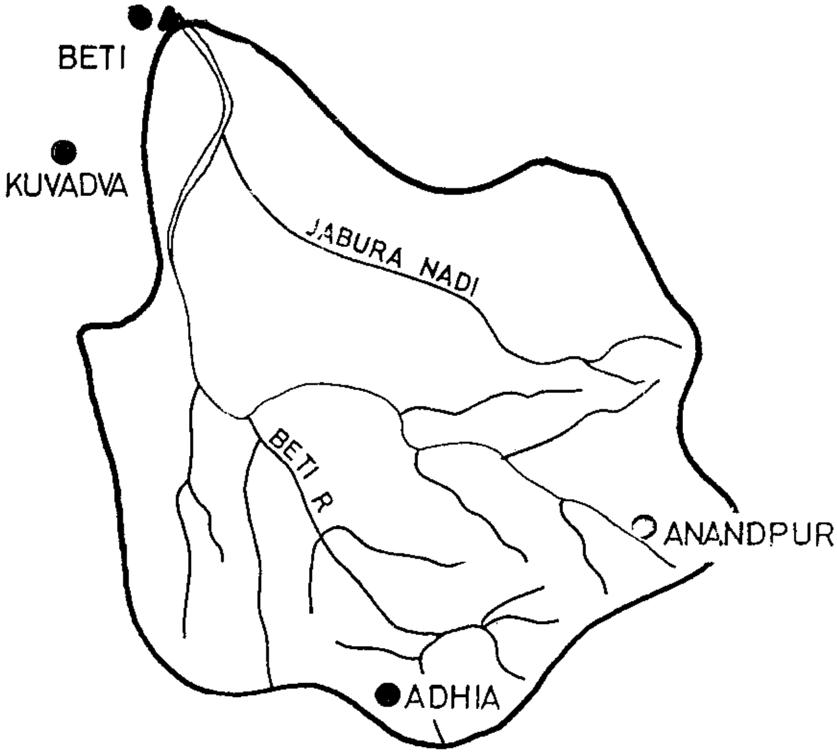


FIG. 3 - MAP OF THE BETI SUB BASIN

Details about the various types of data are given as follows:

3.2.1 Rainfall Data

Daily rainfall data of three ordinary raingauge stations viz. Anandpur, Adhiya and Kuvadwa and hourly rainfall data of Beti self recording raingauge station have been used in carrying out simulation studies for the Beti sub-basin. The hourly data of Beti self recording raingauge have been used for converting the daily rainfall data of the above mentioned raingauges. All the raingauges except Kuvadva lie inside the basin. The self recording raingauge Beti lies near the boundary of the sub-basin very close to the gauging site.

3.2.2 Evaporation Data

The sub basin is characterized by just one pan evaporation measurement station viz. Rajkot lying outside the sub-basin. Monthly pan evaporation data is available for the period 1984 to 1988. The evaporation data for the year 1988 was also used for the year 1989. In the absence of daily or weekly pan evaporation data, monthly data were adopted in the simulation study.

3.2.3 Runoff Data

The river Beti is a seasonally flowing river.Discharge measurement site is located near Beti village. The stage-discharge measurements on the daily and 4 hourly/hourly basis are available at CDO,Gujarat Irrigation Department. The above data for the period 1982-1989 were collected. River cross-section details at Beti for the years 1982, 1983, 1984 and 1987 were also collected. The river bed being quite hard does not exhibit much variation for various years. In addition to the above mentioned data rating curves for the Beti site for the year 1982, 1983 and 1984 as well as the equations of the rating curves were also collected.

3.2.4 Ground Water Data

Ground water levels for pre-monsoon and post-monsoon period from 1983 to 1988 for 25 wells located in the Beti sub-basin or near its basin boundary were collected. However, observations of all the wells in each year are not available.

3.2.5 Topographic Data

The topographic maps were procured from Survey of India, Dehradun in the scales 1,250,000 and 1:50,000. The following toposheets represent the basin:

Scale	Toposheet Numbers
1:250,000	41J, 41N
1:50,000	41J/15, 41J/16. 41N/3, 41N/4

The topographic elevations for land and river channels were derived from the above mentioned toposheets in the scale 1:50,000.

3.2.6 Soil and Landuse Data

No systematic soil survey of the Beti sub-basin has been carried out so far. Some information about a part of the catchment area under the command of Machhu-I irrigation scheme lying on the left bank of the river Machhu flowing from South West to North West is available in CWC (1982). The soils in the command area are mostly of residual origin derived from basaltic Deccan trap (amygdaloidal porous basalt) and have morillonite as the clay material. The soils in 12.3% of the command area are very deep (more than 90 cm) and in 41.1% of area are moderately deep (45 to 90 cm) and in 46.6% area are shallow to moderately deep (less than 45 cm).The soil colour varies from dark greyish brown to dark drown in the sub-surface.

In the absence of any detailed soil map of the study area. The depth of soil has been based on the topographic elevation of the sub-basin.

Beti sub-basin is the upper most part of the Machhu basin. The area has unirrigated agriculture as its main landuse. A part of the sub-basin is characterised by wasteland. Agricultural atlas of India was used to prepare the landuse map of the sub-basin. The SHE being a physically based distributed model uses vegetation and soil properties of the basin as input. There is a general lack of direct information about vegetation and soil properties, root zone depths, soil moisture, aquifer properties and leaf area index variation of various types of vegetation with time. For the simulation purpose, the information has been derived indectly from various reports and papers available for the neighbouring areas or by standard hydrological derivations.

4.0 DATA PROCESSING AND PREPARATIONS

4.1 General

Application of the SHE involves three phases data preparation, execution of the SHE and retrieval and graphical display of the SHE results. Service programs are used in the data preparation phase and the presentation of the results. A vast amount of parametric data organised in an array of data files are required for the SHE application. A data file is attached to each of the components.The organisation of data files and the data flow among the various auxiliary routines in the SHE software is shown in Fig. 4.

The files are named in such a manner that the specific basin is identified followed by three letters indicating the component, such as:

BETI.FRD	Frame
BETI.OCD	Overland and Channel flow
BETI.ETD	Evapotranspiration
BETI.UZD	Unsaturated Zone
BETI.SDZ	Saturated Zone

In addition, a set of data files containing time series data is also needed.These are needed both as input to the SHE and for calibration and validation purposes. The input data required as time series are arranged in a suite of separate data files. They are stored in the similar way so that they can be read by the SHE or read and displayed by the Graphical Display Routine SHE.GD. A series of data like measured discharge data, groundwater table elevations etc. used for calibration and validation are also stored in data files. The naming of time series files, follows the component files, as given below:

BETI.PRD	Precipitation data
BETI.EPD	Potential evaporation data
BETI.VED	Vegetation data (LAI and root depth)
BETI.TED	Temperature data
BETI.EXD	Groundwater abstraction rates
BETI.QOD	Observed discharge data
BETI.POD	Observed groundwater heads.

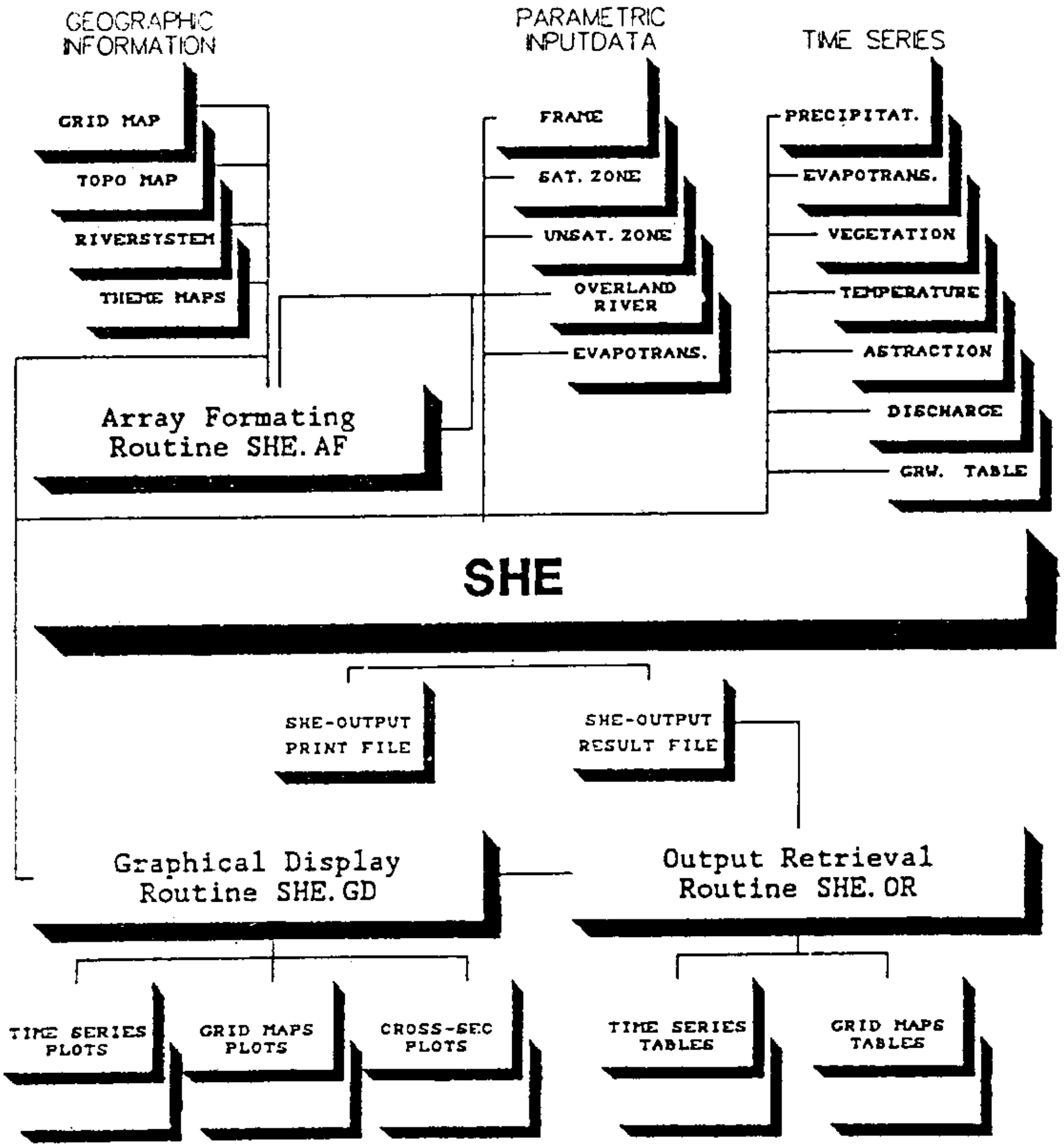


Fig. 4 : Flow chart of the SHE Programme Package.

4.2 Data Processing

A large amount of data need to be processed for application of the physically based and distributed catchment modelling system the SHE. It includes transfer of rainfall, evaporation and discharge data to computer files, checking of the files for errors and digitization of the topography and river system etc. A number of reports were referred for obtaining the relevant information on basin properties. The details of processing of various types of data are given below:

4.2.1 Rainfall data

Only one self recording raingauge (Beti) was available and this was used to distribute the daily rainfall records for rest of the stations. Distribution of domains for each rainfall station was based on Thiessen polygon approaoch. The Thiessen weights for the four raingauges namely Anandpur, Adhiya, Kuvadwa and Beti are 36.6%, 33.6% 13% and 16.8% respectively. Thiessen polygons of raingauge stations are shown in fig.5.

4.2.2 Discharge data

The outlet discharge values were available for some of the years at hourly and four hourly intervals. Apart from this, the stage values of rest of the period were converted in discharge values using the equation of the rating curve ($Q=25.118(G-136.70)^{2.314}$

This rating equation has been derived by the Central Design Organisation, Gujarat Irrigation Department. Similar type of rating equations were obtained at the institute using the observed stage-discharge values. However, for converting the stage values in discharge the above referred equation was used.

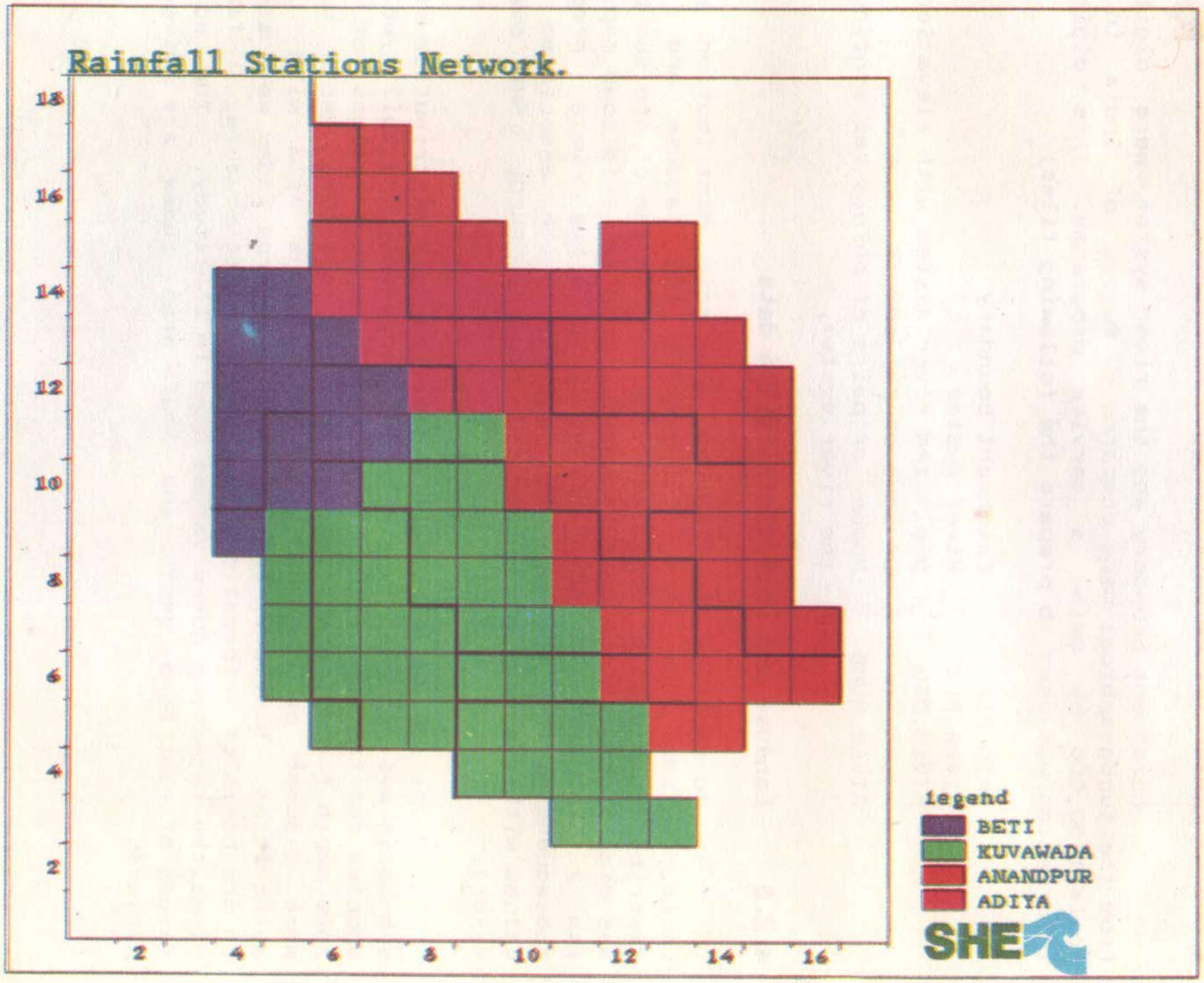
4.2.3 Evaporation data

Monthly pan evaporation data of Rajkot pan evaporation measurement station were multiplied by a pan coefficient of 0.70 to get the potential evaporation data for the simulation study. However, provision of hourly evaporation rates from the monthly records involves considerable temporal lumping.

4.2.4 Topographic data

Topographic elevations were read from 1:50,000 scale contour maps superimposed on a grid system of 1 km x 1 km(2 cm x 2

Fig. 5 : Area of the Beti Sub-basin represented by the raingauge stations



cm). The grids were connected to the longitudinal and lattitudinal coordinates to have identical origin in the cartesian coordinate system.The topographic representation maps of the basin were prepared in 1 km. x 1 km.,2 km. x 2 km.and 4 km.x 4 km. grid sizes.Figs. 6,7 and 8 show the topographic representations of the sub basin in 1 km x 1 km., 2 km x 2 km and 4 km x 4 km grid scales.

4.2.5 River system data

Catchment boundary and the river system were digitized from the topographical maps prepared by Survey of India in the scale 1:50,000 by using a service programme. This digitized information was used to prepare the following files:

GRID.DIG	Catchment boundary
RIVER.PLOT	River system
RIVER.DIG	Digitized river system with elevations of some of the points
RIVER.NUMB	Number or pairs of points represnting the river system.

4.2.6 Landuse and soil distribution data

To describe the landuse and soil distribution under various grids, the maps illustrating the landuse and soil distribution had to be digitized. The landuse map of the sub-basin was digitized with the help of service program. Grid code maps of 1km x 1km, 2kmx2km and 4kmx4km grid sizes were prepared subsequently, from the digitized polygons with associated code values with the help of a service program SHEOL (SHE overlay maker).

As any map showing the detailed soil distribution of the sub-basin was not readily available, hence only one soil type was adopted for the sub-basin. In absence of actual values of root zone depth for different vegetations, the root zone depth values were assumed on the basis of discussions held with local authorities. Similarly the values of leaf area index were adoptec on the basis of information available in literature. Table-3 gives the retention curve values used in the study. The adopted values of root zone depth and leaf area index are given in Table-4.

Fig. 6 : Topographic representation of the Beti Sub-basin in 1 km x 1 km grid size

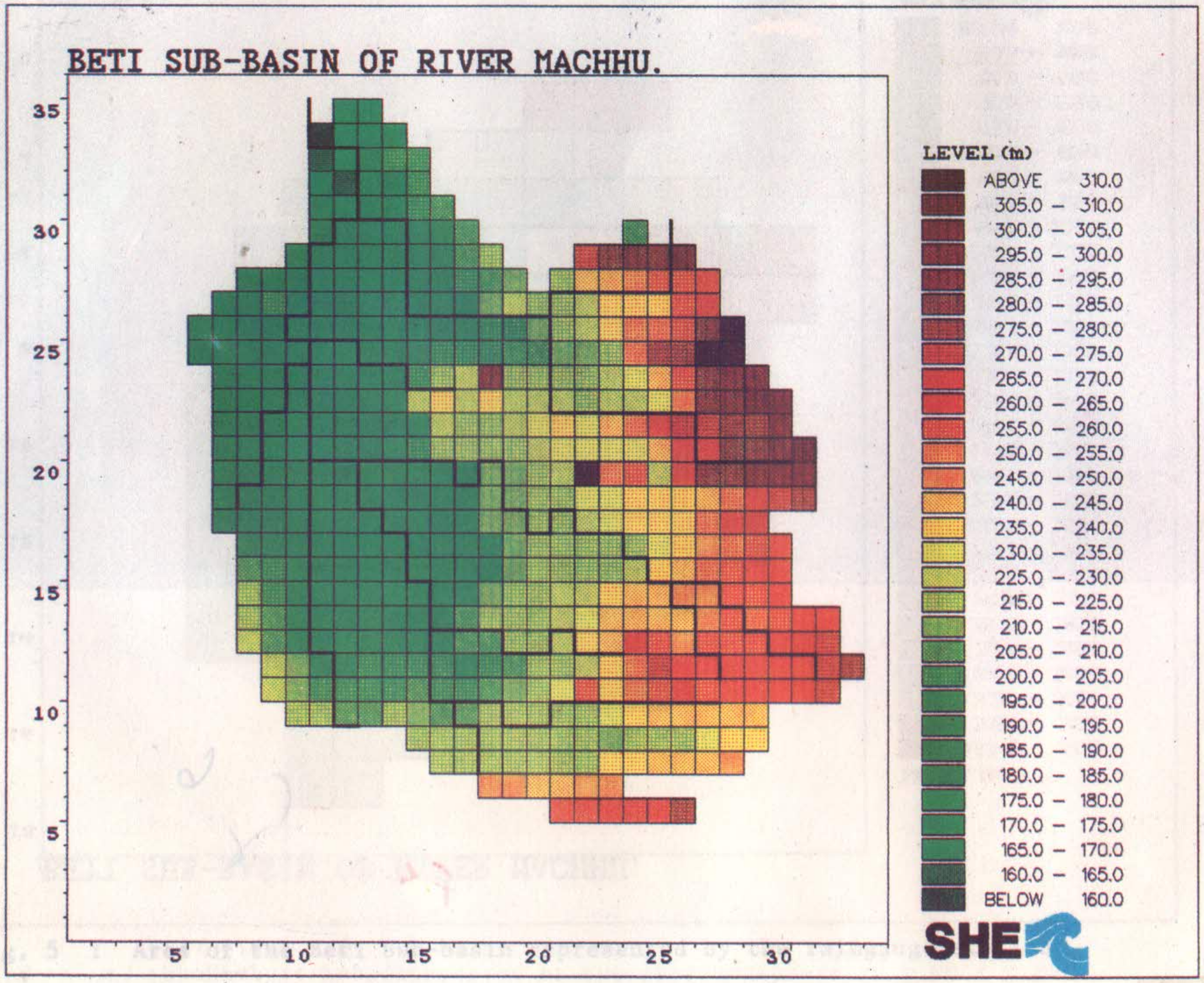


Fig. 7 : Topographic representation of the Beti Sub-basin in 2 km x 2 km grid size

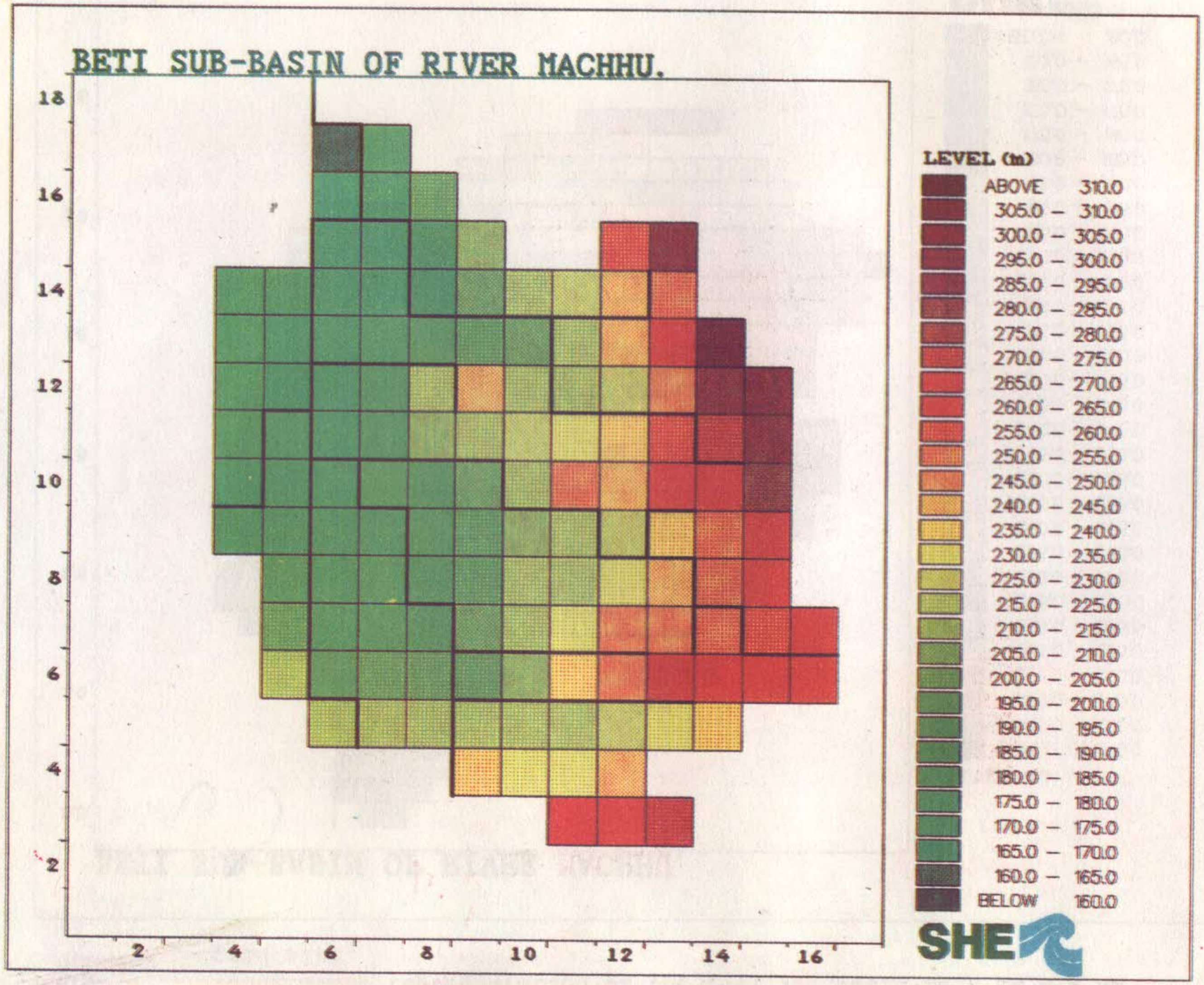


Fig. 8 : Topographic representation of the Beti Sub-basin in 4 km x 4 km grid size.

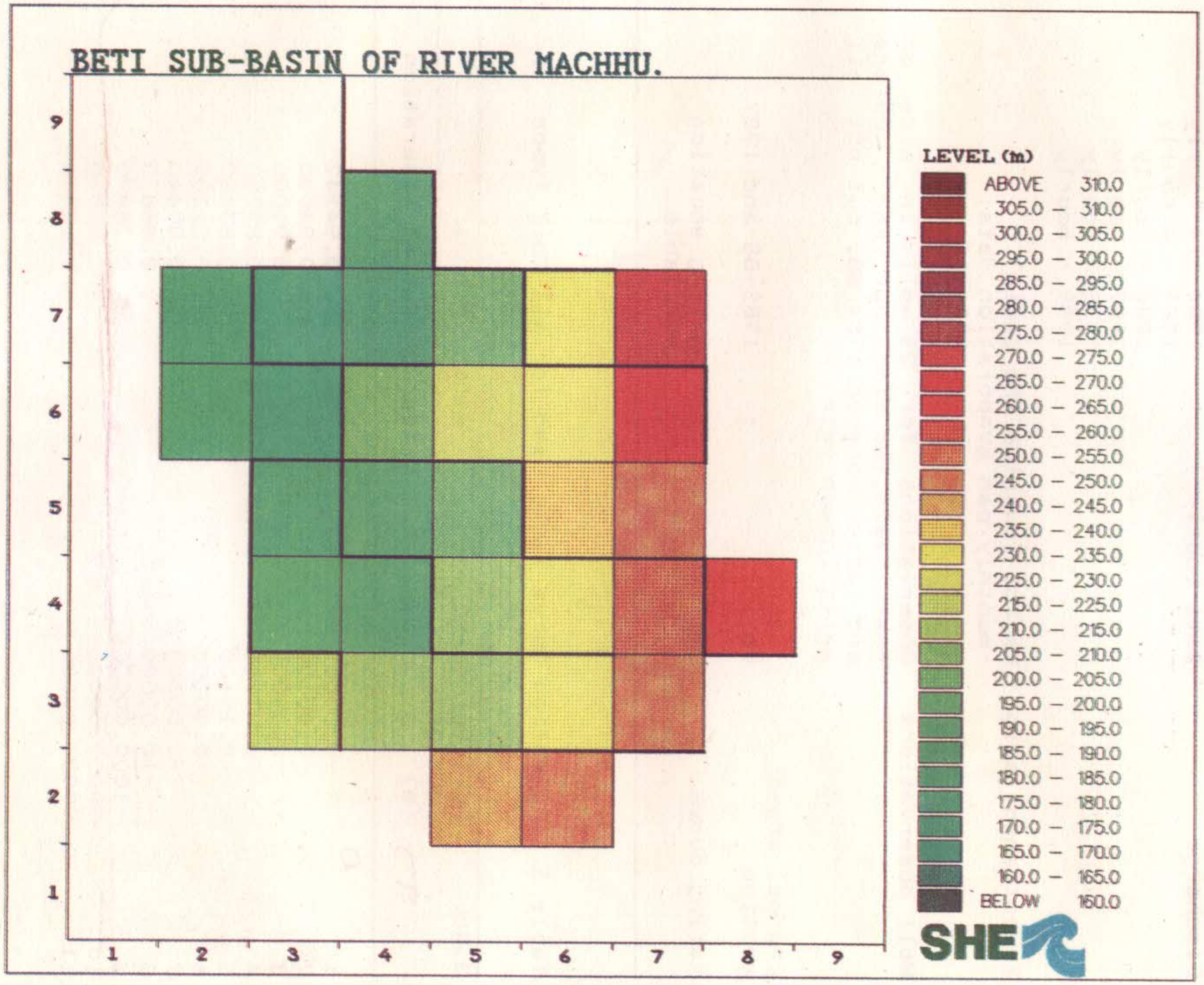


Table 2 : Data Availability for the Beti sub basin

DATA TYPE	DATA AVAILABILITY		
Rainfall	DAILY		
	Adiya	:	1984-89
	Anandpur	:	1984-89
	Kuvadva*	:	1984-89
	Beti	:	1984-89
	*Station lies outside the basin		
	HOURLY		
	Beti	:	1984-89
Discharge	Beti (outlet)	:	1984 - 4 hourly 1985 - 4 hourly 1986 - hourly 1987 - hourly 1988 - hourly 1989 - hourly
Evapotranspiration	Rajkot (outside the basin) -monthly pan evaporation data: 1984-88		
Well observations	Observations for 25 wells in side or near basin,two times per year - before and after monsoon 1984-88, but not all wells ineach year		
Channel cross-section	Beti	:	1982-85 and 1987
Rating curve	Beti	:	Rating equation available

Table 3 : Retention Curve Table used for all Soil Types

S.No.	Soil Moisture Tension (m)	Water Content / Water Content at Saturation
1	-0.00001	0.94142
2	-0.00100	0.94000
3	-0.05000	0.91000
4	-0.07940	0.85200
5	-0.15000	0.83480
6	-0.50000	0.81200
7	-1.00000	0.80440
8	-10.00000	0.66670
9	-1000.00000	0.28890
10	-90000.00000	0.00890
11	-99999.00000	0.00440

5.0 CALIBRATION AND VALIDATION OF THE SHE FOR BETI SUB-BASIN

In principle, the parameters of a physically-based, distributed model should not require calibration. As these parameters are supposed to be based on field measurements and are representative of that part of the catchment where they were measured. However, within the model there are inevitably approximations in the representation of the physical processes. In addition to this the distributions of the parameters are based on lumping to a grid scale which may not be true of the scale relevant to a particular hydrological process. A degree of calibration or optimisation of parameter values is therefore needed to minimise the differences between observed and simulated hydrographs.

It is not realistic to obtain an accurate calibration by gradually varying all the parameters singly or in combination. A better approach is to attempt a coarser calibration using only a few parameters to which the simulation is more sensitive. The only way in which the SHE can simulate a suitable response is by computing the rainfall excess and its travel to the channel network as overland flow. During low flow conditions, it becomes important to simulate the transmission of saturated sub-surface flow. The parameters which determine the quantity of rainfall which is diverted into overland flow and rate of movement of that overland flow should be attached more importance. Prominent among these are flow resistance coefficients for overland and channel flows, values of unsaturated zone conductivity and moisture content, soil moisture tension curve for unsaturated zone and saturated zone conductivity.

5.1 Calibration

Data for the years 1988 and 1989 have been used for calibration. Basin representation in 2 km x 2 km grid scale was adopted. Calibration was carried out by adjusting a few important parameters and studying their effects on the simulated hydrographs. The Strickler roughness coefficients for overland and channel flow were primarily used to calibrate hydrograph peaks, conductivity of unsaturated zone for amount of infiltration and hydrograph volume and saturated zone conductivity for studying the effects on baseflow. Soil crack, surface detention and drainage models were used to account for the effects of cracking of the soils, detention storage over the catchment and to incorporate the drainage through natural topographic characteristics of the catchment.

In the final calibration run, Strickler coefficient for overland flow was adopted as 2. Its value for channel flow has been adopted as 20. Conductivity values for saturated and unsaturated zones have been taken as 14 m/day and 0.10 m/day, respectively. The final values of physical characteristics of soil adopted after the calibration are given in Table-5. A comparison of volumes and peaks of observed and simulated runoff is given in Table 6. The observed and simulated hydrographs for calibration period are shown in Fig.9. Variation of ground water table, moisture content variation with soil depth, observed poitential evaporation and simulated actual evapotranspiration and rainfall for a grid are shown in Fig.10. Fig.11 shows variation of ground water table for the calibration periods under different land uses of specific grids viz. waste land on hilly area, unirrigated agriculture on semi-hilly area and unarrigated agriculture on low land. The ground water table variation for pre-monsoon and post-monsoon period for the years 1988 and 1989 are shown in Fig.12 through Fig.15.

5.2 Validation

Data for the period 1984 to 1986 were used for validation of the model. However, there was very little flow during the years 1985 and 1986 and the runoff as well as other simulated and observed hydrological variables were not compared for these years. In validation run, the model set up and the parameters were kept same as during the final calibration run. The validation results show that the simulated monthly runoff volumesare much higher than observed. This may be due to the fact that the discharge observations for the year 1984 are not at hourly interval but are at 7 AM, 11 AM, 3 PM and 7 PM only and the peak discharge as well as higher discharges might have passed unrecorded. A comparison of volumes of observed and simulated runoff is given in Table 7.

Table 4 - Root Zone Depth and Leaf Area Index

Month	Unirrigated Agricultural Land		Waste Land	
	Root Zone Depth (m)	LAI	Root Zone Depth (m)	LAI
January	0.6	4.0	0.3	0.3
February	0.6	4.0	0.3	0.4
March	0.6	4.0	0.3	0.4
April	0.3	2.0	0.3	0.5
May	0.3	2.0	0.3	0.5
June	0.3	2.0	0.3	0.5
July	0.6	3.0	0.3	0.5
August	0.6	5.0	0.3	1.0
September	0.6	5.0	0.3	0.8
October	0.3	2.0	0.3	0.5
November	0.1	0.5	0.3	0.4
December	0.4	2.5	0.3	0.3

Table 5 : Physical Characteristics of Soil

S.No.	Soil Parameter	Value
1.	Water content at saturation (eaual to the porosity of the soil)	0.478
2	Effective water content at saturation, adjusted for trapped air volumes	0.450
3	Water content at field capacity	0.384
4	Corresponding tension at field capacity	-1.000 m
5	Water content at wilting point	0.210
6	Residual water content (inaccessible water content in soil due to adsorption)	0.180
7	Saturated conductivity	0.100 m/day
8	Exponent for conductivity/ moisture content relation	10.000

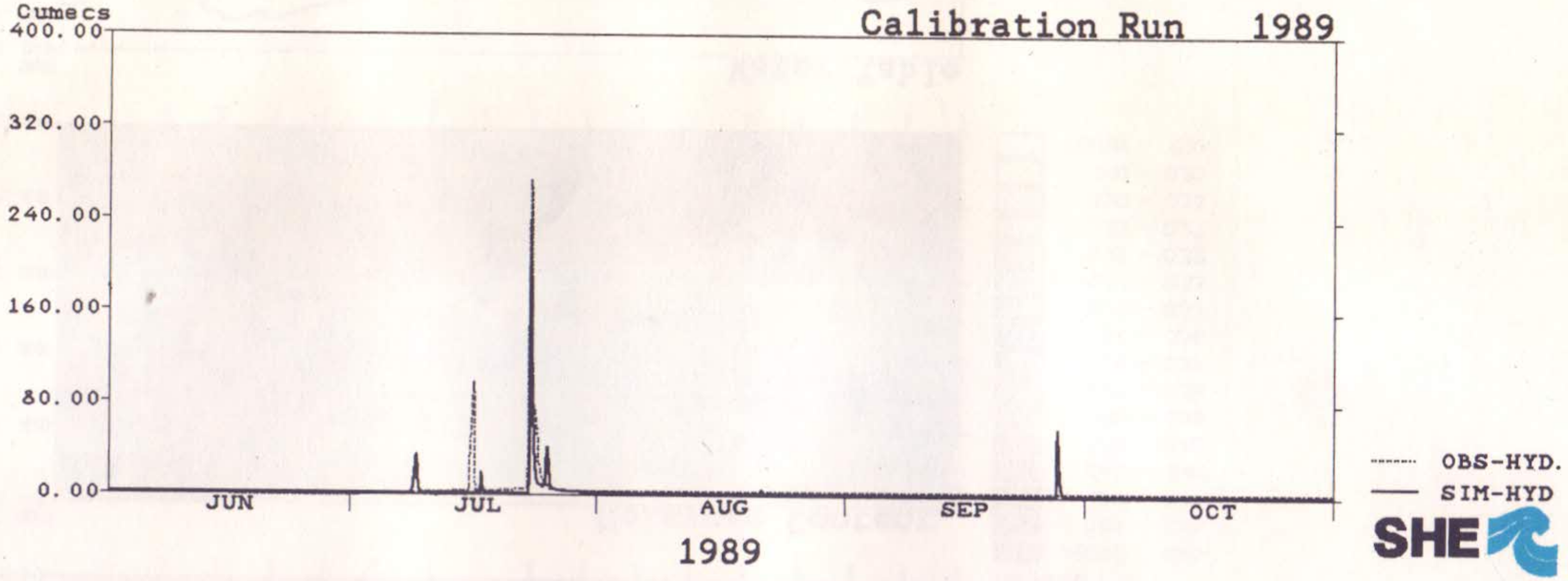
Table-6 Comparison of Volumes and peaks of observed and simulated runoff for calibration period

Year	Month	Rainfall	Observed Runoff (mm)	Simulated Runoff (mm)
1988	June	66.1	14.9	12.6
	July	451.7	78.5	102.1
	August	135.8	56.9	24.0
	September	159.1	39.3	24.4
	October	0.0	1.5	20.5
	TOTAL	812.7	192.1	183.6
	Peak (Cu.m./s)	-	280.0	345.8
1989	June	47.5	0.0	8.8
	July	248.3	55.0	31.7
	August	60.5	15.4	8.9
	September	67.1	14.9	10.3
	October	0.0	15.4	
	TOTAL	423.4	100.7	59.7
	Peak (Cu.m./s)		274.9	233.7

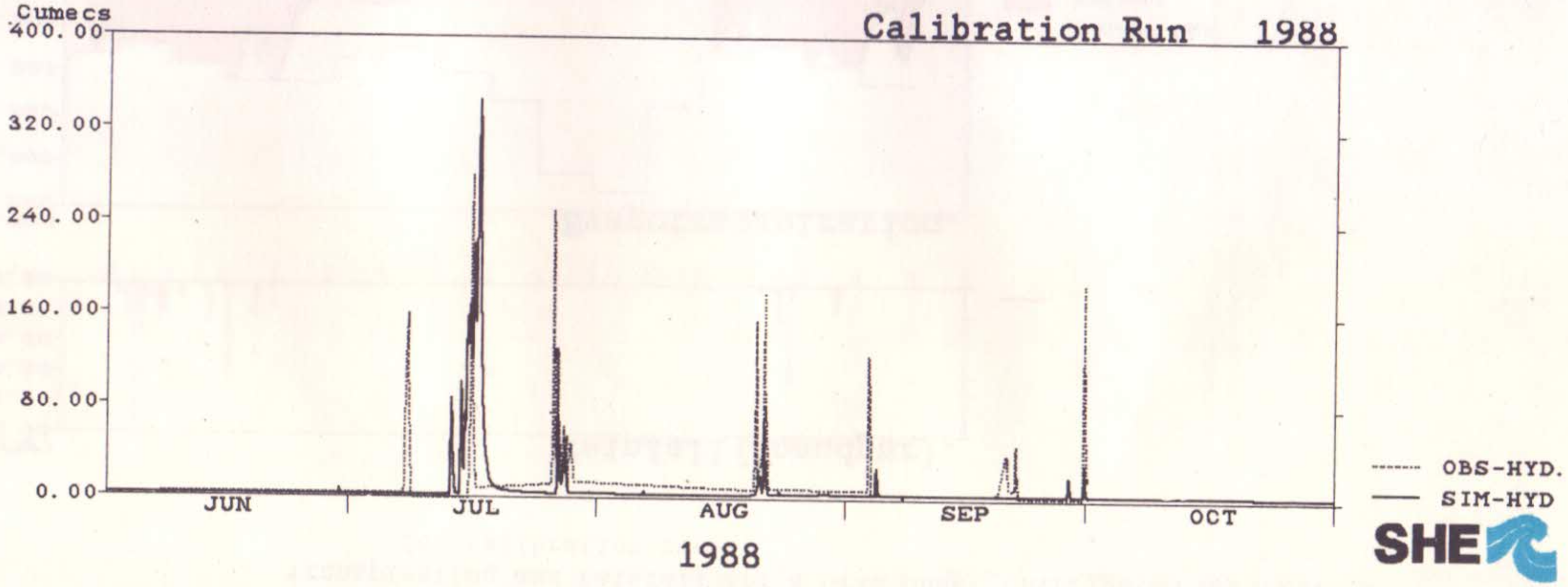
Table- 7 Comparison of Volumes of observed and simulated runoff for Validation Period

Year	Month	Rainfall	Observed Runoff (mm)	Simulated Runoff (mm)
1984	June	21.1	12.5	12.2
	July	71.4	0.0	14.5
	August	113.4	24.5	11.3
	September	428.4	65.7	303.9
	October	0.0	0.0	9.0
	TOTAL	634.3	102.7	351.8

Fig. 9 : Comparison of Simulated and Observed Hydrographs at the Beti Gauging Site for Calibration run



Calibration Run 1989



Calibration Run 1988

Fig. 10 : Variation of Groundwater Table, Moisture Content, Evapotranspiration and Rainfall for a Grid under Unirrigated Agriculture for calibration run

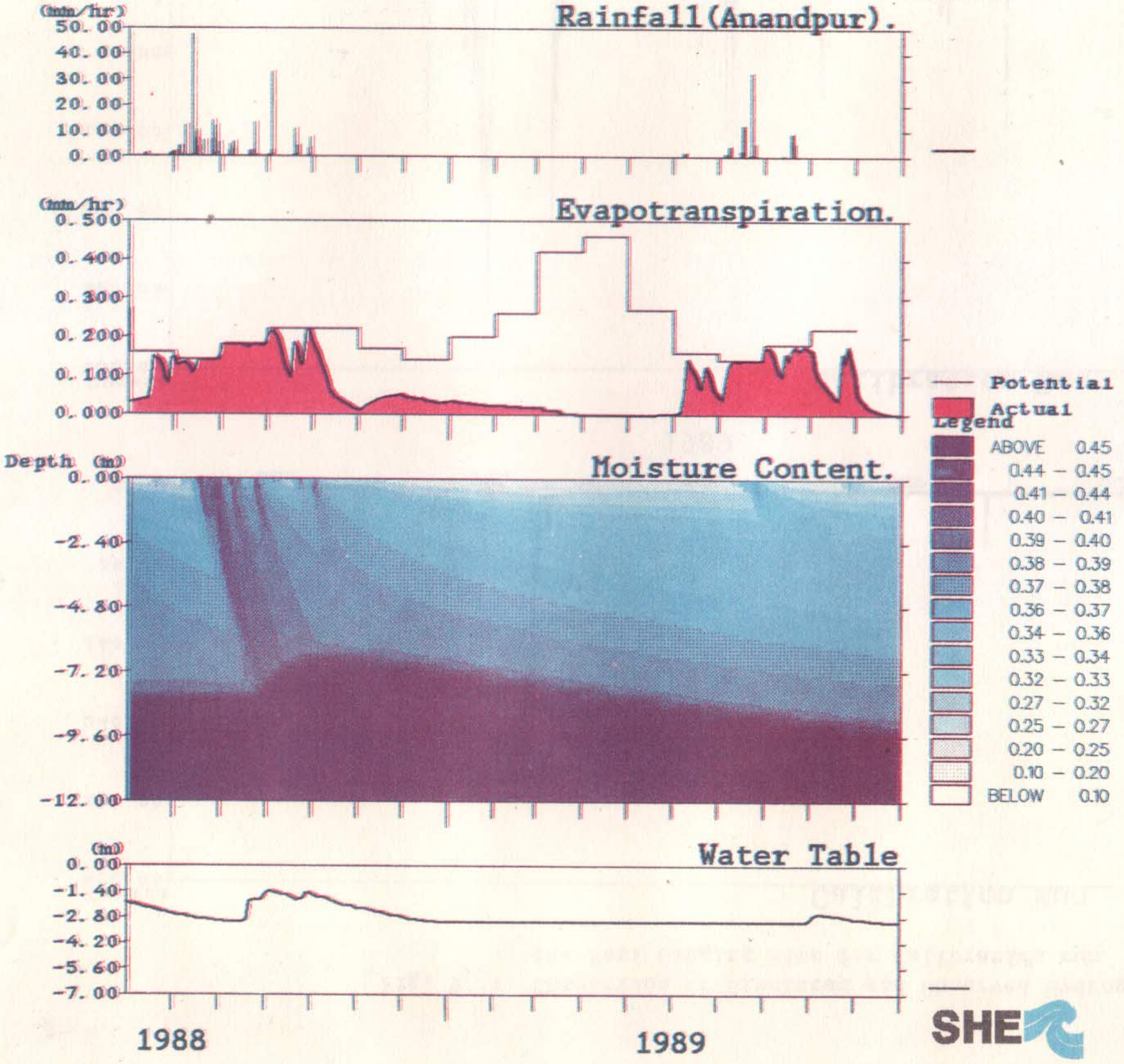
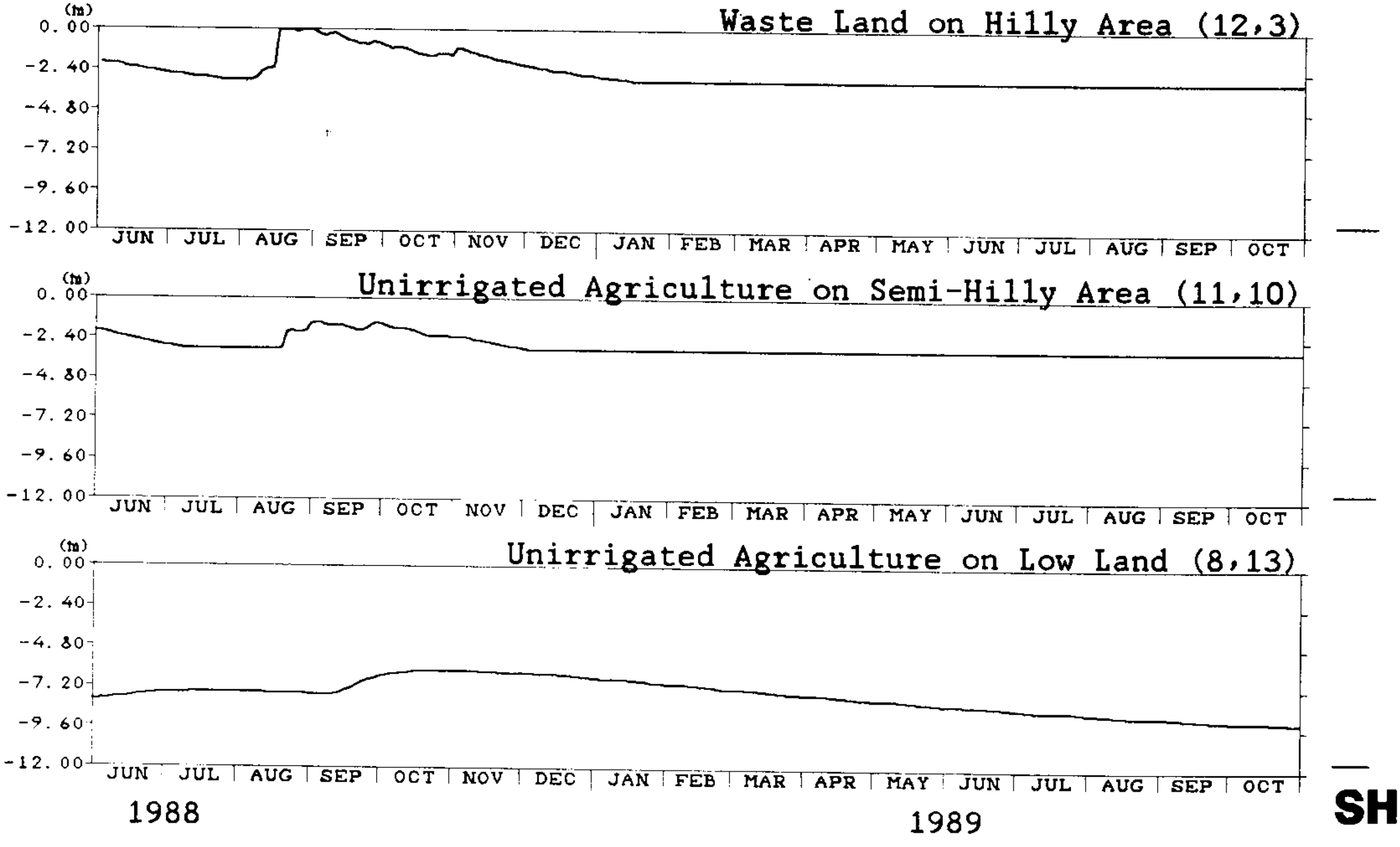


Fig. 11 : Variation of Groundwater Table for Grids under various Landuses for Calibration Run



Waste Land on Hilly Area (12,3)

Unirrigated Agriculture on Semi-Hilly Area (11,10)

Unirrigated Agriculture on Low Land (8,13)

SHE

Fig. 12 : Depth of Groundwater Table for Beti Sub-basin for pre-monsoon period of 1988

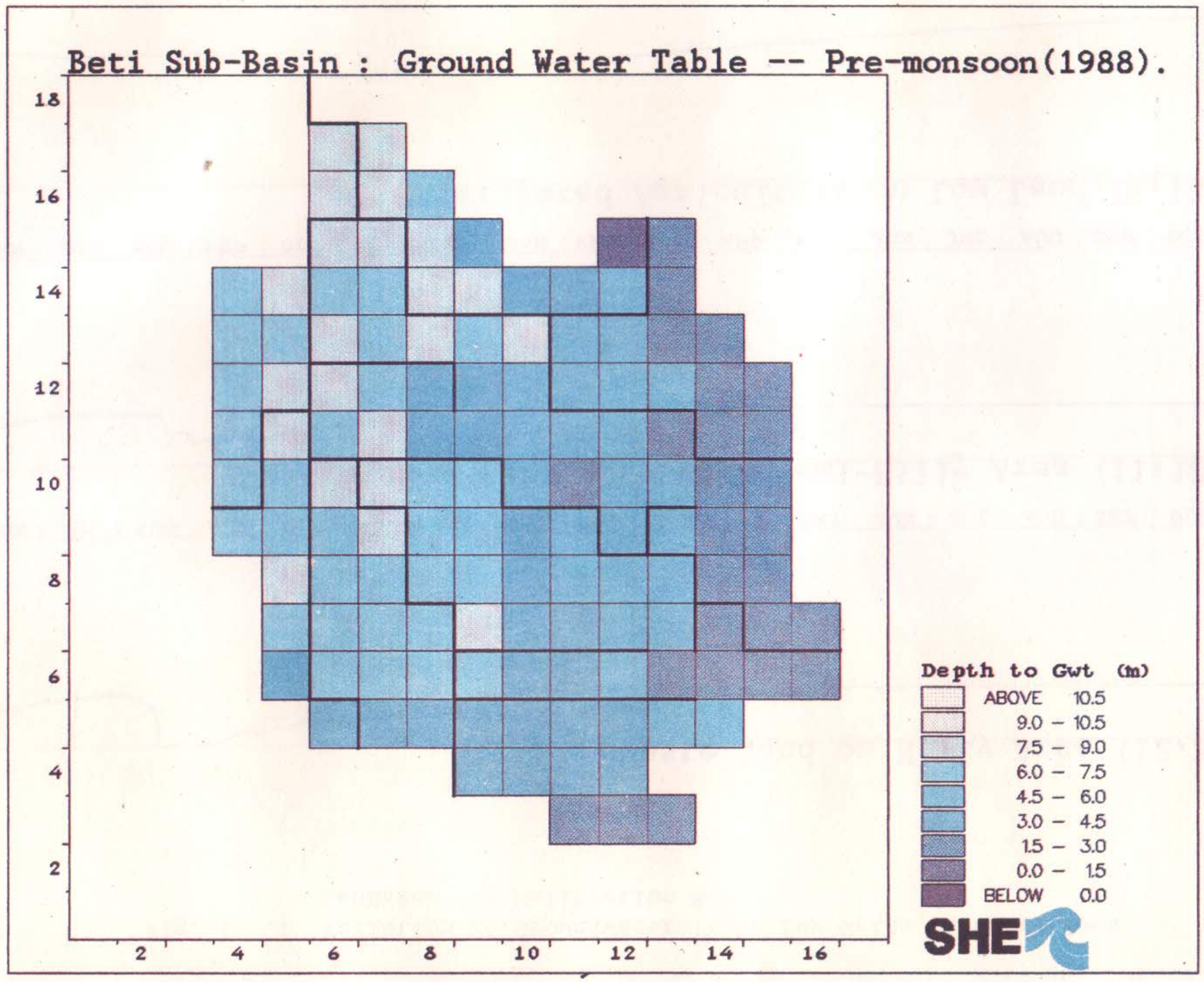


Fig. 13 : Depth of Groundwater Table for Beti Sub-basin for post-monsoon period of 1988

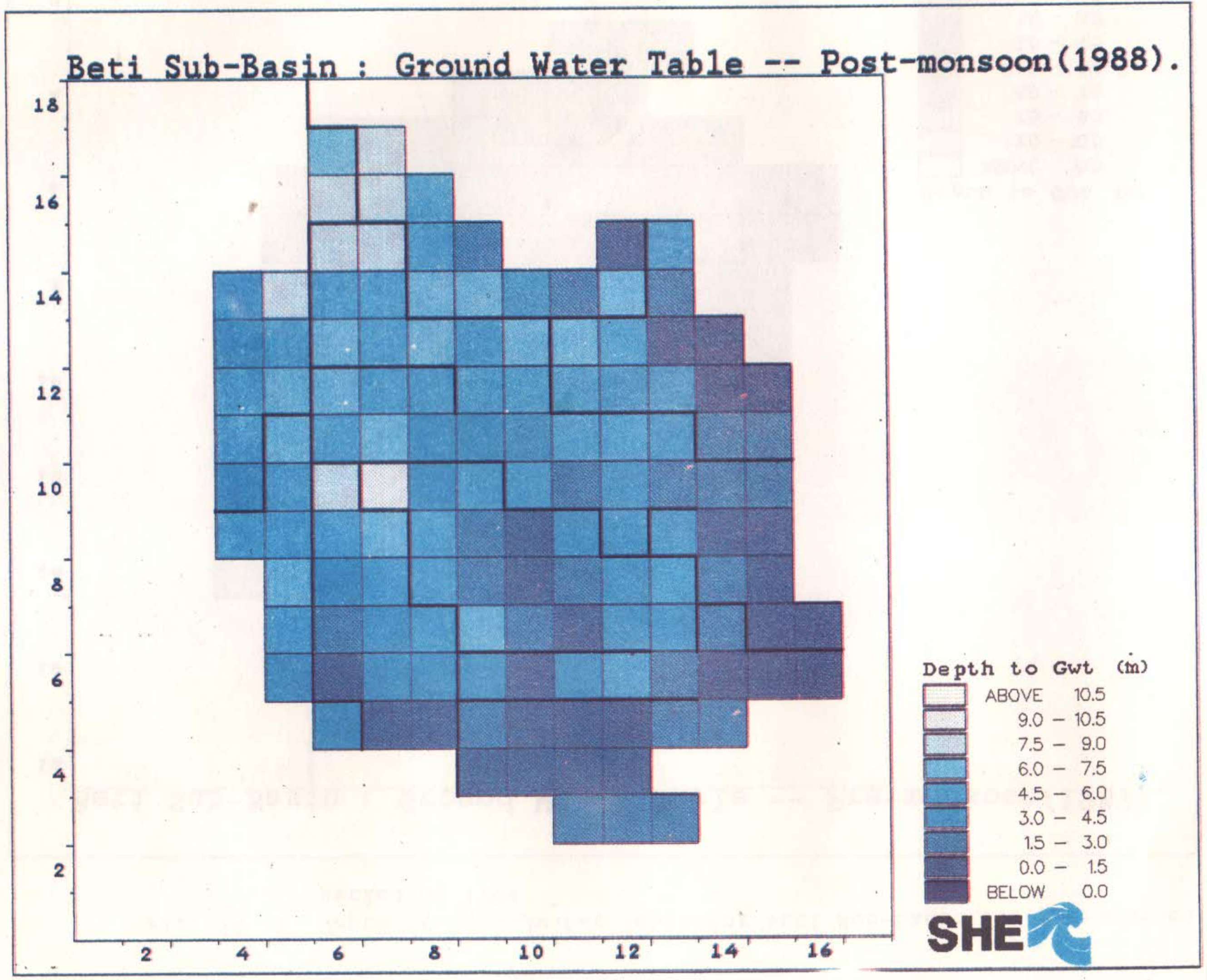


Fig. 14 : Depth of Groundwater Table for Beti Sub-basin for pre-monsoon period of 1989

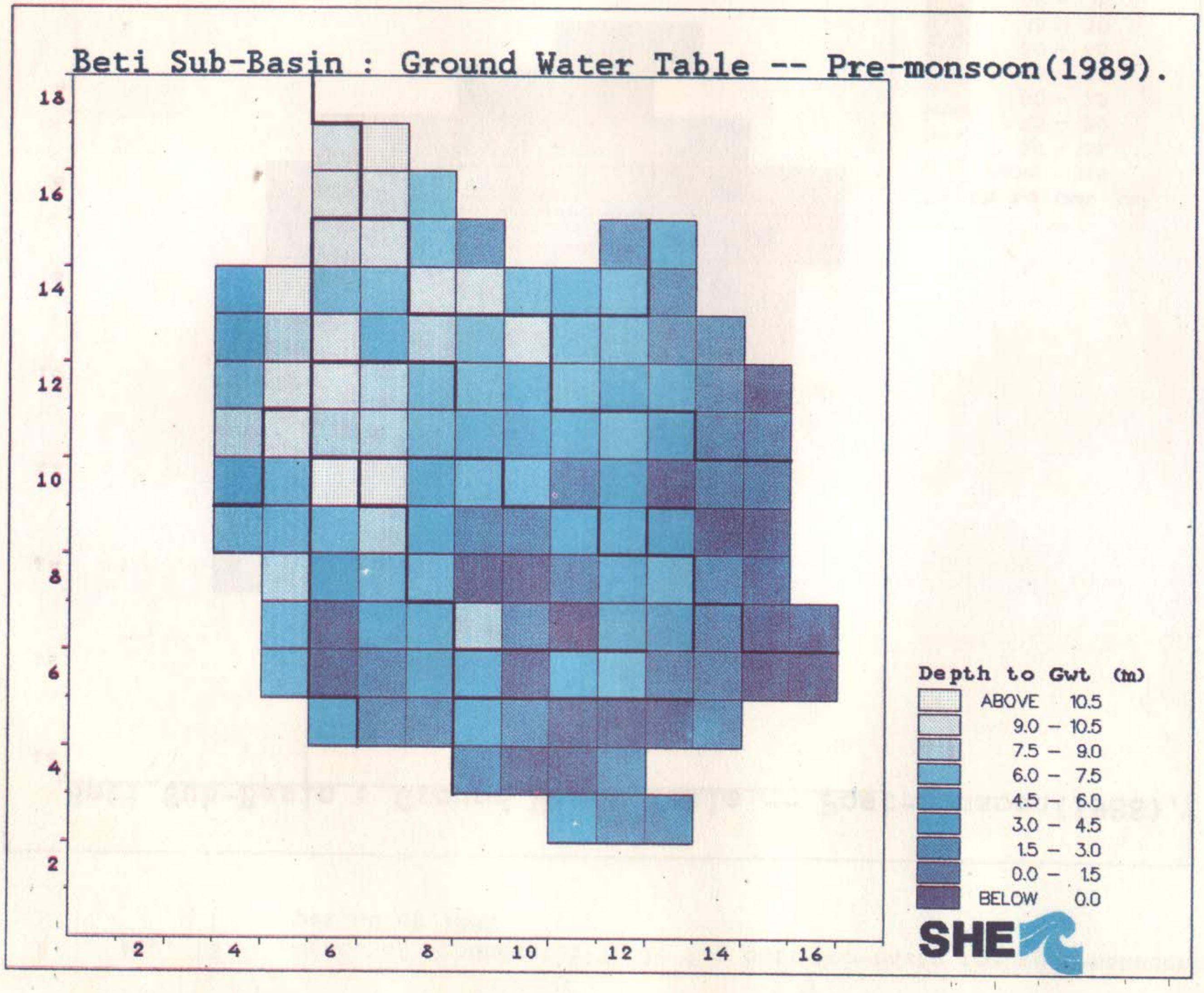
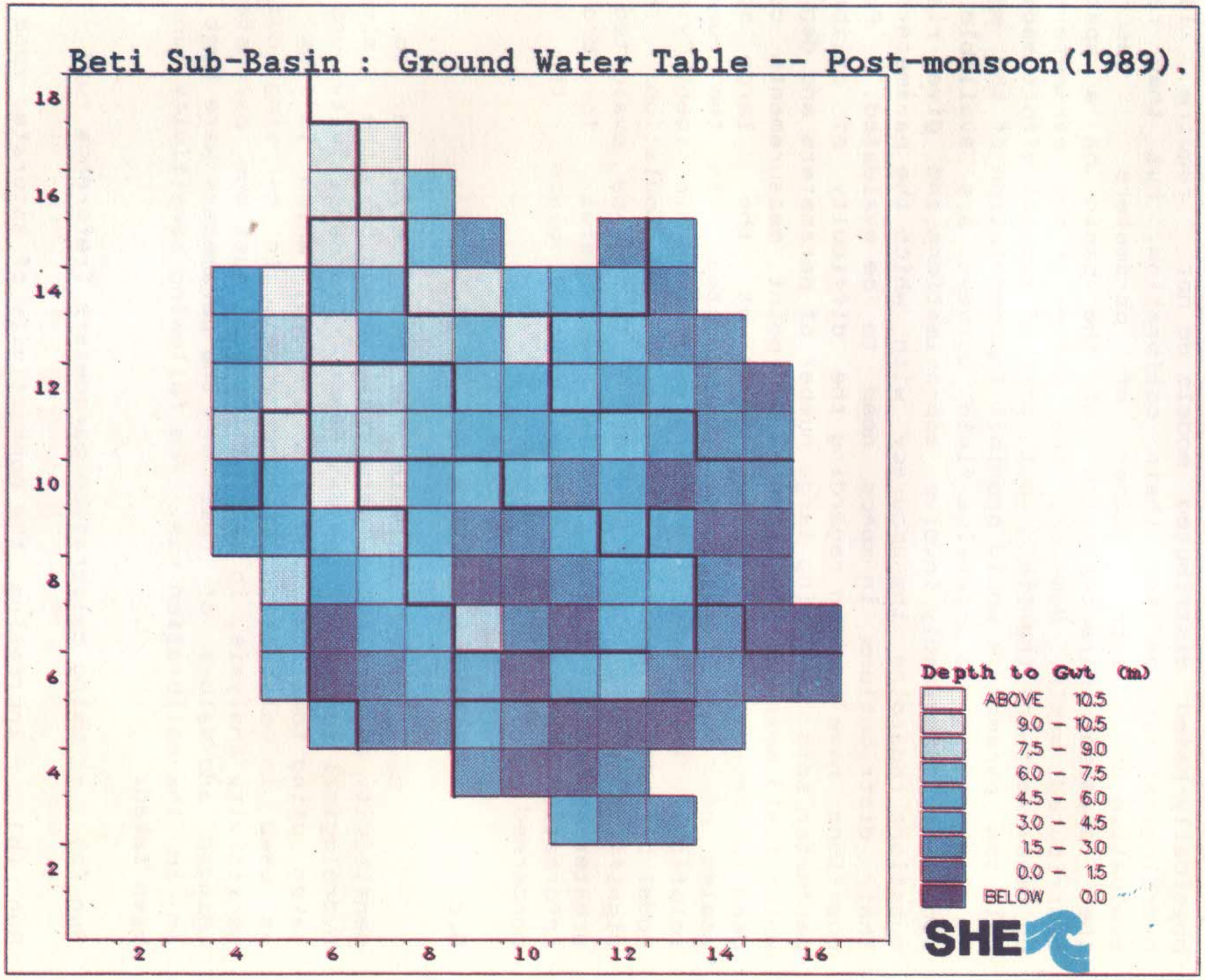


Fig. 15 : Depth of Groundwater Table for Beti Sub-basin for post-monsoon period of 1989



6.0 SENSITIVITY ANALYSIS

6.1 General

The objective of sensitivity analysis is to examine the sensitiveness of important calibration parameters and other input parameters on the simulation results. Though, the physically-based distributed models do not require lengthy hydrological records for their calibration, but they require evaluation of a large number of parameters describing the physical characteristics of the basin on a spatially distributed basis. However, the values of the parameters can be measured in the field but cost of such an effort made for all the parameters would prohibit implementation of the models. As alternatives to intensive field surveys are available but, since they inevitably involve approximations and give rise to questions regarding the accuracy with which the parameters and their distributions in space need to be evaluated. Further questions have arisen regarding the difficulty of calibrating parameter sets involving large number of parameters and degree to which field measurements which are point measurements can be used to represent average conditions at the large spatial scales of the grid squares adopted in the numerical solutions. Thus, sensitivity analysis helps in identifying the model parameters which influence the simulation results significantly and therefore need to be evaluated with greater accuracy. Further, it is also useful for providing information on how well the model can simulate the various concerned hydrological processes.

6.2 Sensitivity Analysis

Sensitivity analysis has been performed to study sensitivity of different parameter values on the simulated hydrological regime of the catchment. The sensitivity runs were taken using the 1988 and 1989 record, which is the same as used in calibration of the model. In carrying out the sensitivity analysis, in each of the run, just one parameter was changed and values of rest of the parameters were kept same as in the calibration run. The following sensitivity runs have been taken:

Run (a) - Using calibration parameters (reference run)

Run (b) - Increasing the conductivity of saturated zone from 14 m/day to 21 m/day.

Run (c) - Reducing the conductivity of saturated zone from 14 m/day to 7 m/day.

Run (d) - Reducing the conductivity of unsaturated zone from 0.10 m/day to 0.025 m/day.

Run (e) - Increasing Strickler coefficient for overland flow from 2 to 4.

Run (f) - Increasing the Strickler coefficient for river flow from 20 to 30.

Run (g) - Increasing n the exponent used in the Averjanov's formula (for calculation of conductivity of unsaturated zone) from 10 to 14.

Run (h) - Reducing grid size from 2 km x 2 km to 1 km x 1 km.

Table 8 gives a comparison of simulated monthly runoff volumes and annual peak discharges of the reference run with different sensitivity runs. The comparison of simulated monthly evapotranspiration for the reference run and the various sensitivity runs is given in Table-9.

Run (a) - In Run (a) which has been referred as the reference run in the following discussion, the parameter values and the record length has been kept same as in the calibration run. The detailed discussion of the run is given in section 5.1. In the following runs the sensitivity of some of the important parameters of the model has been tested.

Run (b) - Increasing the conductivity of saturated zone from 14 m/day to 21 m/day.

Saturated zone flow (i.e. the base flow) is modelled as horizontal flow by the Boussinesq equation in which the major soil parameter is conductivity K(SZ). For the reference run simulations, the conductivity values K(SZ) = 14 m/day were adopted for all the grids of the basin. In the present run, the conductivity of the saturated zone was increased from 14 m/day to 21 m/day. The runoff volume reduced from 183.6 mm to 148.3 mm for the year 1988 and to 57.2 mm from 59.7 mm for the year 1989. Thus a decrease of 18.9% and 4.2% is observed in runoff for the year 1988 and 1989 respectively. Variation of ground water table, moisture content variation with soil depth, observed potential evaporation and simulated actual evapotranspiration for a grid is shown in Fig. 16, for this run.

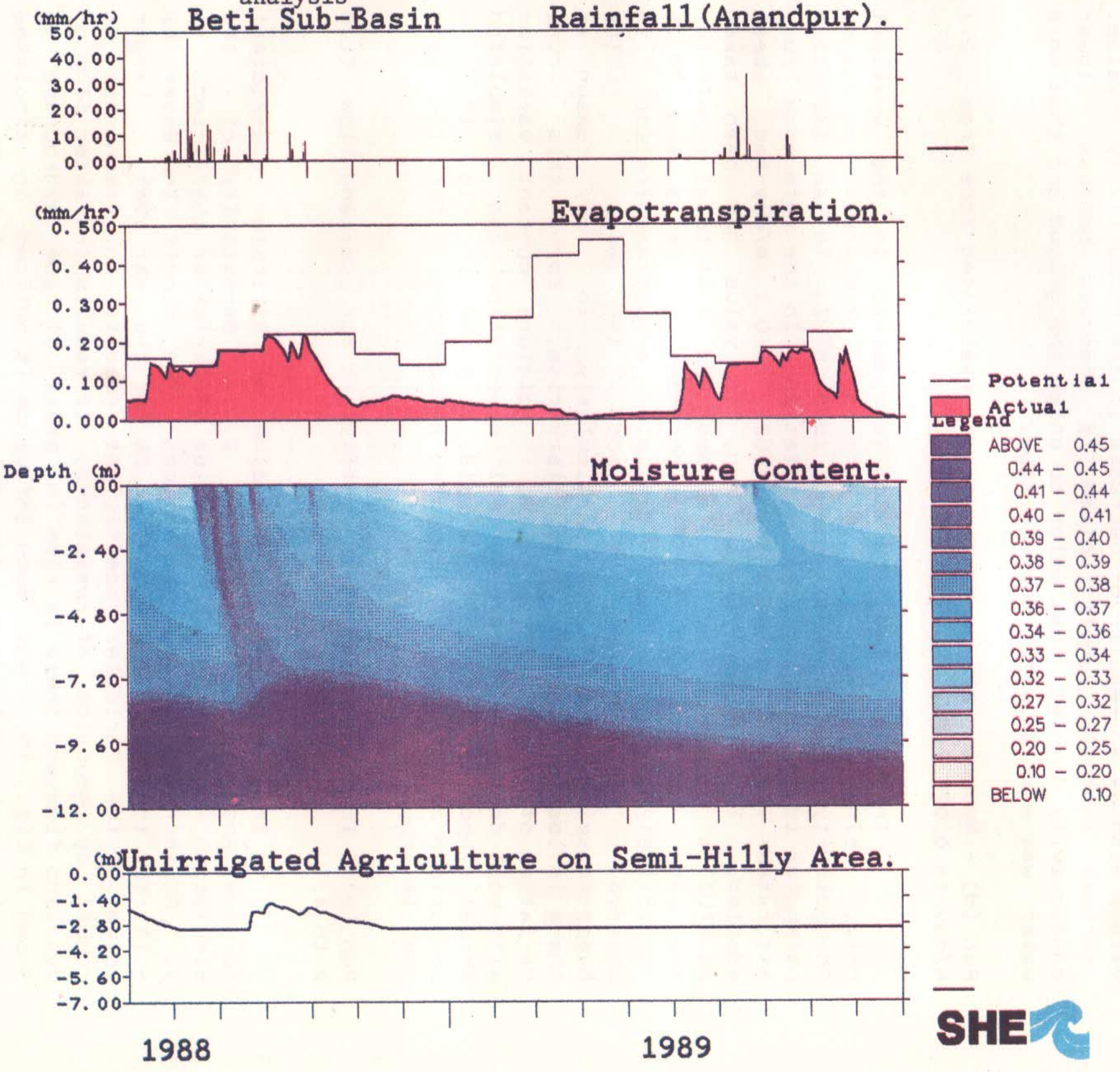
Table-8 Comparison of Simulated Runoff for Sensitivity Runs

Year	Month	Reference Run	K(SZ) inc.14 to 21	K(SZ) red.14 to 7	K(UZ) red.0.1 to .025	Strickler Cofft. for OLF inc.2 to 4	Strickler Cofft.for RF inc.20 to 30	n inc. from 10 to 14	Grid size reduced to 1 km x 1 km
1988	Jun	12.6	6.9	17.6	11.9	12.7	12.6	11.6	15.2
	Jul	102.1	96.5	106.4	215.7	113.5	102.1	155.4	113.0
	Aug	24.0	16.6	29.3	26.3	24.3	24.0	20.7	26.4
	Sep	24.4	15.8	30.4	17.9	24.7	24.4	19.5	20.7
	Oct	20.5	12.5	25.9	11.5	19.7	20.5	16.2	15.8
TOTAL		183.6	148.3	209.6	283.3	194.9	183.6	223.4	191.1
Peak (Cu.m./s)		345.8	344.8	346.6	505.2	423.6	353.5	428.5	355.8
1989	Jun	8.8	6.4	10.4	7.2	8.7	8.9	9.2	4.8
	Jul	31.7	29.6	32.6	67.8	36.7	31.8	50.9	31.5
	Aug	8.9	6.9	9.5	7.5	8.2	8.9	12.2	6.0
	Sep	10.3	8.6	11.0	13.7	11.7	10.3	15.0	8.7
	Oct		5.7	7.7	6.6	4.3	7.4	8.8	4.1
TOTAL		59.7	57.2	71.2	102.8	69.6	67.3	96.1	55.1
Peak (Cu.m./s)		233.7	233.1	234.0	291.4	354.2	250.7	266.1	207.3

Table-9 Comparison of Simulated Evapotranspiration for Sensitivity Runs

Year	Month	Reference Run	K(SZ) inc.14 to 21	K(SZ) red.14 to 7	K(UZ) red.0.1 to .025	Strickler Cofft. for OLF inc.2 to 4	Strickler Cofft.for RF inc.20 to 30	n inc. from 10 to 14	Grid size reduced to 1 km x 1 km
1988	Jun	70.4	69.5	69.5	63.4	69.6	69.6	58.2	62.6
	Jul	101.1	100.8	100.8	100.3	100.8	100.8	98.9	104.8
	Aug	134.4	134.1	134.1	134.3	134.2	134.2	132.9	134.6
	Sep	138.2	138.4	138.4	135.0	138.2	138.3	121.4	154.9
	Oct	72.3	73.8	73.5	61.6	72.1	73.6	47.5	74.5
	Nov	36.5	36.5	36.1	29.1	35.4	36.3	21.9	42.3
	Dec	37.5	38.0	37.2	31.1	36.6	37.6	27.9	40.5
1989	Jan	30.9	31.6	30.4	22.9	30.0	31.0	20.4	33.1
	Feb	22.8	23.5	22.2	14.7	22.0	22.8	12.1	23.2
	Mar	15.2	16.2	14.8	6.9	14.7	15.5	4.4	13.1
	Apr	6.1	6.7	5.4	0.02	5.5	6.0	0.0	2.6
	May	10.6	11.3	9.8	0.04	10.1	10.6	0.0	6.7
SUB TOTAL		676.0	680.7	672.2	599.4	669.2	676.3	545.6	692.9
1989	Jun	62.6	62.8	61.6	54.9	61.9	62.3	50.1	63.8
	Jul	94.4	93.4	93.1	91.76	93.3	93.4	90.7	95.3
	Aug	122.5	122.9	122.0	119.3	122.1	122.5	113.6	123.4
	Sep	81.6	83.2	81.7	74.4	81.5	82.3	72.6	51.6
	Oct	14.4	15.6	14.8	12.0		15.1	11.8	6.4
SUB TOTAL		375.5	377.6	373.2	352.36	358.8	375.6	338.8	340.5
TOTAL		1051.5	1058.3	1045.4	951.72	1028.0	1051.9	884.4	1033.4

Fig. 16 : Variation of Groundwater Table, Moisture Content, Evapotranspiration and rainfall for Run (b) of Sensivitity analysis



Run (c) - Reducing the conductivity of saturated zone from 14 m/day to 7 m/day.

In the present run, conductivity of the saturated zone K(SZ) was reduced from 14 m/day to 21 m/day. The total volume of runoff increased by 14.2% for the year 1988 and by 19.3% for the year 1989. There is an increase in peak discharge values also as a result of decrease in the conductivity value. Increase in total runoff volume is observed because lower conductivity allowed less water to enter the ground and thus more water was available for surface flow.

Run (d) - Reducing the conductivity of unsaturated zone from 0.1 m/day to 0.025 m/day.

The unsaturated zone flow is modelled in the vertical only, using the one dimensional Richard's equation. Conductivity of the unsaturated zone K(UZ) is an important parameter to be used in the simulation. In the reference run, saturated vertical conductivity K(UZ) = 0.1 m/day has been adopted. In this sensitivity run, its value has been taken as K(UZ) = 0.025 m/day. It is observed that total runoff for the year 1988 and 1989 increases by 54.3% and 79.7% respectively. The actual simulated evapotranspiration is observed to decrease for both the years. The evapotranspiration is reduced particularly in dry season as there is loss of moisture by capillary rise. For this run, variation of ground water table, moisture content variation with soil depth, observed potential evaporation and simulated actual evapotranspiration for a grid, is shown in Fig. 17. A comparison of observed and simulated hydrographs for the year 1989 is shown in Fig. 18.

Run (e) - Increasing Strickler coefficient for overland flow from 2 to 4.

In the reference run, value of Strickler coefficient for overland flow was used as 2.0. Sensitivity of the simulation was tested using a value of Strickler coefficient as 4. An increase in runoff is noticed. The runoff increases by 6.1% for the year 1988 and by 16.8% for the year 1989. Larger value of the Strickler coefficient results in flashiness of runoff by reduction of resistance. It results in faster flow of overland flow and there is rise in peaks of the hydrograph as shown in Fig. 19. Not much influence is noticed on simulated actual evapotranspiration. For this run, variation of ground

Fig. 17 : Variation of Groundwater Table, Moisture Content, Evapotranspiration, and Rainfall for Run (d) of Sensitivity Analysis

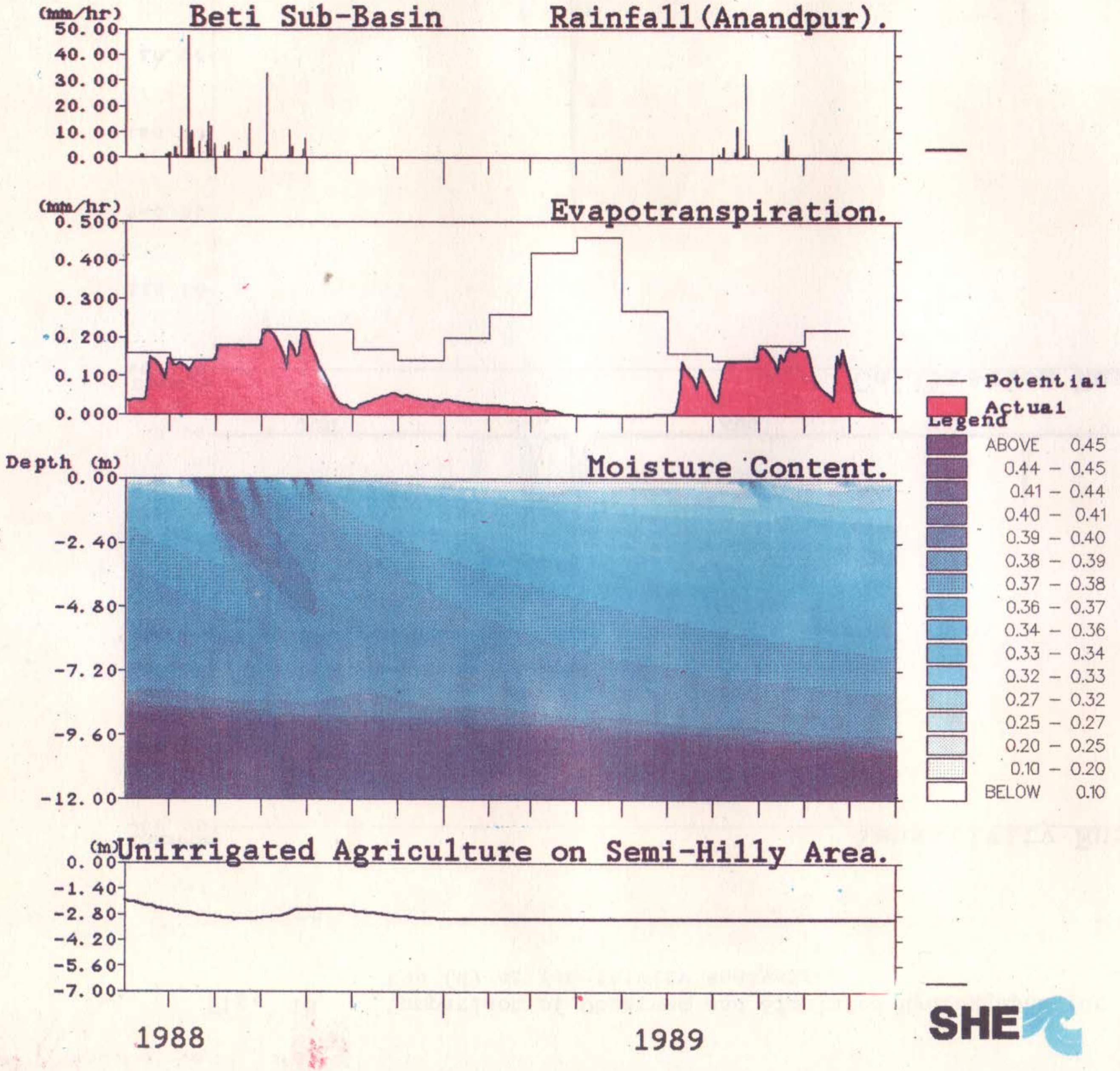


Fig. 18 : Comparison of Observed and Simulated Hydrographs for Run (d) of Sensitivity Analysis

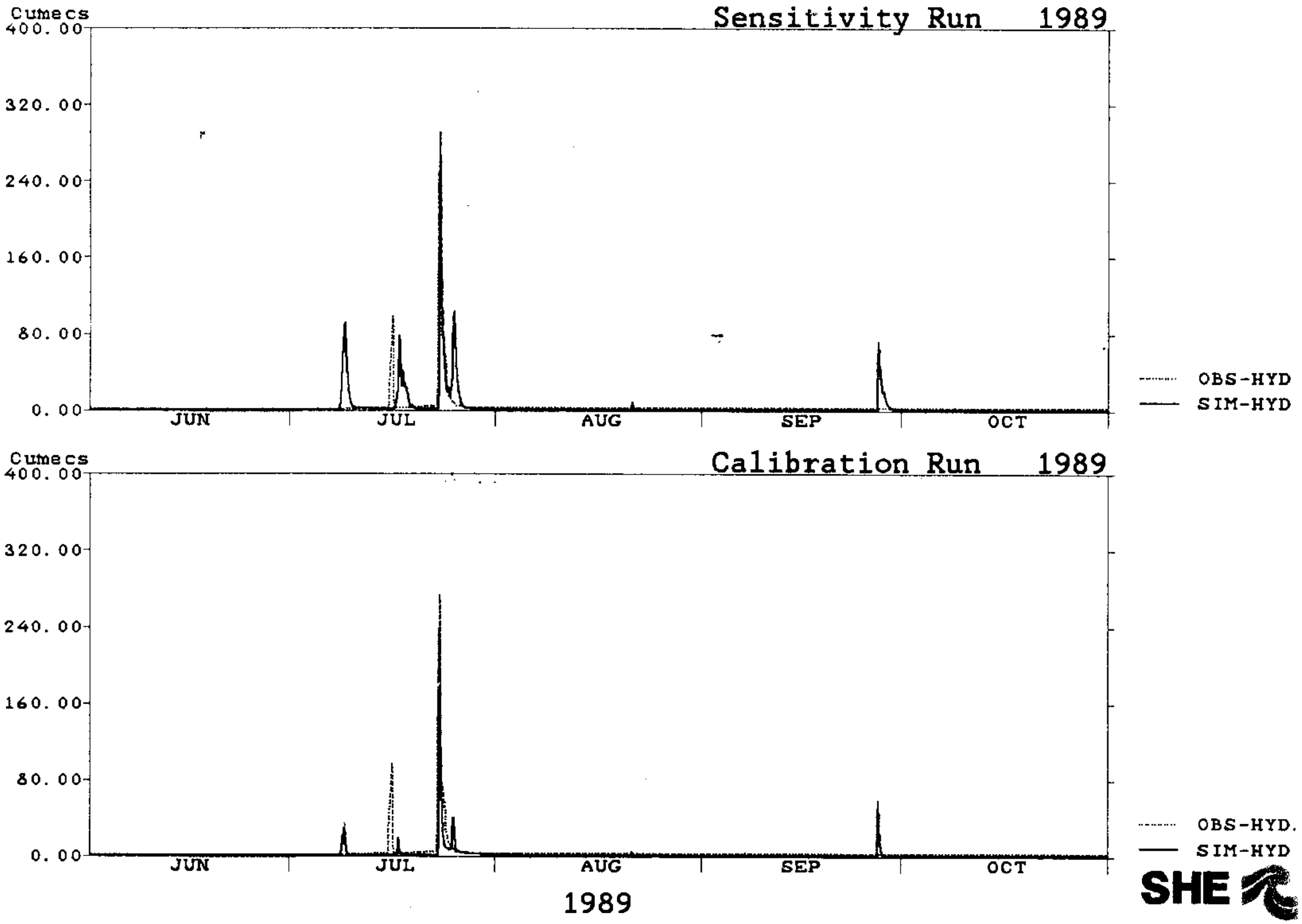
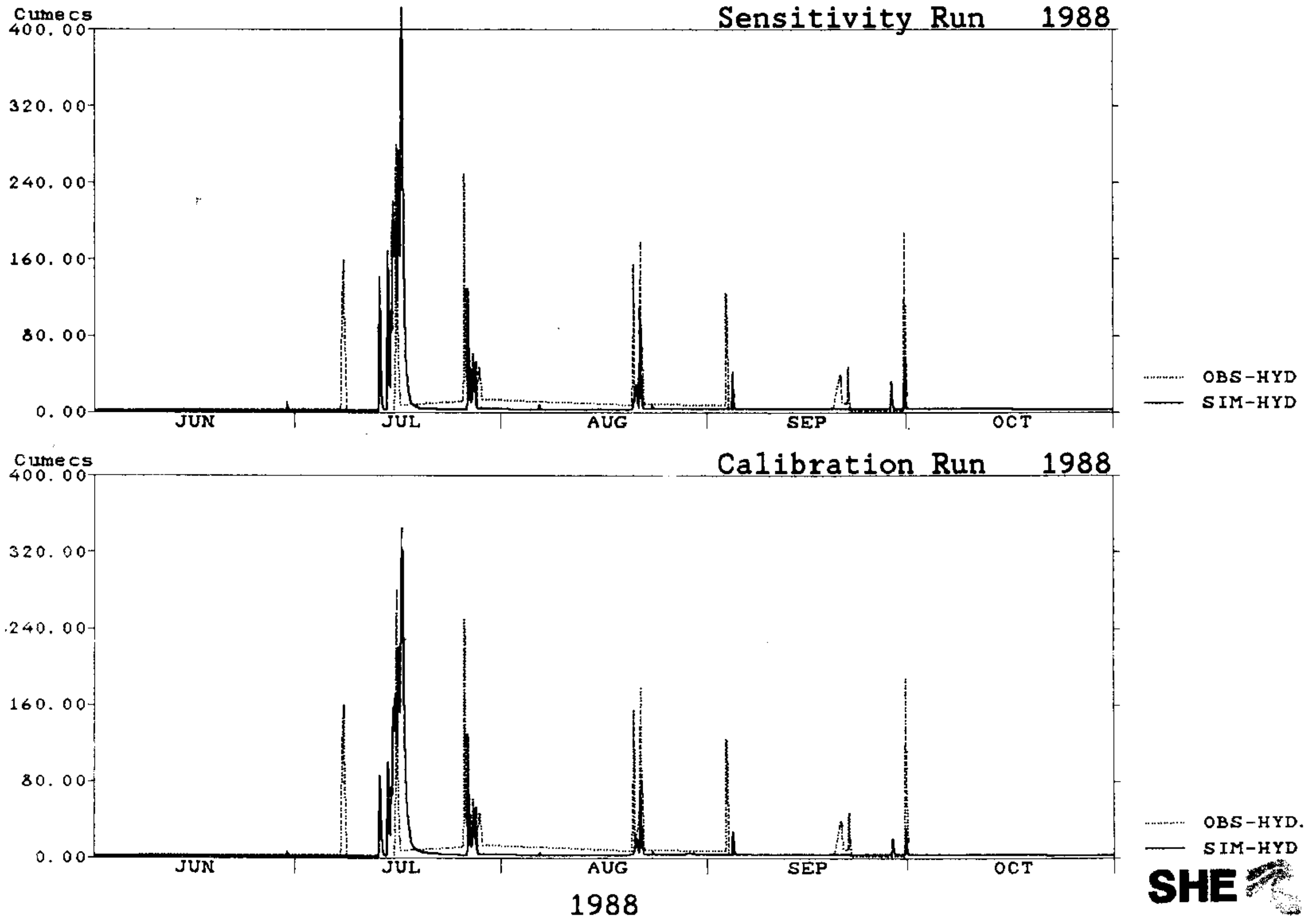


Fig. 19 : Comparison of Observed and Simulated Hydrographs for Run (e) of Sensitivity Analysis



water table, moisture content variation with soil depth, observed potential and simulated actual evapotranspiration for a grid is shown in Fig. 20.

Run (f) - Increasing the Strickler coefficient for river flow from 20-30.

To study the sensitivity of Strickler coefficient of river flow; its value was increased from 20-30 for all the rivers of the basin. As a result of this, an increase in peaks of the hydrographs is observed. Though, no significant influence on the total volume of runoff is noticed. Fig. 21 shows that there is not much influence on simulated actual evapotranspiration also as compared to the reference run.

Run (g) - Increasing the exponent used in Averjanov's formula (for calculation of conductivity of unsaturated zone) from 10-14.

In the SHE, the hydraulic conductivity, K (θ) is described as a function of the effective saturation, Se:

$$K(\theta) = K_{sat}\, S_e^{\,n}$$

where, $S_e = \theta - \theta_r / \theta_s - \theta$

θ_s θ and θ_r are saturated, actual and residual moisture contents, respectively. n is the exponent appearing in the Averjanov's formula for computation of unsaturated conductivity as a function of θ. It can be observed from the above formula that by increasing n, the soil conductivity reduces at a given moisture content. In the reference run, values of the exponent n=10 has been adopted. This value was increased to 14 for this sensitivity run. It is observed that total runoff volume increases by 21.6% for the year 1988 and by 60.9% for the year 1989 as shown in Fig.22. It is also noticed that simulated actual evapotranspiration reduces very significantly. Fig.23 shows lesser depletion of moisture content during non-monsoon season as compared to the reference run. This occurs because of lesser loss of water through evapotranspiration by capillary rise.

Run (h) Reducing the grid size from 2km x 2km to 1km x 1km.

Grid size is one of the important parameters in the SHE model, as larger the size of the grid lesser is the computational requirement in simulation. It is desirable to make it as large as possible from computational requirement point of

Fig. 20 : Variation of Groundwater Table, Moisture Content, Evapotranspiration and Rainfall for Run (e) of Sensitivity Analysis

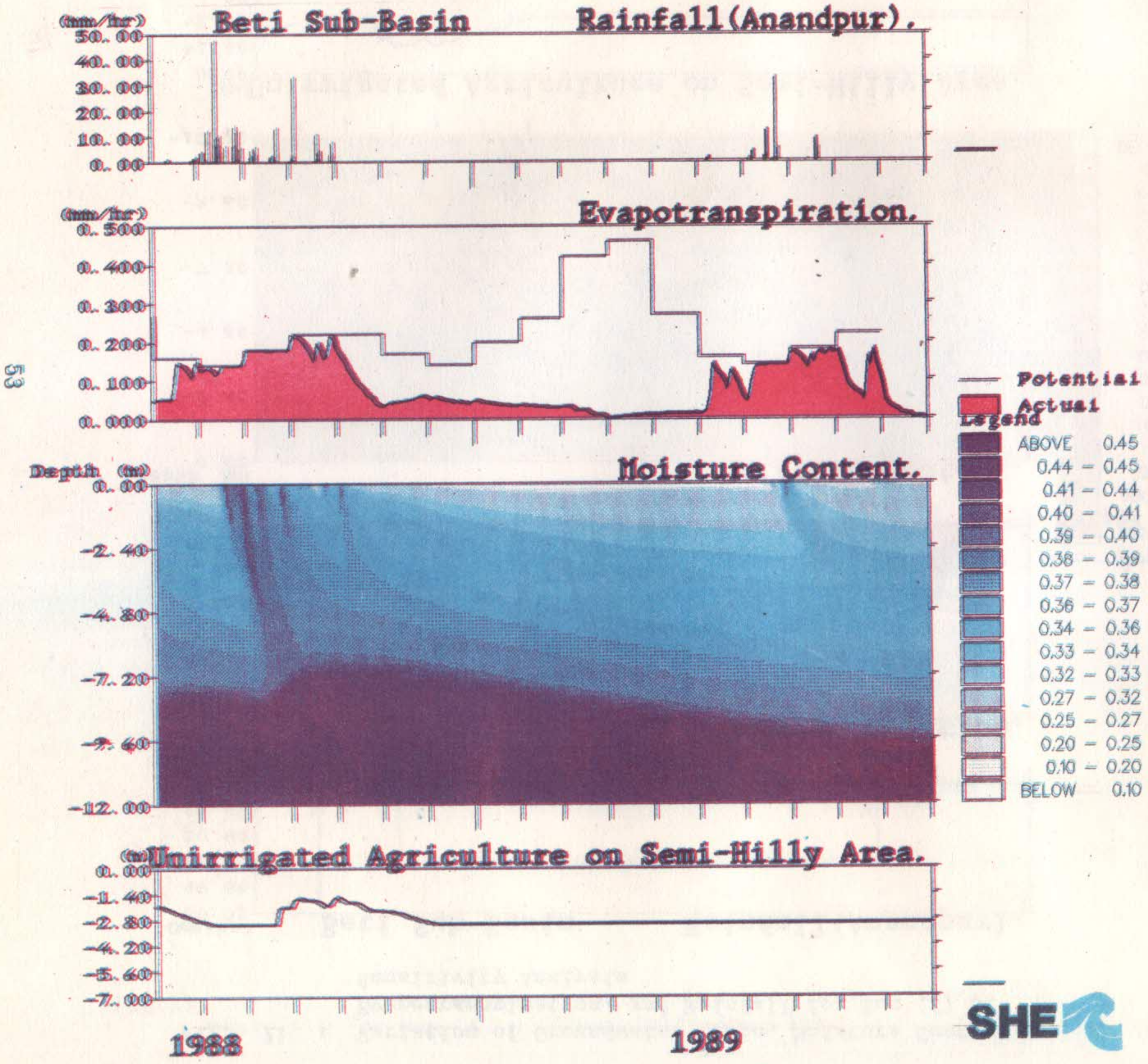


Fig. 21 : Variation of Groundwater Table, Moisture Content, Evapotranspiration, and Rainfall for Run (f) of Sensitivity Analysis

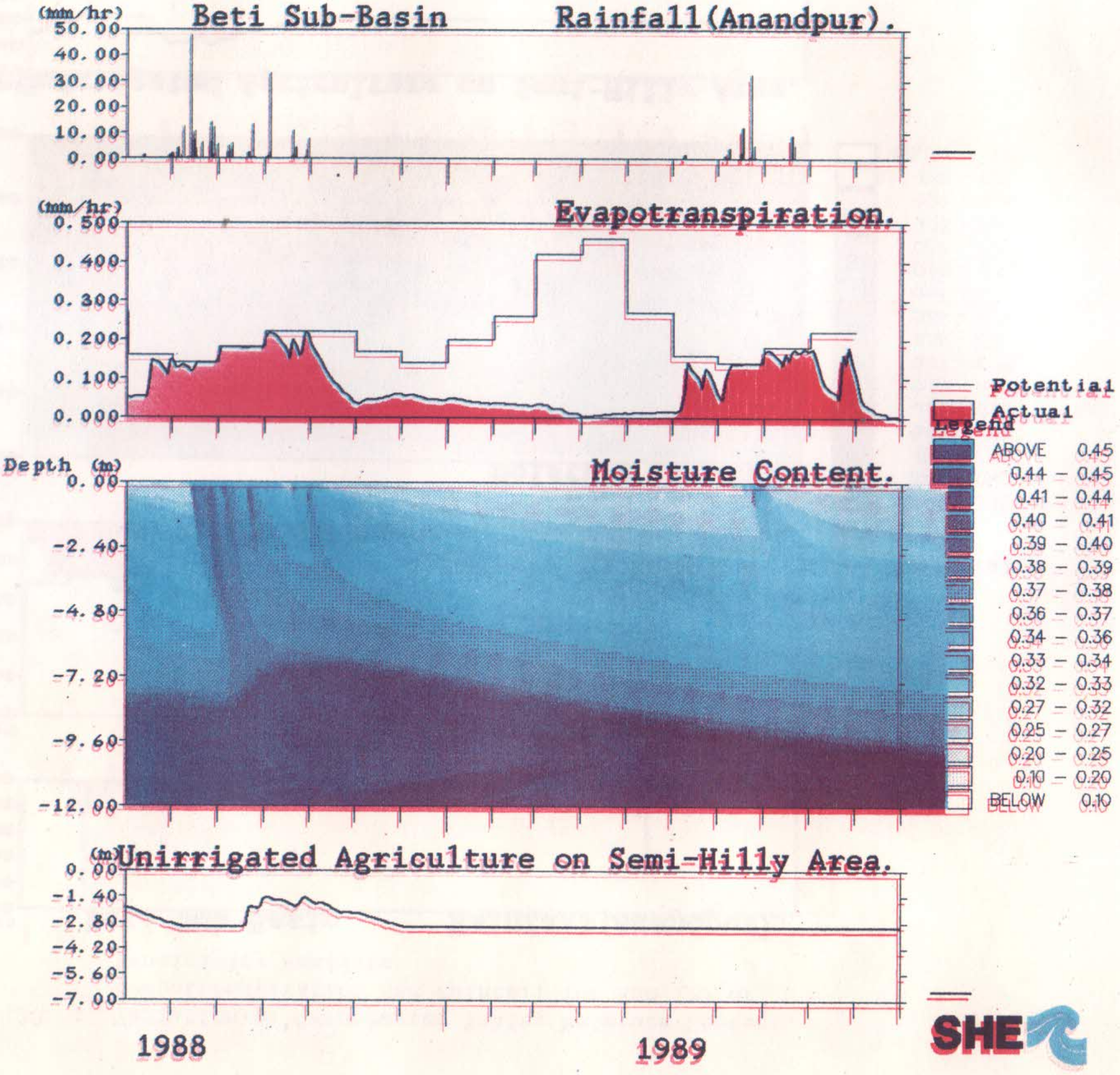


Fig. 22 Comparison of observed and simulated Hydrographs for Run (g) of Sensitivity Analysis.

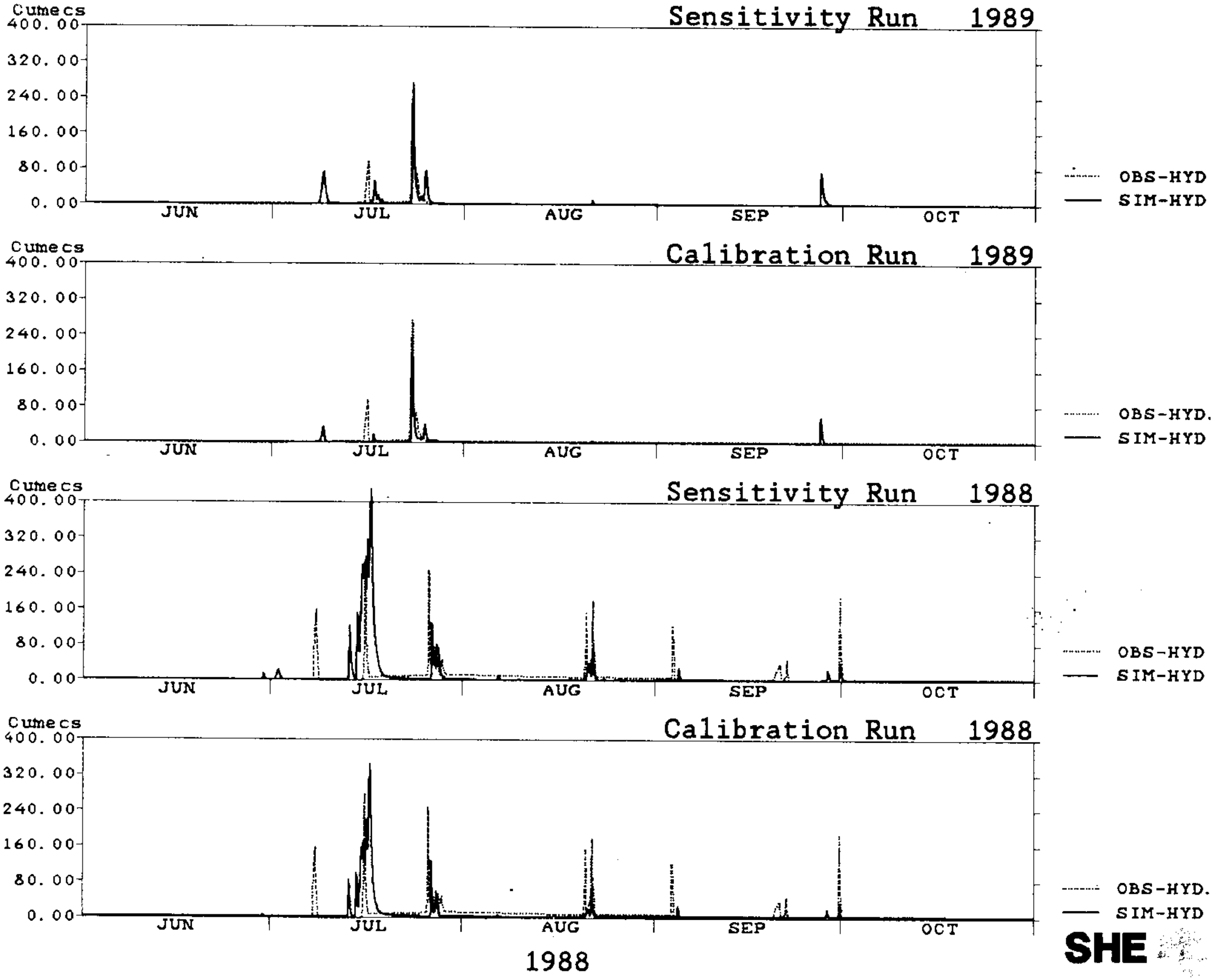
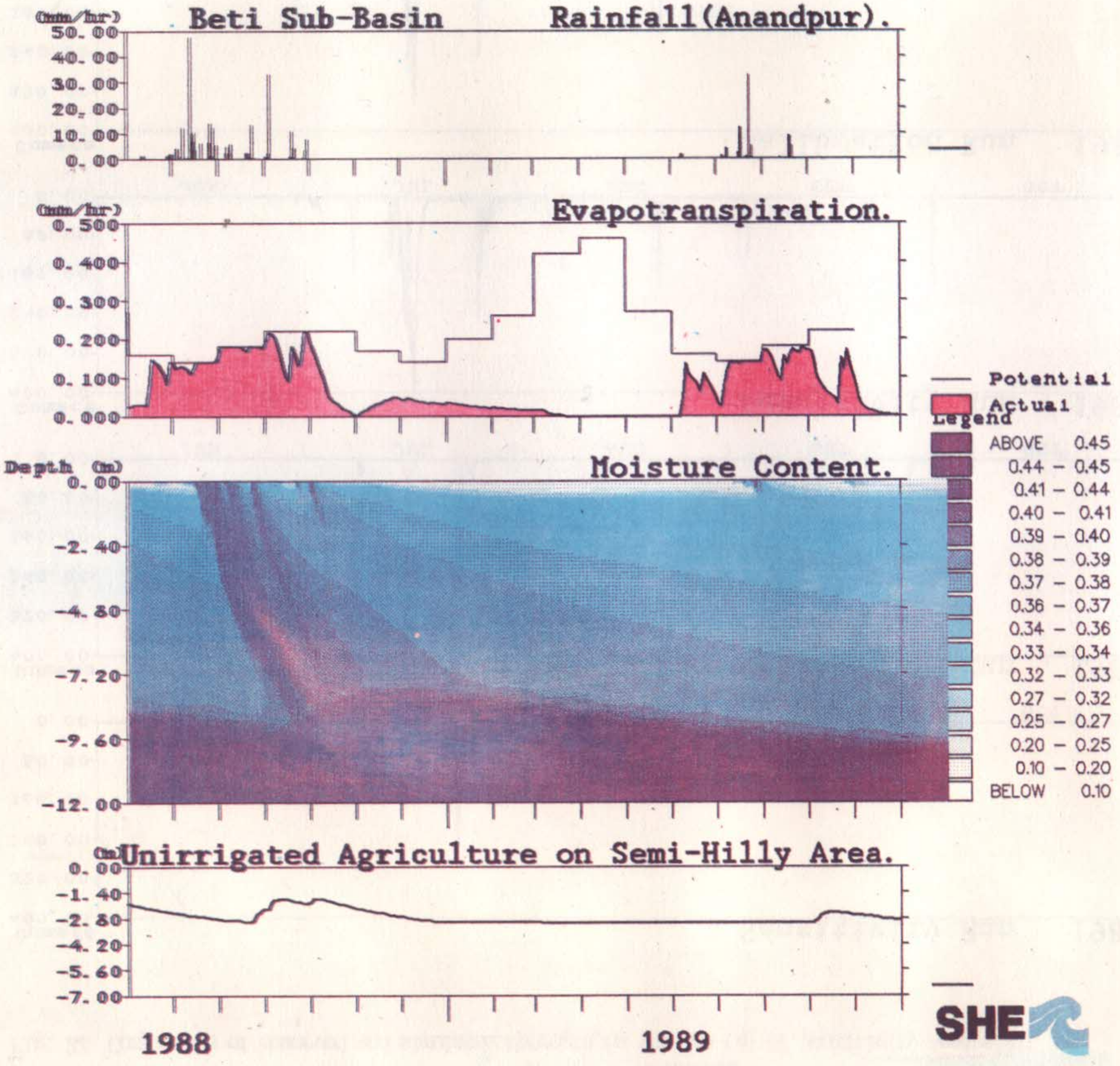


Fig.23 Variation of Ground Water Table, Moisture Content, Evapotranspiration nd Rainfall for Run (g) of sensitivity Analysis.



view. But by adopting larger value of grid sizes, the possibility of inaccurate representation of the basin increases. In order to study the effect of grid size on simulation results this sensitivity run was taken by adopting a smaller grid size of 1km × 1km. The volume of runoff increased by about 4% for the year 1988. There was not significant effect on the runoff volume for the year 1989. No significant effect on total simulated actual evapotranspiration was observed. Thus it can be concluded that adopting a grid size of 2km × 2km reasonably well represented the basin representation with comparable accuracy of 1km × 1km grid size for the Beti sub basin.

7.0 CONCLUSIONS AND REMARKS

The SHE has been applied to model the entire landphase of hydrological cycle for the Beti sub-basin of river Machhu within the limitations of data availability and assumptions made. The application indicates deficiencies in the available data of the sub-basin. As the Beti river remains dry for most of the parts of the year, only a few events were available for comparison of the observed and simulated hydrographs of runoff at the catchment outlet. Conventional hydrological data of daily and hourly rainfall for some stations (inside/outside the basin) and daily/4 - hourly/hourly stage-discharge data at the basin outlet were available. Data for the period 1982 to 1989 were collected. However, out of these, very little flow could be observed for the years other than 1984,1988 and 1989. Data for the year 1988 and 1989 were used for calibration and that of 1984 for validation of the model. Pan evaporation data of Rajkot pan evaporimeter lying outside the basin have been used.For simulation the grid size of 2 km x 2 km was adopted for 522 sq.km. catchment area of the sub-basin. Sensitivity analysis has been carried out for some of the important parameters of the model such as conductivity of saturated zone, conductivity of unsaturated zone, Strickler coefficient, exponent appearing in the Averjonov's formula and grid size of the catchment. On the basis of the above study, following concluding remarks can be made:

a) There are considerable uncertainties in the input data particularly with reference to consistency in rainfall and runoff data. Further, the values of soil and vegetation parameters, which play a significant role in the simulation, in the absence of their availability for the basin, have been derived from indirect sources and available literature. Simulation runs have been made assuming uniform soil and vegetation over the basin. The spatial distribution of soil depth and root zone depth for the different vegetations have been assumed on the basis of information gathered from field visits and general experience.Simulation results of the study are therefore affected by these assumptions.

b) Due to limitations of data the calibration and validation results do not show reproduction of desirable level of streamflow volumes, peaks and hydrographs. However, with further improvement in data availability and data quality, better reproduction of hydrographs could be achieved. Similar response has been observed in simulating groundwater response. Further, in the absence of observed values, the simulated soil moisture conditions and actual evapotranspiration could not be compared with the actual values.

Improvement of the calibration needs a more adequate and reliable rainfall runoff records, more accurate evaluation of the models parameters such as soil and vegetation properties along with their spatial distribution through field measurements and more accurate information regarding the initial phreatic surface levels.

c) It is observed from sensitivity analysis that a decrease in the hydraulic conductivity of unsaturated zone leads to lesser actual evapotranspiration, specially in dry season due to lesser loss of moisture by capillary rise. Actual simulated evapotranspiration and runoff are very sensitive to the exponent appearing in the Averjanov's formula. It is observed that total runoff volume increases and simulated actual evapotranspiration reduces as a result of increase in its value. On the basis of sensitivity analysis, it can be concluded that soil parameters as well as the surface and channel roughness should be accurately represented for realistic simulation of the hydrological response of a basin.

d) In the present simulation, no spatial variation was considered for Strickler coefficients, soil cracks, detention storage, vegetation and soil types. There is a need to account for spatial variability of these parameters in future simulation studies.

e) This systematic study has provided a good idea of quality and adequacy of existing data and also identification of information and data to be collected through observations, field measurements and laboratory tests for proper application of physically based-distributed models like the SHE, to the Beti Sub basin. These are listed as follows:

i) Hydrological and Hydrometeorological Observations:

* Rainfall data including hourly data atleast for a few SRRGs in the basin.

* Hourly discharge data or hourly stage data and daily stage-discharge data to develop the rating curves.

* Hourly/daily pan evaporation data.

ii) Field Measurements data:

* Spatial distributions of soils

* Soil profile and soil depth.

- Strickler roughness coefficients for overland and channel flows
- Landuse pattern
- Leaf area index
- Temporal variation of root depth for each type of vegetation
- River cross sections
- Temporal variation of water table positions
- Soil cracking coefficients

iii) Laboratory Tests:

- Soil moisture tension relationship
- Unsaturated Hydraulic conductivity as a function of moisture content
- Saturated hydraulic conductivity of saturated zone
- Temporal variation of soil moisture with soil depth

f) The present form of the SHE does not allow consideration of water bodies like reservoirs, lakes, irrigation canals etc. existing in the basin and their interaction with hydrological processes of runoff generation and groundwater recharge. The river network is represented along the boundaries of the grids and as such increase in grid sizes leads to distortion in the river representation. There is no scope for simulating the effect of soil erosion or deposition in the model. The extensive physical data for soil and landuse and computational requirements are the major limitations of the model particularly for developing countries like India. Where only conventional hydrological data and toposheets are usually available. As such the application of this model is not warranted for ordinary situations for which simpler techniques/models may suffice. However, for dealing with situations such as conjunctive use of water and evaluation of effects of landuse/landcover changes on hydrological regime, distributed models like the SHE are quite useful.

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