CS - 28

APPLICATION OF SHE MODEL TO THE GANJAL SUB-BASIN OF RIVER NARMADA

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NATIONAL INSTITUTE OF HYDROLOGY
JAL VIGYAN BHAWAN
ROORKEE-247667 (U.P.)
INDIA

PREFACE

The water resources development activities of the Narmada Basin have caused a considerable impact on its hydrological regime. SHE Model has been applied to the Ganjal sub-basin of Narmada basin, with the objective that conventional rainfall/runoff models are inappropriate to many hydrological problems; especially those related to the impact of man's activities of landuse change and water quality. These problems can be solved through the use of models like the SHE, which have physical basis and allow for spatial variations within a catchment. Though, the existing data base of Narmada basin is not exhaustive, it is reasonably adequate .for modelling exercise. It was therefore, considered appropriate to carry-out typical application studies of the SHE model using data of some of the sub basins of river Narmada.

The present study is a part of the project concerned with transfer of the System Hydrologique Europeen (SHE)- 'Hydrological Modelling System' to the National Institute of Hydrology, Roorkee and is intended to increase India's capabilities for formulating water and land resources development strategies through numerical modelling. The project is financed by Agreement ALA 86/19, Hydrological Computerized Modelling System, signed between the Commission of the European Communities (C.E.C.) and the Government of India. Under the project, six N.I.H. Scientists have been trained in theoretical and practical aspects of the SHE, at Danish Hydraulic Institute, Denmark.

Ganjal sub-basin is one of the six sub basins selected for the model application in the Narmada basin. The present study 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 'B' under the guidance of Dr. S M Seth, Scientist 'F' and Project Coordinator, SHE Model studies, in close interaction with the Consultants.

SATISH CHANDRA
DIRECTOR
NATIONAL INSTITUTE OF HYDROLOGY
ROORKEE

CONTENTS

Page No.

PREFACE

3.0 DESCRIPTION OF STUDY AREA AND DATA AVAILABILITY

4.0 DATA PROCESSING AND PREPARATION

LIST OF TABLES

LIST OF FIGURES

ABSTRACT

The Narmada basin is presently undergoing changes in its hydrological regime, as a result of water resources development activities. The conventional rainfall/runoff models are in appropriate to deal with many hydrological problems; epecially those related to the impact of man's actiavities of landuse change, conjunctive use of surface and groundwater, soil moisture conditions 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 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 the 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 grid element boundaries. Basic processes of land phase of hydrological cycle are modelled in separate components viz. interception, by Rutter accounting procedure; evapotranspiration, by the Penman-Monteith equation; or by an approach developed by Kristensen and Jensen (1975); overland and channel flow, by simplifications 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 bedget method.

The present study deals with the application of the SHE model to the Ganjal sub basin of river Narmada. The Narmada basin extends over an area of 98, 796 sq.km. and lies between lattitudes 21^{0} 20'N to 23^{0} 45'N and longitudes 72^{0} 32'E to 81^{0} 45'E. The Ganjal rises in the Satpura range in the Betul district of Madhya Pradesh at an elevation of 800 m and flows for a length of 89 km. in north westerly direction to join the Narmada from left. The Ganjal drains a total area of 1,930 sq.km. upto its confluence with Narmada; but in the present study, the Ganjal sub basin with boundary defined by the Central Water Commission gauging site at Chhidgaon has been taken into consideration. The Ganjal sub basin upto chhidgaon has an areal extent of 1,729 Km^{2} and lies between the latitudes of 21^{0} 58'N to 22^{0} 25'N and longitudes 77^{0} 17'E to 77^{0} 45'E.

The conventional hydrological data of daily and hourly rainfall for some stations lying inside/outside the sub basin and hourly stages and daily stage-discharge at basin outlet were readily available, with concerned organisations for use in this study. Pan evaporation data of Jabalpur station, which lies outside the sub basin have been used. Digitized information from Survey of India Toposheets in the scale 1:50,000 has been used to assign elevations to the grids of the sub basin. Split sample approach has been used for simulation using 2 km x 2 km grid size. Data for the period March 1982 to February 1985 have been used for

calibration of the model and data from march 1985 to December 1987 have been used for validation of the model. Sensitivity analysis has been carried out for potential evaporation data of four pan evaporation measurement stations as well as for the important parameters; such as, exponent in the Averjaneov's formula used in the SHE, water content at wilting point and residual water content, as well as saturated conductivity of unsaturated zone.

In this application study, the SHE model has been successfully used for modelling entire landphase of hydrological cycle for Ganjal sub basin with a reasonable accuracy, within the constraints of data availability and assumptions made. The simulation results show good reproduction of streamflows volumes, peaks and hydrographs. However, the performance of the model in simulating groundwater response in the basin was not of the desired level. In the absence of observed values, the simulated soil moisture conditions could not be compared with the actual values. It is observed from sensitivity analysis, that simulation results are not much sensitivity to potential evaporation data. Runoff and actual evapotranspiration are very sensitive to the exponent appearing in Averjanov's formula as well as water content value at wilting point and residual water content. An increase in the value of saturated conductivity of unsaturated zone leads to higher rate of infiltration and results in greater actual evapotranspiration in dry season, due to loss of moisture by capillary rise.

1.0 INTRODUCTION

1.1 Water Resources Development

Water resources of a country constitute one of its most vital assets. Water is a basic input for agriculture, industries, drinking purposes and other domestic activities. India is a vast country with a wide variety of climatic and hydrological environments; snow clad mountains of the Himalayas in the north, a long coastline in the south, desert in the western part, alluvial plains to the north and hard rock regions to the south. Rainfall is seasonal in nature and most of it falls during the four monsoon months of July to October with erratic patterns leading to floods as well as droughts in the different parts of the country. The principal Indian water resouraces are i) surface water resources through rivers and streams and ii) Groundwater. Systematic assessment of water resources began after the formation of the CWINC in 1945-46. A scientific assessment of the groundwater potential of the country was not taken until the 1979.

To meet the increasing demands of growing population, there has been considerable development of water resources in the country, since independence. The nation has marched forward towards self sufficiency in agricultural production through irrigation and hydropower generation. A large number of water resources projects such as Tehri dam on river Ganges, Narmada Sagar and Sardar Sarovar in Narmada Basin are still in progress. The increasing rate of water resources development activity and utilization of water for various uses such as Irrigation, hydro electricity generation, domestic and industrial purposes recreation, fishing, wild life, drainage and navigation have focused attention on environmental aspects and more particularly water quality. India is fortunate to have numerous rivers, big and small which traverse the land in pracatically every direcation carrying the much needed water through its dry and thirsty lands. But the development of water resources is a complex problem and those concerned need to keep several factors in view which include the net availability of water, its quality, location, distribution and variation, climatic conditions, nature of soil, landuse pattern and various demands etc. Further, the catchments of rivers are no longer virgin, and the process of development and man's activities are continuously changing the hydrological regime of the river basins. The application of the science of hydrology is increasingly becoming necessary in all aspects and stages of water resources development and management. As the cost of water resources development has increased, so there is a pressing demand for appropriate approach to hydrological modelling to help optimal project planning.

1.2 Modelling as a tool-Suitability of Distributed Approach

A model represents the physical, chemical and biological characteristics of the catchment and simulates the natural hydrological processes. Simulated results of a model aid in making decisions, particularly where data or information are scarce or there are large numbers of options, to choose from. It is not 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.

A large number of hydrological models exist. However, many of the models function in basically the same way. For instance, atleast 20 different rainfall-runoff models of the lumped, conceptual type exist. Although these models at first sight may look very different they have fundamentally the same structure and basically function according to same principles. For some hydrological problems the selection of model type is more or less obvious; for example, probabilistic models for frequency analysis or stochastic time series models for generation of long time synthetic streamflow series. Empirical (black box) models are mainly of interest as single event models or as subcomponents of more complicated models. Lumped, conceptual models are especially well suited to simulation of rainfall runoff process when hydrological time seraies sufficiently long for a model calibration exist. Thus typical fields of application are i) extension of short streamflow records based on long rainfall records and ii) real time rainfall-runoff simulation e.g. for flood forecasting. Other fields of possible application, to which the lumped conceptual models are not especially suited but where they can be used if no better model is available are i) prediction of runoff from ungauged catchments,i.e. catchments where calibration is not possible. In such cases the model parameters are typically estimated by calibrating against hydrologically homogeneous, near by catchments. ii) general water balance studies, availability of groundwater resources, irrigation needs, analyses of variations in water availability due to climatic variability, etc.

Physically-based distributed models can in principle be applied to almost any kind of hydrological problem. Obviously there are many problems for which the necessary solutions can be obtained using cheaper and less sophisticated empirical, lumped conceptual or statistical models. But, for the more complicated problems use of physically based distributed models acquires great importance.

Physically-based distributed models are based on our understanding of the physics of the hydrological processes which control catchment response and use physically-based equations to describe these processes. From their physical basis such models can simulate the complete runoff regime, providing multiple outputs, e.g. river discharge, phreatic surface level and evaporation loss. Physically based models are spatially distributed since the equations from which they are formed generally involve one or more space coordinates. They can therefore simulate the spatial variation in hydrological conditions within a catchment as well as simple outflows and bulk storage volumes. But these ,models require large computers, computational time and extensive data and are expensive to develope and operate. Unlike lumped conceptual models ;physically based, distributed models do not consider the transfer of water in a catchment to take place between a few defined storages. Instead the transfers of mass, momentum and energy are calculated directly from the governing partial differential equations, for example the St. Venant equations for surface flow, the Richards equation for unsaturated zone flow and Boussinesq equation for groundwater flow. These cannot be solved analytically for cases of practical interest and solutions must instead be obtained using approximate numerical methods.

Physically-based distributed models can in principle be applied to any range of data and are limited only by the range of applicability of the physical laws within the model. On the other hand black box models should not be extrapolated beyond the range of conditions for which they are calibrated.

Black box models must be calibrated for each catchment because their parameters vary in a way which has no physical meaning and cannot therefore be derived from measurements of a catchment's characteristics. A lengthy hydrometeorological record is required for calibration. While physically based models use parameters which have physical meaning and can in principle be evaluated from direct measurement. Thus these models can be applied to catchments without lengthy hydrometeorological records and can be helpful in studying the hydrological regimes of the catchments under the impact of landuse changes.

Physically-based models are applicable to a wider range of catchments, because the physical laws describing the hydrological processes are the same all over. On the other hand, black box models may not apply to all catchments because the various hydrological processes are not accounted for separately.

Physically-based models can make use of all available information viz. topography, soil and landuse, remote sensing data, soil physics and plant physiology, historical information on extreme event characteristics and may be designed to improve as new ideas on hydrological processes are developed.

1.3 SHE Model Project at NIH - funded by C.E.C.

The project is aimed to transfer the Systeme Hydrologique European - European Hydrological System (SHE) to the National Institute of Hydrology (NIH) at Roorkee, India, and is intended to increase India's capabilities for formulating water and land resources development strategies through numerical modelling. The project is financed by agreement ALA86/19, Hydrological Computerized Modelling System, signed between the Commission of the European Communities (CEC) and the Government of India (GOI). The transfer is being carried out by the consultants, a group headed by the Danish Hydraulic Institute (DHI) and composed also of SOGREAH (France) and the U.K. NERC's Water Resource Systems Research Unit at the University of Newcastle upon Tyne (UON). The two major strands of the project are the application of the SHE to focus projects in the Narmada River Basin, India, and the training of NIH staff in the use of the SHE at both NIH and DHI. Two batches of scientists, three in each batch have been trained at DHI during 1988 and 1989. Simulation studies using data of six sub basins of Narmada river, have been carried out under the project. This report deals with one such case study for Ganjal sub basin.

2.0 SHE MODEL

The System 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 (LHF).

2.1 Salient Features

The SHE was developed from the perception that conventional rainfall/runoff models are inappropriate to many hydrological problems, especially 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 vertcal 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 appraoch developed by Kristensen and Jensen (1975); overland and channel flow, by simplifications of St.Venant equations; unsaturated zone flow, by one dimensional Richards equation; saturated zone flow by the two dimensional Boussinesq equation and snowment, 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 mode 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 of simply a lack of data may create significant uncertainties in the values of the catachment 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 sensitiavity 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.

Table-1 summarises some possible fields of application. 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).

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		Catchment
Agricultural practices	ET/UZ/SZ	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

Though the existing data basic is not exhaustive, it reasonably adequate for modelling exercise. It was therefore, considered appropriate to carryout typical application studies of SHE model using data of some of the subbasins of river Narmada under this project of technology transfer.

2.2 Typical Approaches for Modelling of Different Processes

The SHE is physically based distributed modelling system as each of the primary components of the land phase of hydrological process constituting the hydrological cycle, namely overland flow, unsaturated and saturated sub surface flow, evapotranspiration, snow melt and canopy interception is modelled either by finite difference representations of the theoretiacal partial differential equations of mass, momentum and energy conservation or by empirical equations derived from independent experimental research. Spatial distribution of basin parameters, rainfall and hydrological response are obtained in the horizontal through the representation of the basin by an orthogonal grid network and in the vertical by a column of horizontal layers at each grid square. The river channels are superimposed along the boundaries of the grids. The schematic diagram of a catchment and a quasi three dimensional physically based distributed SHE model is shown in fig. 1.

The various components of the SHE for modelling the different hydrological processes are described as following:

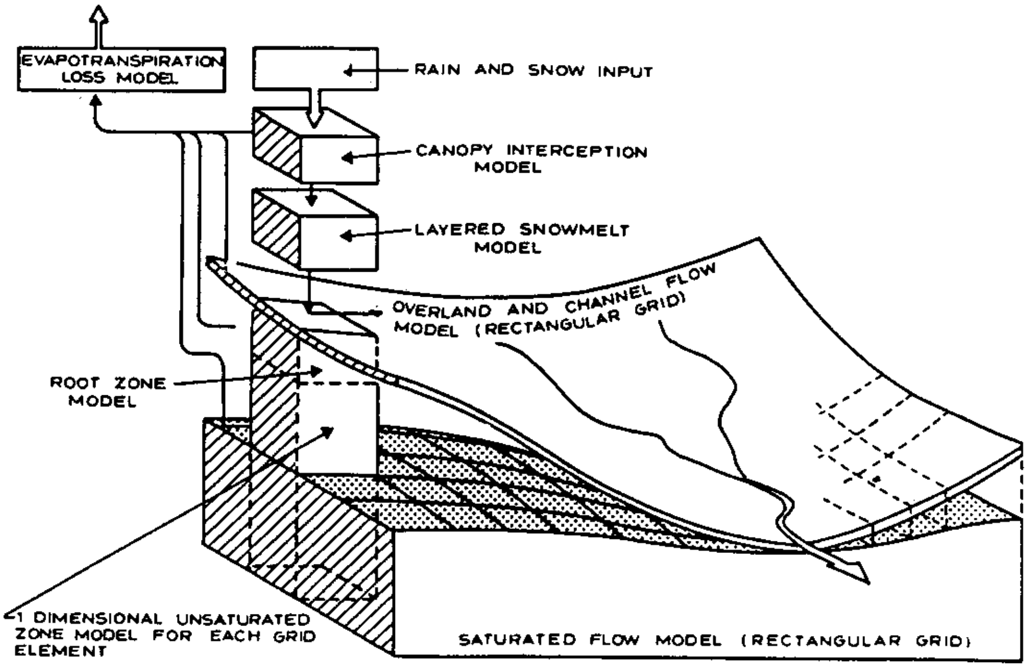


Fig. 1 Structure of the European Hydrologic System.

2.2.1 Frame Component

The Frame or central component of the SHE coordinates the running of the other components by selecting their different time scales and organising their data interchanges to ensure an orderly and consistent execution.

In brief it performs the following functions:

i) steers the reading of data for each component and the initialization of all computation variables.

ii) controls the sequence in which each component is called to perform its computations, and controls the timesteps of the computations.

iii) controls the data flow from one component to another, i.e. processes the results of the computation in one component into the correct from for input to another component as internal boundary data.

iv) prints a summary of the results at specified intervals.

v) records the calculation results on permanent storage, for further processing by use of the SHE output Retrieval and Graphical Display packagae, of SHE User's Guide

vi) maintains a check on the water mass balance for the whole model except the river

2.2.2 Interception and Evapotranspiration Component

The part of precipitation which does not fall directly on bare soil is held by vegetation or other surface covers and a part of it may thereby be evaporated back to atmosphere, thus never reaching the soil is termed as the interception loss. The remainder of the intercepted precipitation may eventually reach the soil after some time. The quantity of water stored on the wetted surface of the vegetation cover is defined as interception storage. The magnitude of interception storage is dependent on other surfaces including layering of canopies in the vertical. Rain passes through the vegetation canopy by through fall on stemflows and thus delivers water to the ground. The loss of water by evaporation is from two main aspects. The first, evaporation from an open water surface, the direct transfer of water from lakes, reservoirs and rivers to atmosphere. The second form of evaporation loss occurs from the transpiration from vegetation. This is sometimes called evapotranspiration, since loss by direct evaporation of intercepted precipitation on plant surfaces is also included.

For simulation of the interception and evapotranspirtion processes, SHE offers two models. In the first model, the interception processes are modelled by a modified version of Rutter model, and the evapotranspiration is modelled by the Penman-Monteith model. In the second model, a model developed by Kristensen and Jensen (1975) is used.

OPTION 1

Interception

Meteorological and vegetative input data are used to simulate the total evapotranspiration and net rainfall amounts from the processes of:

1) Rainfall interception by vegetation canopy
2) Drainage from the canopy
3) Evaporation from the canopy surface
4) Evaporation from the soil surface
5) 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 turn gives information on soil moisture conditions in the root zone. It is assumed that the temperature is above $0^{o}C$ and that there is no snowpack. Otherwise the proacess is modelled by the snowmelt component. As interception has significant effect on evapotranspiration the two processes are modelled within the one overall component.

The interception model calculates net rainfall reaching the ground through vegetation canopy, the amount of water stored on the canopy and evaporation from canopy. Interception it modelled by modified Rutter model developed by Rutter et al (1975) which is an accounting procedure for the amount of water stored on the canopy. The canopy is considered to have a surface storage of capacity S which is filled by rainfall and emptied by evaporation and drainage. This capacity may be regarded as the minimum depth of water required to we't all canopy surfaces. When the depth of water C on the canopy equals or exceeds S the evaporation from the canopy is assumed to occur at the potential rate, E_p.When C is less than S the rate is assumed to be Ep. $\frac{C}{S}$. The rate of change of storage is when calculated as:

$$\frac{\partial C}{\partial t} = Q - ke^{b(C-S)} \qquad (1)$$

where,

$Q = p_1p_2(P - E_p \frac{C}{S})$ when $C < S$

$Q = p_1p_2\ (P - E_p)$ when $C \geqslant S$

C = depth of water on the canopy

S = canopy storage capacity

P = rainfall rate

P_1= proportion of ground in planview hidden by vegetation

P_2= ratio of total leaf area to area of ground covered by vegetation, and

$P_1P_2 = P_1P_2$ when $P_2 < 1$,

$P_1P_2 = P_1$ when $P_2 \geqslant 1$ since P_1P_2 can not exceed P_1;

Ep = potential evaporation rate

k & b = drainage parameters;and

t = time

This model is expecpted to work in a very satisfactory manner under conditions of a completely wetted canopy ($C \geqslant S$). However, by introducing the ratio C/S, the various terms can be modified so that the response from dry, through partially wetted, to fully wetted canopy is coantinuous. Equation (1) is solved by analytical integration.

Limitations of the Interception Model

Generally the canopy storage C and the model parameters S, k, b, p_1 and p_2 cannot be measured directly in the field but are estimated indirectly from measurement of rainfall, net rainfall below the canopy and evapotranspiration. Variation in vegetative cover with time on account of seasonal growth or landuse changes can be incorporated by varying S, p_1 and p_2 with time.

The above discussed model was developed for trees; yet the model is used in the SHE for different types of vegetations, since the physical principles remain the same. Further, interception is modelled for only one vegetation in each grid square. The effect of secondary vegetation is neglected. For example, if an area is characterised by trees, the grass below tree cover is ignored.

b) Evapotranspiration

The evapotranspiration model 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 vegetation canopy varies from dry to partially wetted and fully wetted state. The loss term is then used in the calculation of soil moisture changes by the unsaturated zone component. Potential and actual evapotranspirations are calculated. When the supply of water to the plant or soil system with dry canopy is unlimited there occurs the potential evapotranspiration. On the other hand actual evapotranspiration should have the potential rate as an upper limit and otherwise be reduced by restrictions in the supply of water from the soil to the plant roots or by stomatal resistence within the plants. Actual evapotranspiration in the SHE is calculated by using Penman-Monteith equation

$$Ea = \frac{R_n\Delta + (\rho c_p \delta e)/\gamma_a}{\Delta + \gamma\left(1 + \frac{\gamma_c}{\gamma_a}\right)} \qquad (2)$$

where;

Ea = actual evapotranspiration

R_n = net radiation

Δ = rate of increase with temperature of the saturation vapour pressure of water at air temperature

ρ = density of air

C_p = specific heat of air at constant pressure

δe = vapour pressure deficit of air

γ_a = aerodynamic resistence to water vapour transport

= latent heat of vaporisation of water

= psychrometric constant

γ_c = canopy reistence to water transport

The parameter γ_c represents average stomatal resistence in dry conditions and is zero for a wet canopy since evaporation of intercepted water is already occurring at the potential rate. Due to difficulties in determining all the parameters in equation (2), particularly γ_c; the three modes of operation are specified for the calculations:

a) γ_c is constant for each type of vegetation

b) γ_c varies as function of soil moisture tension as well vegetation type

c) γ_c is zero

Thus equation (2) then gives Ep , the potential evapotranspiration rate. The ratio Ea/Ep is then used to calculate actual evapotranspiration rate Ea as a linear function of soil moisture tension (Feddes et al. 1976).

Total actual evapotranspiration calculated for each grid square is dependent on the extent of wetness of canopy and on degree of ground coverage by the canopy:

$$E_t = p_1 p_2 E_p \ C/S + p_1 p_2 \ Eat \ (1-\frac{C}{S}) + 1(1-p_1 p_2)Eas \quad (3)$$

Where;

Et = total evapotranspiration

Ep = potential evapotranspiration

Eat= total evapotranspiration from uptake through the roots

Eas= evaporation for bare soil

Extraction of moisture for transpiration from the root zone is distributed according to the vertical distribution of root mass in the root zone. Soil evaporation moisture is obtained from the top of the soil column.

OPTION - 2

Interecption

The second option offered in the SHE has been developed at the Royal Veterinary and Agriculture University in Denmark (Kristensen the Jensen, 1975). In this option the actual evapotranspiration is calculated on the basis of potential rates which are required as input data and the acatual soil equations is based on comparisons with actual measurements. The interception process is modelled by introducing and interception storage, which has to be filled before through flow to the ground surface takes place. The interception storage is diminished by direct evaporation. The size of the interception storage capacity, Imax, depends on the vegetation type and its stage is the ratio of total area of leaves to the total ground area covered by the tree or vegetation.

$$I_{max} = C_{int} \ LAI$$

where,

C_{int} = interception parameter (mm)
LAI = leaf area index

The parameter C_{int} is independent of vegetation type, but depends on the time resolution. On the basis of interception storage capacities given in the literature for different vegetation types a typical value of C_{int} is 0.05mm. The exact value may be assessed from calibration. The leaf area index usually varies between 0 to 7.

b) Evapotranspiration

The transpiration from the vegetation, Eat depends on the density of the green crop material, described by the leaf area index and the actual soil moisture content in the nodes in the root zone. It also depends on the root density.

$$Eat = f_1\ (LAI)\ f_2\ (\theta)\ RDF.E_p$$

where;

Eat = transpiration

RDF = root distribution function

$f_1(LAI)$= is a function of leaf area index and parameters C1 and C2

E_p = potential evapotranspiration

$f_2(\theta)$ = is a funtion of soil moisture for constant C3 and varying E_p

$$f(\theta) = 1 - \left(\frac{\theta_f-\theta}{\theta_f-\theta_w}\right) \frac{C_3}{E_p}$$

where;

θ = Volumetric moisture content

θ_f = volumetric moisture content at field capacity

θ_w = volumetric moisture content at wilting point

C_3 = empirical parameter (mm/day)

Equation (4) is applied to all the nodes in the rootzone. It is seen that the equation (4) includes the root distribution function RDF, which is calculated in the model assuming a logarithmic variation with the depth in accordance with the usual distribution of the root mass. It is seen that the evapotranspiration routine contains three emperical parameters, C_1, C_2 and C_3. This approach is discussed in detail by Kristensen and Jensen (1975).

2.2.3 Overland and Channel flow Component

When the net rainfall rate exceeds the infiltration capacity of the soil, water is accumulated on the ground surface. This water is routed down gradient towards the river system as surface runoff. The exact flow direction and quantity is governed by the topography the flow resistence as well as the losses due to evaporation and infiltration. The water joining the river system as surface and sub surface flow is routed downstream in a separate node point system. Also, there is an exchange between channel and aquifer to allow for seepage losses and groundwater input. Overland flow as well as channel flow are modelled by approximations of the St. Venant equations of continuity and momentum.

a) Overland flow

The two dimensional solution based on the diffusion wave approximation of the St. Venant equations ignoring the inertia terms can be expressed as:

$$\frac{\partial h}{\partial t} + \frac{\partial (uh)}{\partial x} + \frac{\partial (vh)}{\partial y} = q \qquad (5)$$

$$\frac{\partial h}{\partial x} = Sox - Sfx \qquad (6)$$

$$\frac{\partial h}{\partial y} = Soy - Sfy \qquad (7)$$

where,

$h(x,y)$ = local water depth

t = time

x,y = rectangular certesian coordinates

$u(x,y)$ = flow velocity in x direction

$v(x,y)$ = flow velocity in y direction

q(x,y,t) = net precipitation minus infiltration

Sox(x,y),Soy(x,y) = ground slopes in x and y directions

Sfx(x,y),Sfy(x,y) = friction slopes in x and y directions

On applying Strickler/Manning law for each friction slope to equation (5) and (6) the relationship between velocities and flow depths may be expressed as:

$$uh = kx \; G_x^{1/2} \; h^{5/3} \qquad (8)$$

$$vh = ky \; G_y^{1/2} \; h^{5/3} \qquad (9)$$

where;

kx(x,y), ky(x,y) = strickler roughness coefficients for x and y directions respectively.

Gx(x,y), Gy(x,y) = water surface gradients in respective x and y directions.

Equations (5), (8), and (9) are then combined and solved by finite difference method using an explicit procedure.

b) Channel flow

The above mentioned solution is repeated in one dimensional form i.e. for channel flow.

$$\frac{\partial A}{\partial t} + \frac{\partial (Au)}{\partial x} = q_L$$

$$\frac{\partial h}{\partial x} = Sox - Sfx$$

where,

A(x) = cross sectional area of flow

Sox = bed slope of channel

$q_L(x)$ = source/sink st erm for evaporation, rainfall, lateral inflow and outflow stream/aquifer exchange.

Strickler/Manning equation is used and the final solution is obtained by an implicit finite difference scheme.

2.2.4 Unsaturated Zone Component

The unsaturated zone component plays a major role in the SHE as all other components depend on boundary data from this component. It links the two horizontal two dimensional surface and sub surface processes together. The results obtained in the unsaturated zone are in evapotranspiration process also. Soil moisture content and tension, or pressure, distributions in the unsaturated zone are determined by this component. The unsaturated zone extends from the ground surface to the phreatic surface. The flow is described by the one dimensional Richards's equation. The soil water system incorporates the phases of solid, liquid and gas resulting in introduction of nonlinear terms in the Richard's equation. The upper part, the root zone incorporates root extraction for the transpiration process. It shows considerable variations in moisture content as a result of evapotranspiration and rainfall infiltration. This is explicity included in the equation by sink terms. The integral of the sinks over the entire root zone depth amounts the total actual evapotranspiration. Soil evaporation is taken into account in the first sink term below the ground surface. The interaction between the unsaturated and saturated zone is solved by an iterative mass balance method. The lower part of unsaturated mode point system may be solved separately in a pseudo timestep, between two real time steps.

The flow in unsaturated zone is assumed to be in the vertical only, the flow is described by one dimensional Richard's equation:

$$C\frac{\partial \psi}{\partial t} = \frac{\partial}{\partial z}\left(K\frac{\partial \psi}{\partial z}\right) + \frac{\partial k}{\partial z} - S \qquad (10)$$

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

For solutioin of this equation the relationship between volumetric moisture content and unsaturated conductiavity K as well as the relationship between soil tension and volumetric moisture content termed as retention curve are required. The equation is solved by an implicit finite difference scheme. The details of methodology are given by Abbott et al. (1982) and Jenson (1981, 1983).

The upper boundary condition determines infiltration into the soil which may shift from flux controlled conditions to soil controlled/saturated conditions and vice versa. The lower boundary is represented usually by the phreatic surface and mass balance calculation for the saturated zone determine the exchange with the saturated zone.

As the Richard's equation is required to be solved at every grid square in the model, the unsaturated zone component consumes a large part of the total computer time. Hence, for homogeneous regions determined by vegetation, soil types and mearly identical boundary condition the unsaturated zone calculations in the grid squares may be lumped together. Thus, the unsaturated zone calculations are carried out in one representative column within the homogeneous region and the boundary conditions from this column are then transferred to the other equivalent columns. Considerable computer time is saved by adopting this approximation.

2.2.5 Saturated Zone Component

The Saturated subsurface flow in the catchment is computed in the saturated component. The flow is assumed to be horizontal only. The phreatic surface levels are calculated for single layer anisotropic and hetrogeneous unconfined aquifer with spatially varying impermeable bed. There is provision to cope up with multilayered confined/unconfined aquifers, three dimensional unconfined flow and artificial drainage. The variation of phreatic surface level with time at each grid square is described by the nonlinear Boussinesq equation. This combines Darcy's law and the mass conservation of two-dimensional laminar flow in a anisotropic, hetrogeneous aquifer.

$$S \frac{\partial h}{\partial t} = \frac{\partial}{\partial x} \left(k_x H \frac{\partial h}{\partial x} \right) + \frac{\partial}{\partial y} \left(k_y H \frac{\partial h}{\partial y} \right) + R \qquad (11)$$

where,

$S(x,y)$ = specific yield

$h(x,y,t)$= phreatic surface level

$Kx(x,y), Ky(x,y)$= satudrated hydraulic conductivities in 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 i.e.

$$R = \Sigma q - \frac{\partial}{\partial t} \int_{h}^{gs} \theta \, dz$$

where,

Eq = transpiration + soil evaporation + infiltration + stream/acquifer exchange + external boundary flows

$\theta(z,t)$= soil moisture content in the unsaturated zone

gs = ground surface level

The above mentioned equation is solved by an iterative finite difference technique. The saturated zone component provides scope for watertable rise to ground surface. In such cases an exchange of flow between saturated zone and the water at ground surface i.e. overland flow is calculated. Allowance is also made for disappearance of the saturated zone in individual grid square. This is modelled by assuming zero outflow from a grid square, in case the saturated water depth is lowered than a certain threshold value. Both of these provisions are necessary for modelling the groundwater flow in hilly regions with shallow soils like Narmada basin.

2.2.6 River Aquifer Exchange Component

The river system has considerable influence on groundwater reservoirs as it traverses the basin in many directions The river describes usually as head boundary for the aquifers. As in comparison to the grid square discretization usually adoped, the width of river occupies typically a few percentage of grid square. Hence, an appropriate representation of the river requires a separate node system in which the flow and water levels in the river can be computed. This is achieved by allowing the river flow computations to be carried out at nodes on the corners of the grid square. Interaction between the groundwater and the river and overland flow are carried out at intermediate links on the grid square boundaries. River aquifer interactions are simulated for the following cases:

a) phreatic surface in direct contact with a flowing river

b) phreatic surface in direct contact with a dry river

c) phreatiac surface lying below a flowing river

d) phreatic surface lying below a dry river

Further, the river boundary can be described by a hvdraulic conductivity different from that of surrounding aquifer. Thus, lower of higher conductivities which may characterise the sediments in the immediate vicinity of the river are also taken into consideration.

2.2.7 Snowmelt Component

The snowmelt component of the SHE computes, with process based equations, the transfer of moisture resulting from the various snowmelt processes. Keeping in view the data availability two snowmelt computation methods are available in the SHE viz.

i) degreeday method and

ii) energy budget method

However, this component was not required in the present study.

2.3 Data Requirements for SHE Model

The physically based, distributed modelling system SHE in principle does not require long term hydrometeorological data for its calibration but it requires the evaluation of a large number of parameters defining the physical characteristics of the catchment on a spatial distributed basis.It should of course be emphasized , that different types of applications and different hydrological regimes being considered may call for various degrees of accuracy in the estimation of the individual basin parameters, and the evaluation of some parameter values may simply be based on experience. The data availability, however, will in any case determine the degree of reliability, which can be put inot the simulation results.

Abott et al. (1986) mention that in principle the parameters and their spatial distributions can be measured in the field but the expense of such a survery applied to all the parameters would prohibit practical implementation of such a model. Hence, it is necessary to reduce the number of direct measurements and to employ more indirect evaluations. Bathurst (1986a) states a typical approach which involves a few measurements at representative sites in the catchment, providing information on soil properties and channel flow resistance especially. These parameters are likely to have the most influence on simulations of runoff response. These measurements are then assumed, on the basis of their physical nature, to apply to other areas of the catchment. In this manner it is possible to evaluate parameters on the bais of vegetation or soil type within a catchment and also to transfer information from studies carried out elsewhere (Beven and O'Cannel, 1982).

The information about parameters like hydraulic conductivity of soil, soil moisture retention curve, leaf area index, root zone depth required for the model can be obtained from measurements reported in the literature for other field or laboratory studies. Some of the data such as landuse and soil types can be provided by remote sensing techniques. Even after procurement of availabe data there remains the problem of sampling and evaluating the parameters in such a way as to be representative of the grid scale adopted in the model. Many hydrological measurements, for example, are made at the point scale, of the order of a metre, and may or may not be representative of conditions at grid scale of a kilometre or more. It important, therefore, that techniques of measurements used should as far as possible, correspond to the structure and scale of the model (Beven and O'Connell, 1982). Remote sensing technique may play an important role, by providing average parameter values on a grid basis in such cases. In the same way, tracers can be used to provide information on the integrated characteristics of overland and channel flow over given reaches (Beven et al. 1979). In the following a brief introduction to the required data is listed. This comprises of:

Catchment geometry:

- Topography (from toposheets on e.g. 1:50,000 scale)
- Soil depths (distance to impervious layer)
- River geometry (cross sections, route of the river and information about structures)

Land use and soil parametric data

The spatial distribution of soil and vegetation types (from e.g. 1,250,000 maps).

For each vegetation type:

- Temporal variation of either 1) root depth and leaf area index or 2) canopy drainage parameters, soil shading indices and canopy and aerodynamic resistances.

For each soil type

- Soil moisture characteristic $\psi - \theta$ relationship
- Hydraulic conductivity funcation $K - \theta$ relationship
- Horizontal hydraulic conductivity

Surface parameteric data

These data are required for each grid square, and include:

- Strickler roughness coefficient for overland flow and river flow
- Cracking/Bypass coefficients
- Depth to drains and subsurface drainage coefficients

Snowmelt Parametric Data

- Rainfall and meteorological station network, and records of data obtained at these stations (possibly including potential evapotranspiration data).
- Streamflow data
- Other relevant data which can be utilised in the model calibration and validation, e.g. water table, soil moisture data etc.
- Boundary and initial conditions

As mentioned previous, some of these data may not be generally available. For example, a complete information of the $\psi-\theta$ relationship is seldom available. However, experienced users of the SHE may from other application studies already have gained some knowledge about the possible form of this relationship, and utilize this in the evaluation of this curve.

Data Handling Procedures:

The current trend in the SHE applications, where progressively larger amounts of data are being processed, has called for a powerful data handling package. The package attached to the SHE comprises of two parts:

1) A pre-processor package:

This package produces maps of spatially distributed data and enables an automatic setup of input data for the SHE at a desired grid square scale. Digitized data such as contour lines from toposheets are transformed to average elevation values compatible with the chosen grid square size. Also soil and land use maps can be digitized, and codes attached to each type can be allocated to each grid square.

The river system can automatically be established from digitized information at selected points in the river system, where also cross-sectional data are provided. The programme package will interpolate between the points given and produce data in all river links.

2) A post-processor package

With this package, it is possible to retrieve, compile and present simulation inputs and outputs in a convenient form either as tables or as graphs. The graphics are based on the commercial UNIRAS colour graphics software.

A flow chart illustrating the file structure and the complete SHE programme package is shown in fig.2.

2.4 Studies Elsewhere Using SHE Model

The various application studies of the SHE have been carried out in 1) Great Britain ii) Denmark iii) New Zealand iv) Saudi-Arabia v) West Germany vi) Zimbabwe and vii) Thailand. The study carried out in Denmark deals with movement of nitrates in groundwater. In Thailand the effects of difforestation and soil erosion have been studied. The extract of one typical study carried out in Great Britain in summarized below.

Bathurst (1986) implemented SHE for an upland catchment in mid-Wales. The author used basic parameter values derived from field measurements or published data. An approximate calibration was achieved for one hydrograph by varying only a few of the parameters and was then validated against four different hydrographs, largely on the basis of changes in the initial level of phreatic surface. The author noted some deficiencies in the simulations, derived in part from the inability of the then existing version of the SHE to model sub surface flow in natural pipe networks and along interface between soil layers. In general, good agreement between observed and simulated responses in all parts of the catchment, the use of catchment parameters based firmly on field measurements and the ability to improve the simulations by physical reasoning is reported to indicate the considerable power of this type of modelling system.

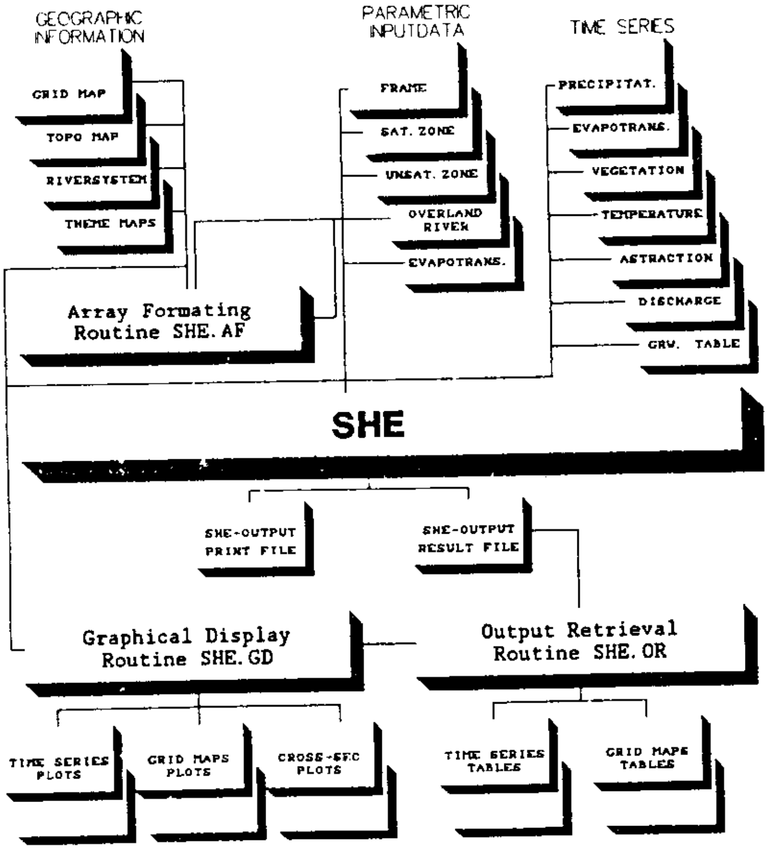


Fig. 2 Flow chart of the SHE Programme Package.

Bathurst (1986) studied the accuracy with which parameter sets for physically based distributed catchment models must be prepared and calibrated. The author carried out a sensitivity analysis of the SHE based on simulations of two streamflow hydrographs for the upland catchment in mid-Wales. A single parameter was varied at a time and for each hydrograph the simulation sensitivity was assessed quantitatively in terms of the changes in peak discharge and in the root mean square value of the differences between measured and simulated discharges taken at intervals through the hydrograph.

The author states that the results show that the simulations can be as sensitivite to model grid spacing and time step as to catchment parameters. The author further observed that catchment parameters to which the simulations are most sensitive (soil and flow resistance coefficients) can be evaluated with sufficient accuracy by point measurements at a few representative field sites, while the least important parameters (vegetation coefficients) can be evaluated using data from literature. The scope for achieving equally satisfactory calibrations based on different combinations of parameter values is reported to be limited; as long as several different hydrographs are considered. The spatial distributions in rainfall and soil parameters are stated to have a relatively minor effect on the simulations.

3.0 DESCRIPTION OF STUDY AREA AND DATA AVAILABILITY

In the present study, SHE has been applied to the Ganjal sub basin of Narmada basin. The salient features of Narmada river, Narmada basin and the Ganjal sub basin are described below:

3.1 Narmada River

The Narmada river as described in Report of the Irrigation Commission, Vol. III part I (1970) rises in the Amaranatak plateau of Maikala range in the Shahdol district of Madhya Pradesh at an elevation of 1058 m.a.s.l. The river travels a distance of 1312 km. before it falls into Gulf of Cambay in the Arabian Sea near Bharuch in Gujarat. The first 1079 km. are in Madhya Pradesh. In the next length of 35 km. the river forms the boundary between the states of Madhya Pradesh and Maharashtra. In the next length of 39 km., it fo rms the boundary between Maharashtra and Gujarat. The last length of 159 km. lies in Gujarat The index map of the basin is shown in fig. 3.

The river has a number of falls in its head reaches. At 8 km. from its source, the river drops 21 to 24 m. at Kapildhara falls, 0.4 km. further downstream, it drops by about 4.6 m at the Dudhara falls. Flowing generally in south westerly direction in a narrow and deep valley, the river takes pin head turns at places. Close to Jabalpur, 404 km from the source, the river drops nearly 15 m at the Dhaundharara falls, after which it flows through a narrow channel carved

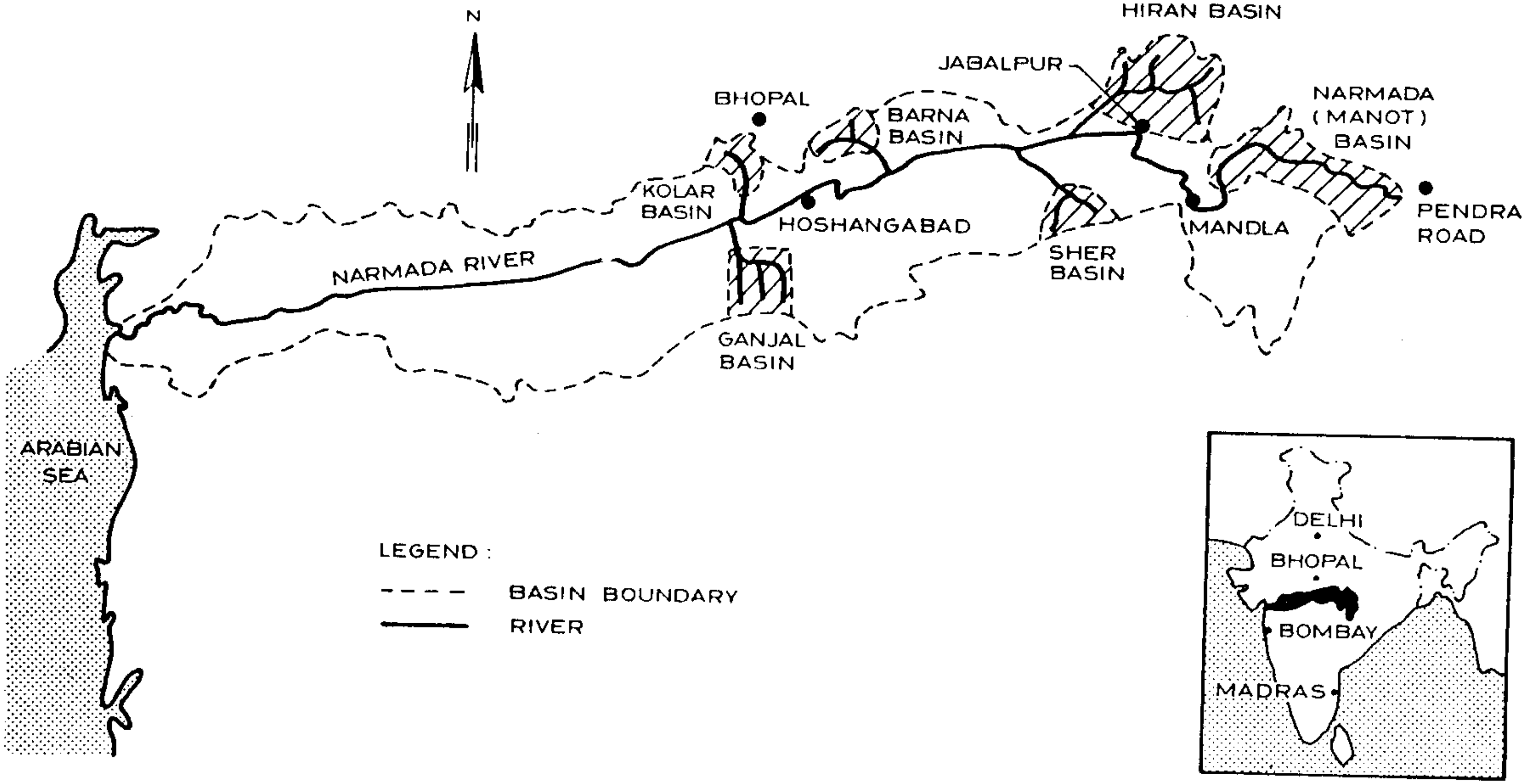


FIG. 3: Location of the Ganjal sub basin in Narmada basin.

through the famous marble rocks. After passing through the marble rocks, the Narmada enters the upper fertile plains, at Nandhar, 806 km from the fource and at Dhardi, 47 km further downstream, the river drops over falls of 12 m at each place. At 966 km. from source, nearly 6.4 km downstream of Maheshwar, the narmada again drops by about 6.7 m at the Sahasradhara falls.

Flowing further west, the river enters the lower hilly regions and flows through a gorge. The 113 km. long gorge is formed by the converging of the Vindhyas from the north and the Satpuras from the Sourth towards the river. Emerging from the gorge, the river enters the lower plains and meanders in broad curves till it falls into Gulf of Cambay in the Arabian sea near Broach.

The river has 41 tributaries of which 22 are on the left and 19 on the right, the important tributaries of the Narmada are the Burhner, Banjar, Sher, Tawa, Chhota Tawa, Kundi, Shakkar, Dudhi, Ganjal, Goi, Karjan, Hiran, Tendoni, Barna, Kolar, Man, Uri, Hatni and Orsang.

3.1.1 Ganjal River

The Ganjal rises in the Satpura range in the Betul district of Madhya Pradesh, north of Bhimpur village at an elevation of 800m at north latitude $22^{0}0$, and east longitude $77^{0}30'$ and flows for a total length of 89 km in a north westerly direction to join the Narmada from the left near Chhipaner village. The Ganjal drains a total area of 1,930 sq.km.

upto its confluence with Narmada. Morand is an important tributary of the Ganjal and it joins Ganjal near Chhidgaon.

3.2 Narmada Basin

The Narmada basin extends over an area of 98, 796 sq.km. and lies between latitudes $21^{0}20'$N to 23^{0} 45' N and longitudes 72^{0} 32'E to 81^{0} 45'E. The statewise distribution of the drainage area is as follows:

State	Drainage Area
Madhya Pradesh	85,859 sq.km.
Gujarat	11,399 sq.km.
Maharashtra	1,538 sq.km.

The basin is bounded on the North by the Vidhyas, on the east by the Maikala range, on the south by the Satpuras and on the west by the Arabian sea. Most of the basin is at an elevation of less than 500 m.a.s.l. A small area around Pachmarhi is at a height of more than 1000 m.a.s.l.

3.2.1 Climate

The climate of the basin is humid tropical ranging from sub humid in the east to semi-arid in the west with pockets of humid or sub-humid climates around hill reaches. The normal annual rainfall for the basin works out to 1,178 mm. South West monsoon is the principal rainy season accounting for nearly 90% of the annual rainfall. About 60% of the annual rainfall is received during July and August months.

3.2.2 Soils

The reconnaisance soil survey made by Central Water and Power Commission in connection with the Bargi, Punasa, Barna and Tawa projects indicated that the Narmada basin consists mainly of black soils. The different varieties are deep black soil, medium black soil and shallow black soil. In addition mixed red and black soil, red and yellow soil and skeletal soil are also observed in pockets; of these deep black soil covers the major portion of the basin.

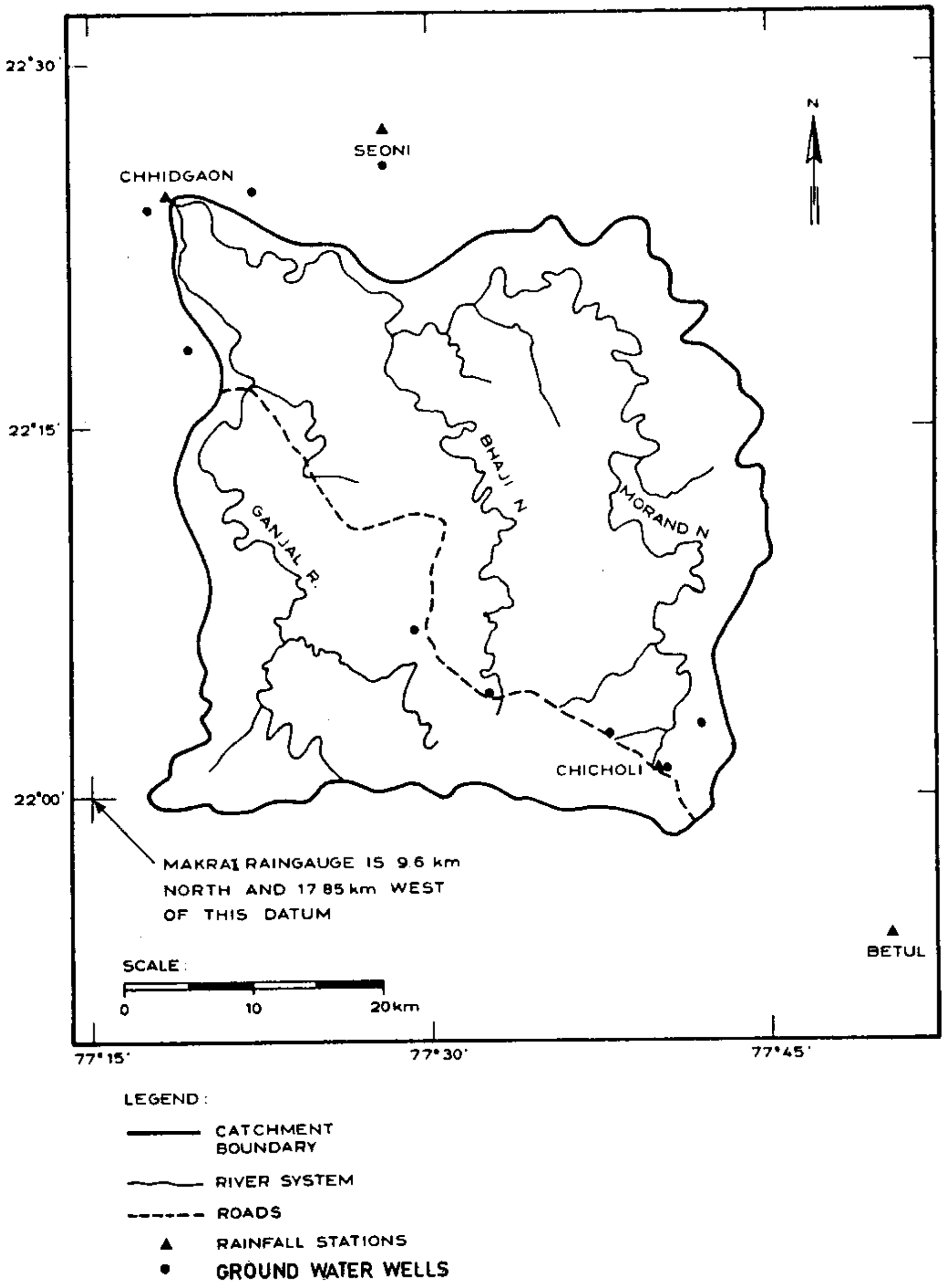
3.2.3 Land Use

About 32% of the area of the basin is under forest and about 60% under arable land and remaining under grassland, waste land etc.

3.3 General Description of Ganjal Sub Basin

The Ganjal sub basin lies between the lattitudes 21^{0} 58'N to 22^{0}25'N and longitudes 77^{0}17'E to 77^{0}45'E. The ganjal river rises in the Satpura range in the Betul district of Madhya Pradesh, north of Bhimpur at an elevation of 800m and flows 89km in a north westerly direction to join the Narmada near Chhipaner village. Its total catchment area is 1930 km^3 but model simulations in the present study have been limited to the approximately 72 km length of channel and 1719 km^2, basin defined by the Central Water Commission gauging station at Chhidgaon. The entire sub basin forms part of two districts Hoshangabad and Betul. The sub basin area upto Chhidgaon is 1729 km^2 but a small part of at southern boundary has been ignored for convenience in digitizing the sub basin. Within the sub basin the Ganjal (at 72 km^2) is shorter, than the Morand tributary which joins the Ganjal just above Chhidgaon and has a length of about 121 km. At present the Ganjal sub basin is not subject to any major development. Location of the Ganjal subbasin is shown in fig. 4.

Topogaraphically, the Ganjal sub basin can be divided into three distinct zones i) low land ii) hill slopes and iii) upland. The part of the sub basin having elevation less than 400m above mean sea level can be considered as low land. Hill slopes are characterized by elevation ranging from 400m to 550m and the part of sub basin having elevation more than 550m can be regarded as upland.About 63% area of the sub basin is covered by dense forest, 12% by agriculture, 19% by waste land and 6% by open forest. In the down stream reach of the river agricultural activity is carried out. Above this agricultural zone open forest is the predominant landuse. Apart from this most of the basin is covered by dense forest and waste land. There are three main types of soils in the sub basin viz. medium black, laterite and shallow black. Shallow black soil lies in the lower reach and the upstream area of the basin. Most of the sub basin is covered by medium black soil.



MAKRAI RAINGAUGE IS 9.6 km NORTH AND 17.85 km WEST OF THIS DATUM

FIG. 4: Map of the Ganjal sub basin.

3.4 Data Availability

The distributed and physically based nature of SHE requires that in each application study, a vast amount of data and parameters describing the physical characteristics of the catchment are available. The present chapter explains the status of data available with various organisatons/departments, and its procurement from these data sources.

3.4.1 General

A data assembly programme was carried out to provide the hydrometeorological data and basin parameters needed to support SHE simulations. In view of data being available with several agencies, both belonging to Government of India and to the State of Madhya Pradesh, which had to be approached, a coordinated effort was set up. A formal letter was sent from NIH to the Control board for Major Projects, Irrigation Department Madhya Pradesh in December 1987, asking for the necessary data and requesting the secretary to the Control board to act as liasion agency on behalf of NIH with the agencies concerned. The data assembly programme was then launched following a meeting in Bhopal on 31st December 1987 between the agencies, including NIH. Different data possessing agencies were contacted during the visits to Madhya Pradesh. Lengthy records of data were copied by hand, as photocopying was not feasible. Various agencies contacted and who have taken a lot of pains to provide relevant data and information to NIH include:

1. M.P. Irrigation Department
   - a) Director, Hydrometeorology
   - b) Upper Narmada Circle
   - c) Superintending Geologist
   - d) Various concerned circles, Divisions and sub-divisions
2. Narmada Valley Development Authority
   - a) Superintending Engineer, Circle 2
   - b) Joint Director (Agriculture)
3. Central Water Commission
4. J.N.K.V.V. Agricultural University, Jabalpur
5. India Meteorological Department, Delhi and its Offices in Pune, Nagpur and Bhopal
6. Central Ground Water Board - North Central Region
7. Survey of India, Dehradun
8. Narmada Control Authority, Delhi and Bhopal
9. All India Soil and Landuse Survey Organisation, New Delhi and Nagpur
10. Director, Department of Agriculture, Bhopal and Zonal Agricultural Research Stations at Powarkheda, Khandwa and Adhartal
11. M.P. Groundwater survey board, Bhopal and its other offices
12. State Forest Research Institute, Jabalpur
13. College of Agriculture, Indore
14. Institute of Decidiuous forest, Jabalpur

15. Offices of Statistics and Land Record in the concerned districts.

3.4.2 Rainfall and Evaporation Data

Daily rainfall data of four ordinary raingauge stations viz. Chhicholi, Chhidgaon, Seoni and Makrai have been used in carrying out simulation studies for Ganjal sub basin. The hourly rainfall data of only Betul self recording raingauge was available for converting the daily rainfall data of the above mentioned raingauges. Ordinary raingauge data were collected from the offices of Director hydrometeorology, revenue departments (statistical and land record wing) of Betul and Hoshangabad and Narmada Control Authority, Bhopal. Data of self recording raingauge were collected from the office of Regional Centre, India Meteorological Department Nagpur and Narmada Control Authority, Bhopal. The location of raingauge stations is shown in fig. 4. Chicholi raingauge lies in the South east part of the basin, Chhidgaon raingauge is located just at the outlet of the basin, Seoni lies outside the basin towards north and Makrai raingauge is located outside the basin towards south west. The self recording raingauge i.e. Betul also lies outside the basin towards south east. The Thiessen weights of the four raingauges stations namely Chicholi, Chhidgaon, Seoni and Makrai are 51%, 17.7%, 23.7% and 7.6% respectively.

Pan evaporation data of Powarkheda, Betul, Jabalpur and Pendra Road pan evaporimeters were available. All the four pan evaporation measurement stations lie outside the basin. The daily data for Jabalpur, Pendra Road and Betul pan evaporimeters were available; where as for Powarkheda monthly pan evaporation data from June 1980 to Dec. 1982 and weekly data from 1983 to 1987 were available.

3.4.3 Runoff Data

There is only one stage-discharge measurement site in the basin located at Chhidgaon. It is maintained by Central Water Commission. Daily stage-discharge data for the period June 1978 to May 1988 and hourly stage data for monsoon seasons (June to October) for the period June 1978 to October 1987 were collected.

Channel cross-section at Chhidgaon for the period 1977-1987 and rating curves, prepared by CWC for the gauging site over the period 1977-1987 (monsoon season) were also obtained. However, these rating curves did not cover the range of stages observed in either of the years.

3.4.4 Soil and Land use Data

The maps showing the soil types and landuse pattern of the Basin were obtained from agricultural Directorate of Narmada Valley Development Authority. These maps are based on LANDSAT TM FCC (1986) with limited field check.

3.4.5 Groundwater Data

The groundwater well observation for 9 wells from Hoshangabad and Betul districts, comprising the sub basin were collected. Some of these wells lie outside the sub basin or near the basin boundary. The observations are available two times a year i.e. before and after monsoons 1978 to 1988.

But observations of all the wells in each year are not available. Locations of these wells are shown in fig. 4.

3.4.6 Topographic Data

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

a) Scale: 1:250,000

i) 55F ii) 55G

b) Scale: 1:50,000

i) 55F/7, ii) 55F/8, iii) 55F/11, iv) 55F/12

v) 55G/5, vi) 55G/9

3.4.7 Other Data/Information/Literature

Besides the above mentioned data, a number of reports covering the information about Ganjal sub basin and its soil, irrigation, ground water etc. were also collected. Some of these have been prepared by M.P. Irrigation Deptt., State Ground Water Survey Deptt. (M.P.), G.S.I., Nagpur, Zonal Agricultural Research Station Powarkheda, Assistant Geologist Hoshangbad and Betul.

The status of data availability for this study is summarised in table 2.

Table: 2 **Data availability for the Ganjal** sub basin

DATA TYPE	DATA AVAILABILITY
Rainfall	<u>DAILY</u> Chicholi : 1980-88 Chhidgaon : 1980-88 Seoni Malwa*: 1978-88 Makrai* : 1978-79, 1982-88 (data for 1980-81 not available) <u>HOURLY</u> Betul* : 1978-87 (except July 1979 which is not available) * Station lies outside the basin
Discharge	Chhidgaon (outlet) - daily gauged discharge June 1978-May 1988; hourly stage record for monsoons June 1978-October 1987
Evapotranspiration	Powerkheda (outside the basin near Hoshangabad) - monthly pan evaporation data June 1980-December 1982; weekly 1983-1987; daily October-November 1987, January-December 1988
Well observations	Observations for 9 wells from Hoshangabad and Betul districts in or near basin, two times per year - before and after monsoons 1978-88, but not all wells in each year
Channel cross-section	Chhidgaon : 1977-87
Rating curve	Chhidgaon : monsoons 1977-87

4.0 DATA PROCESSING AND PREPARATION

SHE is a physically based and distributed model where all the major components of the hydrological cycle are being modelled separately, using governing differential equations. Hence, information about a large number of variables is needed for a successful model application. Data processing and preparation of various types of collected data mentioned in Section 3, for carrying out the present study are described below:

4.1 Topography

The toposheets obtained from Survey of India in the scale 1:50,000 were used for digitizing the catchment boundary, rivers and contours. The contour interval in these toposheets is 20 m. The boundary of catchment was digitized by 690 points. Digitization of contours involved a considerable effort and 84,500 points had to be digitized to cover the Ganjal sub basin in the elevation range of 305 m to 800 m. Fig. 5 shows the digitized contours defining the topography of the sub basin. The elevations for each node of the grids may be estimated using an interpolation software. The interpolated nodal elevation values were used to draw grid network for square grids of different sizes which are integer multiple of 500 m x 500 m grid size. The mean elevation for each of the grids was computed as average value of the nodal elevation values. Figs. 6,7 and 8 show the topographic grid maps of the sub basin in the grid sizes of 0.5 km x 0.5 km, 1 km x 1 km and 2 km x 2 km.

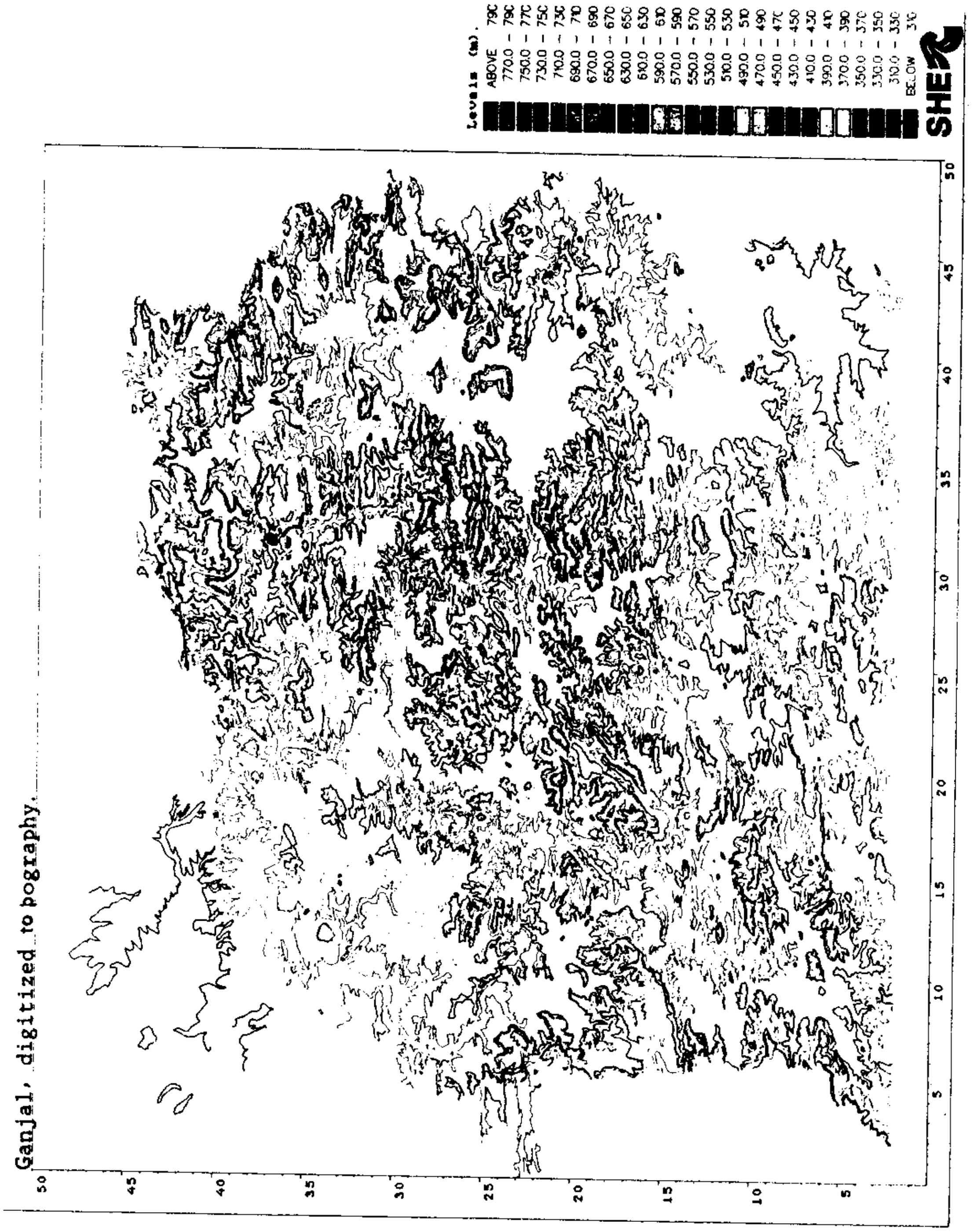


FIG. 5: Digitized contours of the Ganjal sub -basin

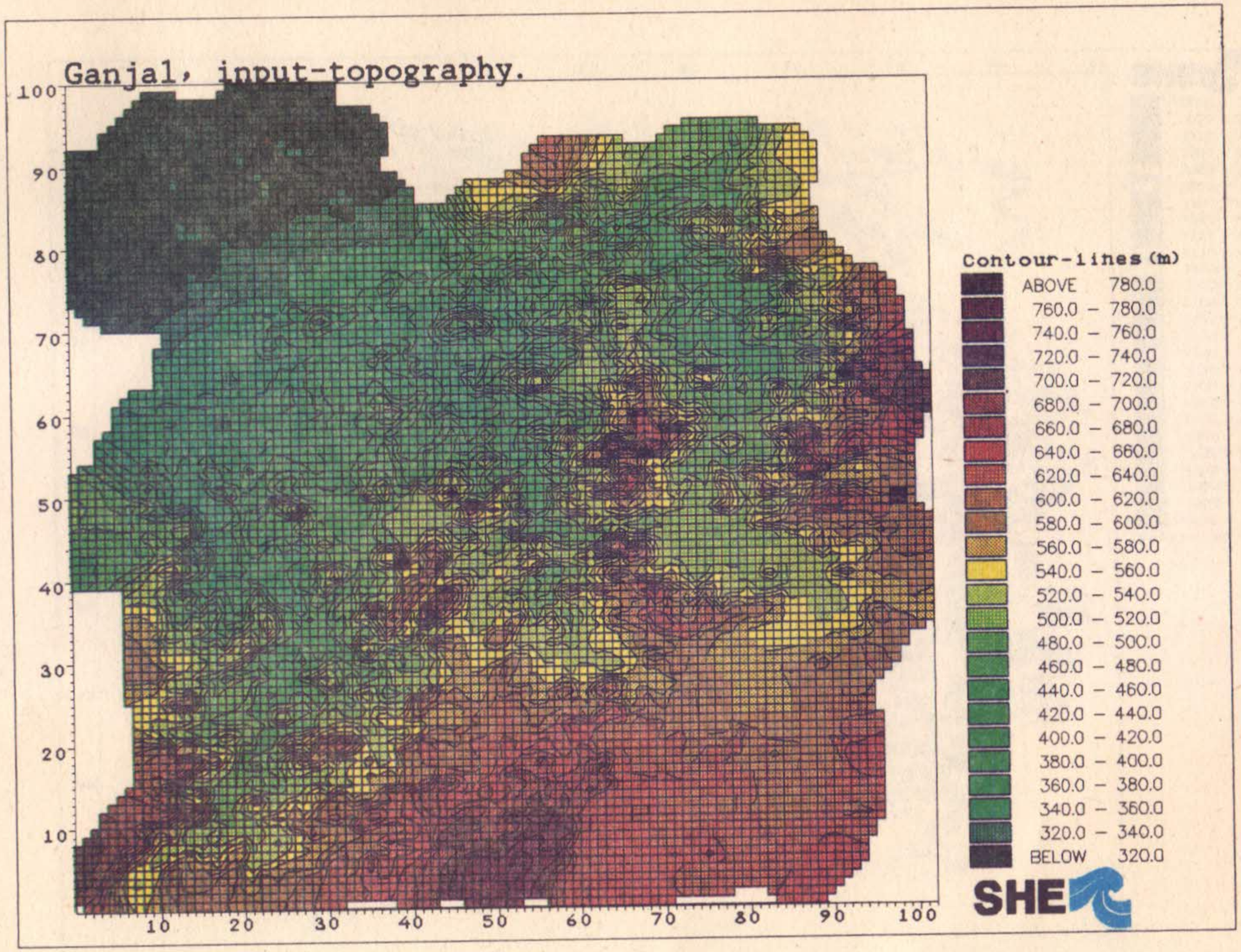


Fig. 6: Topography of the Ganjal sub basin in 0.5 x 0.5 km gridsize.

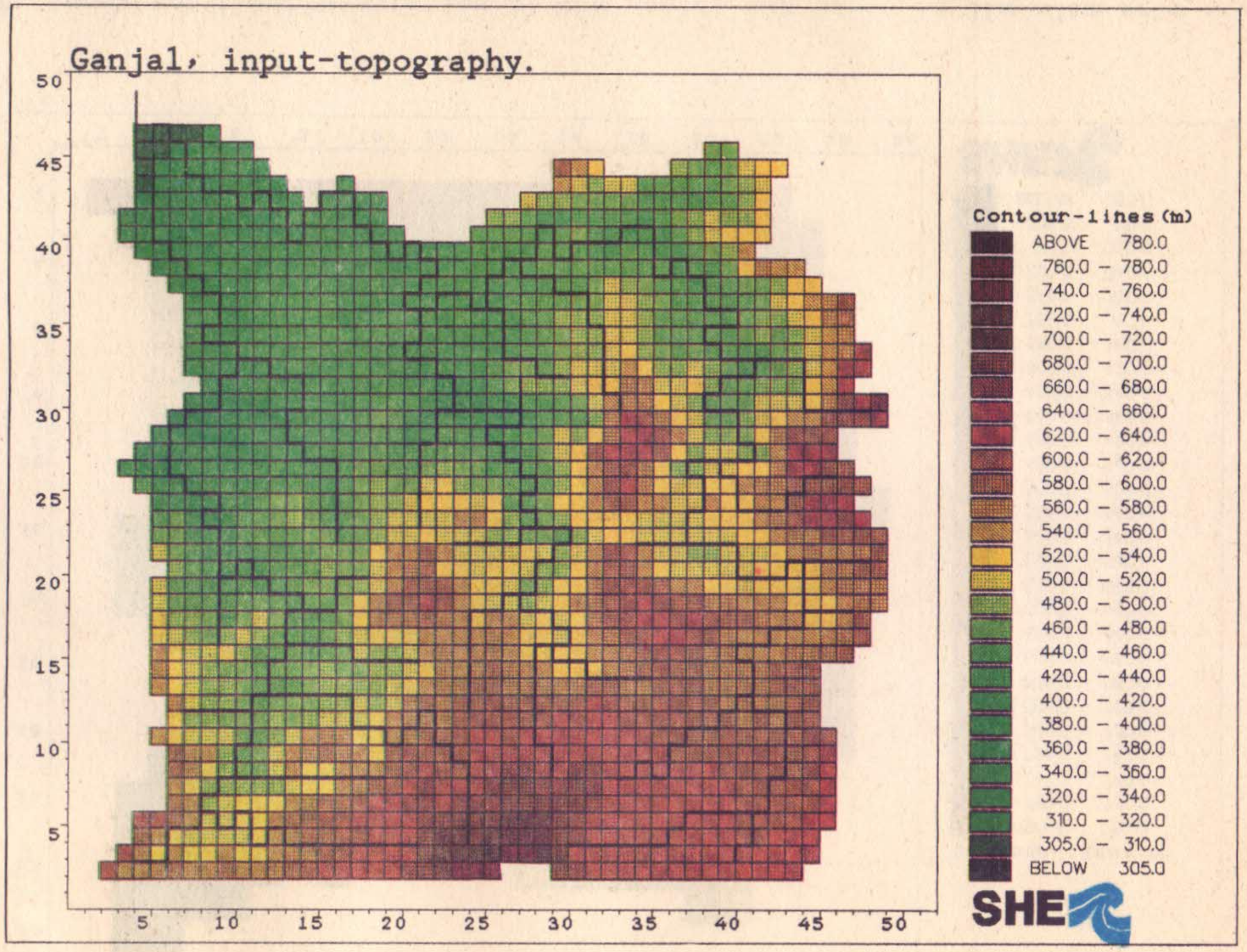


Fig. 7: Topographic representation of the Ganjal sub basin in 1km x 1km grid size.

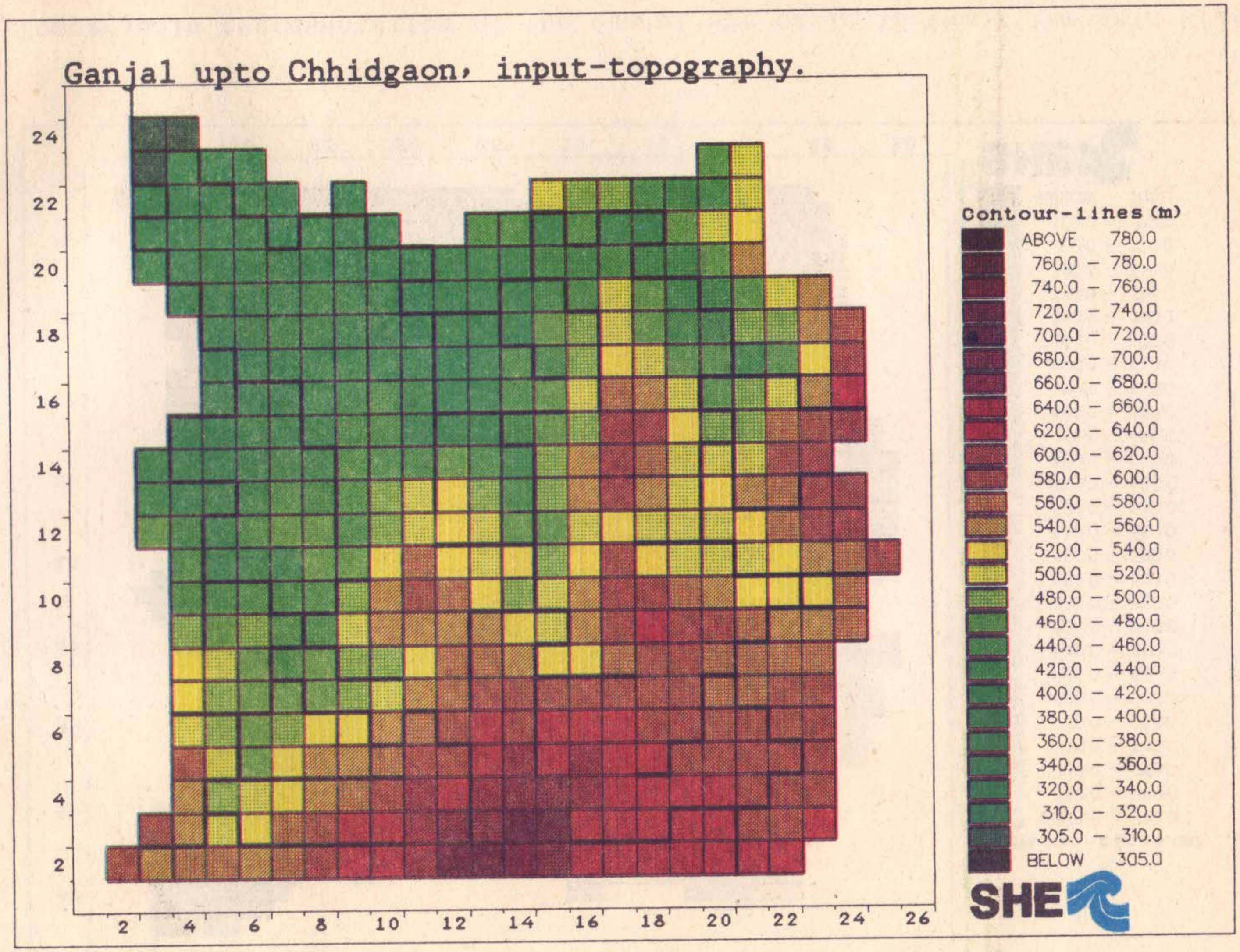


Fig. 8: Topographic representation of the Ganjal sub basin in 2km x2km grid size.

4.2 River System Data

The processing of river system data is described below:

4.2.1 River Network

For representing the river network of the basin, rivers of first order, second order and some of the rivers of third and fourth order were digitized. An effort was made to represent the riaver system of the catchment in a reasonably adequate manner. The river system for the Ganjal sub basin was represented by 25 rivers.

4.2.2 River Cross Section Data

The river cross sections for all the rivers representing the sub basin at their upstream and downstream locations were required for carrying out the present study. For the Ganjal sub basin one cross section at the gauging site at Chhidgaon was available. In order to deal with this, an approach suggested by the consultant was followed. In this regard, use was made of some rough surveys made during the consultant's visit to the Hiran basin. The channel dimensions at various distances along the main stem were obtained. It was assumed that the channel dimensions vary with the upstream drainage area and empirical dependencies were established to enable the dimensions to be calculated at all parats of the river system. In this case, drainage area was considered to be inconvenient parameter to measure. A more convenient parameter to measure was upstream channel length, since it also varies closely with upstream with upstream drainage area as shown in Fig. 9(a), it was used as the basis for calculating channel dimensions. The Hiran data were therefore used to produce the empirical relationships shown in Fig. 9, giving bankful depth d, bankful (or top) width W_t , and bed width W_b as functions of upstream channel length L, measured on a 1:250,000 scale map. These relationships were used to define the channel dimensions at all parts of the Hiran river system as defined for the SHE. Since river lengths represented on the SHE grid system tend to be slightly larger than the map lengths, the relationships between the two lengths was also derived based on a 2 km SHE grid (Fig. 9 b). These relationships were tested for the Ganjal sub basin and were found to be applying reasonably well (Fig. 9). In most of the cases the data points of the Ganjal sub basin lie within the scatter of the Hiran data. Therefore, the relationships were adopted for the Ganjal sub basin.

4.2.3 Overland and Channel Flow Roughness

Due to lack of information on the variation of surface roughness characteristics, the Strickler roughness coefficient for overland and channel flow were assumed to be spatially uniform in the sub basin.

On the basis of experience gained during field visits and review of relevant literature, a rough estimate of the Strickler roughness coefficient for overland flow was made. A value of 2 $m^{1/3}/S$ was used as an initial best

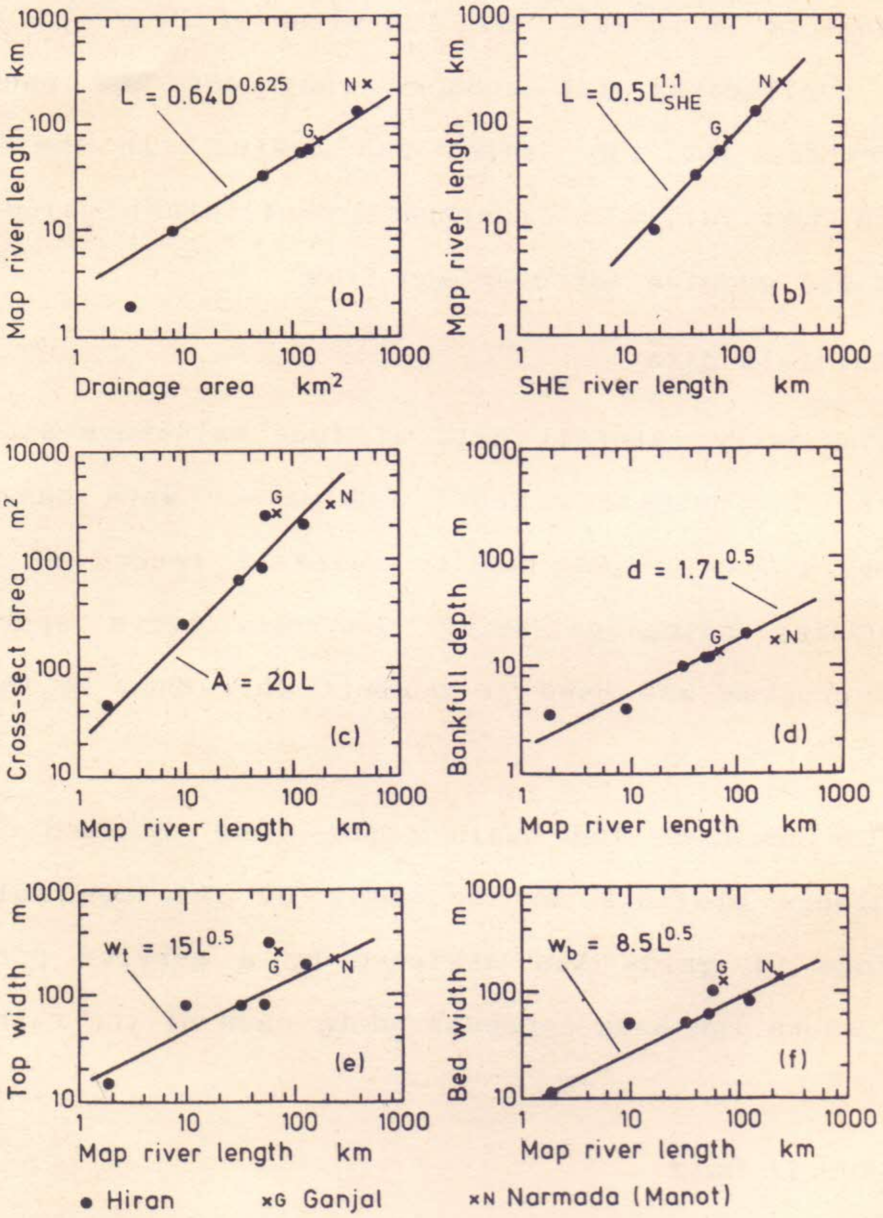


Fig.9: Channel dimensional relationship based on data for Hiran sub basin.

estimate for the Striackler roughness coefficient for overland flow. For the channel flow, sample calculations using measured flow and cross-sectional data gave Strickler co-efficients ;in the range of 18 to $22^{1/3}/S$. The value of 20 $m^{1/3}/S$ as Strickler coefficient for channel roughness was used in the calibration for the Ganjal sub basin. In the final calibration run Strickler roughness coefficient value of 1.5 $m^{1/3}/S$ was adopted for overland flow.

4.3 Rainfall Data

The daily rainfall data of four raingauge stations viz. Chicholi, Chhidgaon, Seoni and makrai were converted into hourly values, using hourly rainfall record of Betul self recording raingauge , using the mass curve approach. A service program was used to convert this data in the SHE format.

The area of the basin represented by each of the four raingauge stations on the basis of Thiessen polygons in the form of grids was assigned by a service program. Figure 10 shows the area represented by each of the raingauge stations.

4.4 Runoff Data

For the outlet discharge data, hourly discharge values were obtained from the measured stage values for each monsoon period. The rating curves had to be extrapolated. The accuracy of extrapolation was tested using the independent calculations of velocity based on the Manning/Strickler

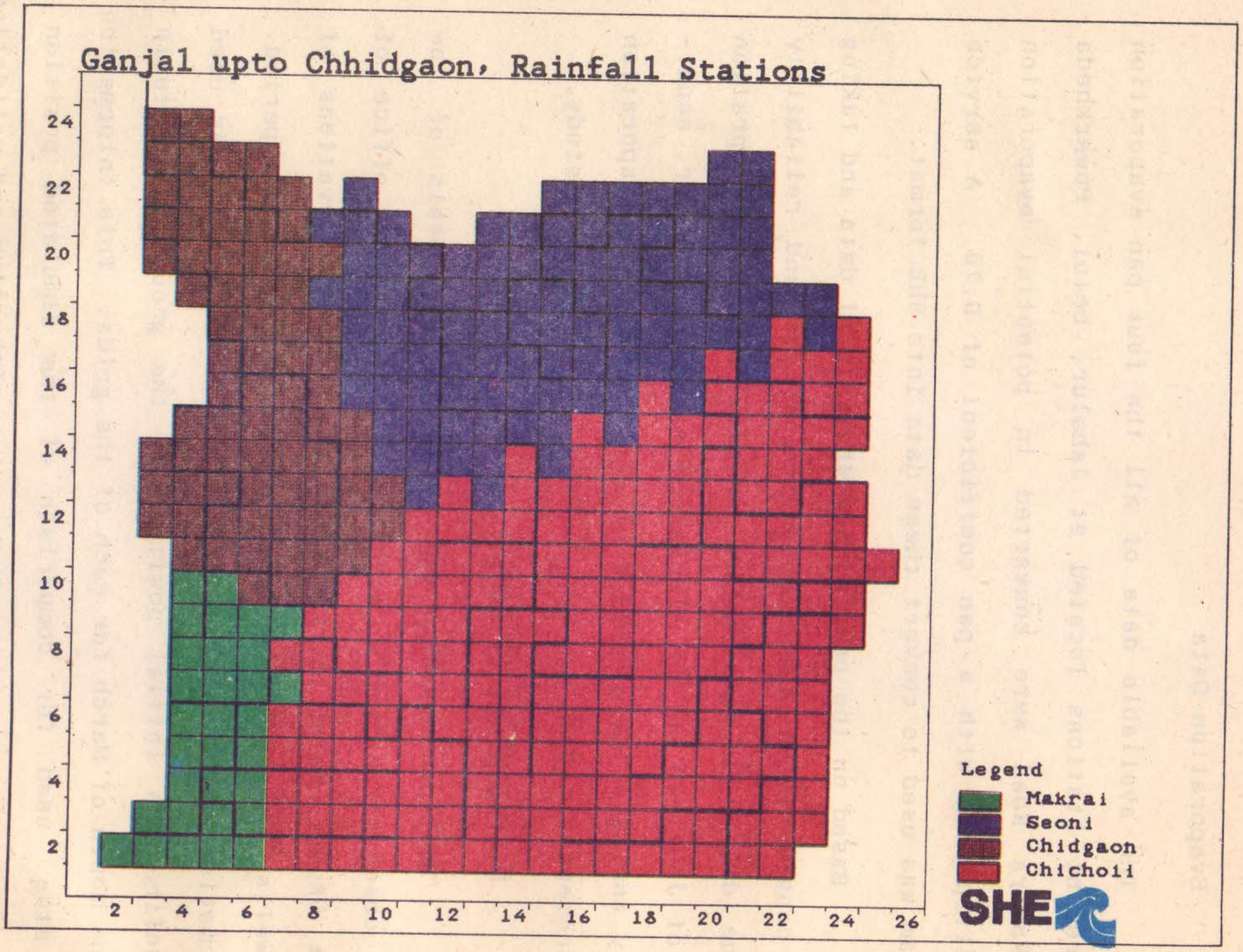


Fig. 10: Area of the Ganjal sub basin represented by the Raingauge stations.

equation and was found to be reasonably adequate.

4.5 Evaporation Data

The available data of all the four pan evaporation measurement stations located at Jabalur, betul, Powerkheda and Pendra Road were converted in potential evaporation by multiplying with a pan coefficient of 0.70. A service program was used to convert these data into SHE format.

Based on the preliminary analysis of data and taking into consideration the maintenance of pan and reliability of the data; it was decided to use potential evapration data of Jabalpur in the simulation studies. However, sensitivity analysis for the data of all the four pan evaporation measurement stations was carried out in the present study.

4.6 Hydrogeological Data

The pre-monsoon and post monsoon levels of the nine observation wells were obtained from the office of state Ground Water Survey, Bhopal. The observations of the wells were available over the varying length of the period. Information gathered from these observation wells was used to define the initial position of the ground water table in the month of March for each of the grids. This information was also used for comparison of the simulated position of the ground water table during the calibration and validation period.

In the absence of any information, the ground water table was assumed to vary with the depth of soil in turn on topographic elevation of the sub basin. Information about the conductivity of unsaturated and saturated zones

was also not available. Hence, the saturated conductivities of unsaturated **zone and** saturated zone were assumed to be spatially uniform.

4.7 Soil Data

The maps obtained from the Agricultural Directorate of Narmada Valley Develpment Authority describing the soil types and landuse of the sub basin were digitized in order to assign soil type and landuse pattern to each of the grids. The Ganjal sub basin was classified into three soil types. The three soil types i) shallow black ii) medium black and iii) Laterite were adopted for defining the soil type under each of the grid in 1 km x 1 km and 2 km x 2 km sizes. If a particular grid had more than one type of soil then the type of soil which had more area under it, was taken to be representative, for that particular grid. The soil map for 2 km x 2 km grid size is shown in fig. 11. However, the soil properties for these different types of soils were not available. Hence, the simulation study was carried out assuming only one type of soil over the entire sub basin. The depth of soil in various grids was assumed to vary with topographic elevation.

The physical properties of soils in the Ganjal sub basin were not directly available. These properties had

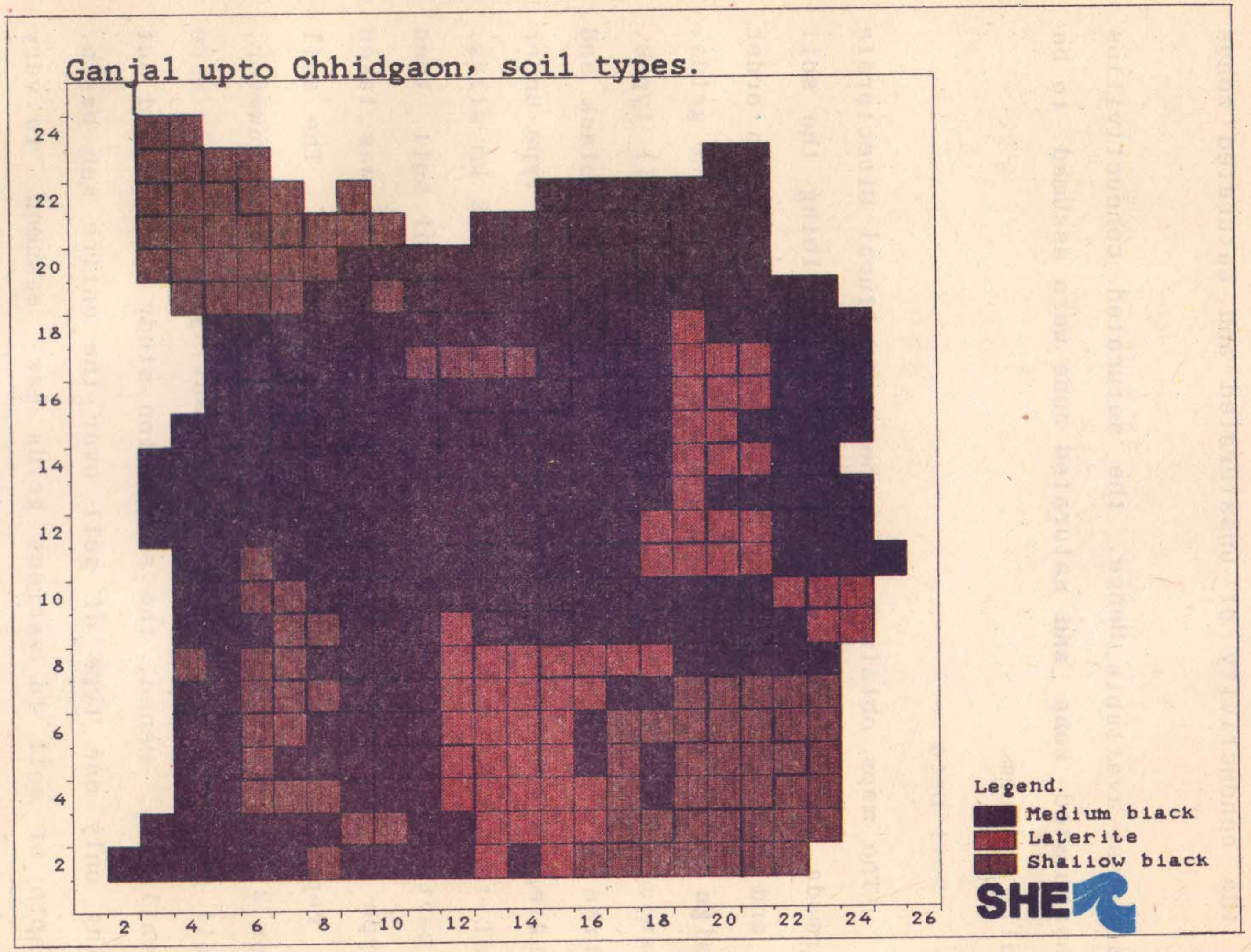


Fig. 11: Soil map of the Ganjal sub basin in 2km x 2km grid size.

to be derived from secondary sources (Kauraw et al. 1983 and Versey et.al. 1982). The soil moisture retention curve used in the earlier simulation study for Kolar basin was adopted for the present study. This retention curve is based upon data from Indian Council for Agricultural Research (ICAR, 1989). The curve is shown in fig. 12.

4.8 Vegetation Data

The landuse pattern for the Ganjal sub basin was covered by i) Agricultural ii) closed forest iii) medium forest iv) scrubland and v) eroded land as per NVDA classification. The scrub land and eroded land were assumed to be lying under one category of waste land as the distinct properties of these two landuses were not available. Thus, the resulting four types of landuses were further sub divided into i) low land (less than 400m above msl) ii) semihilly (400 m to 550 m above msl) and iii) hilly (more than 550 m above msl) on the basis of topographic elevation. Thus the landuse of the basin was characterised by 12 types of the vegetation.

Fig. 13 shows landuse map for the sub basin in 2 km x 2 km grid size. The information about the properties of the different landuses under topographic variation was not available and computatinal requirements under twelve types of land uses had significantly increased. So, it was decided to carryout the simulation study on the basis of the four basic types of landuses, mentioned above.

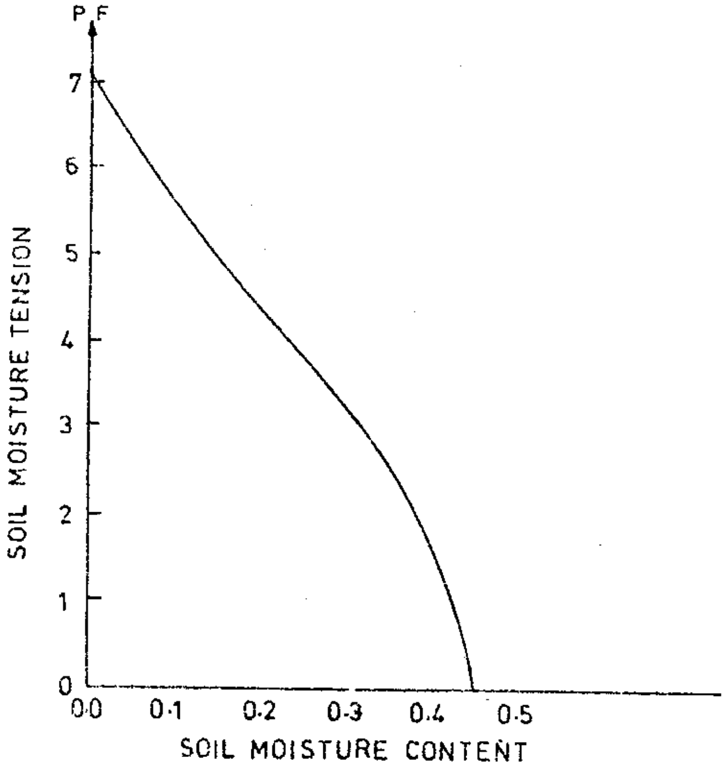


Fig. 12 : Soil moisture retention curve used for all soil types in the simulations. Based on data from ICAR

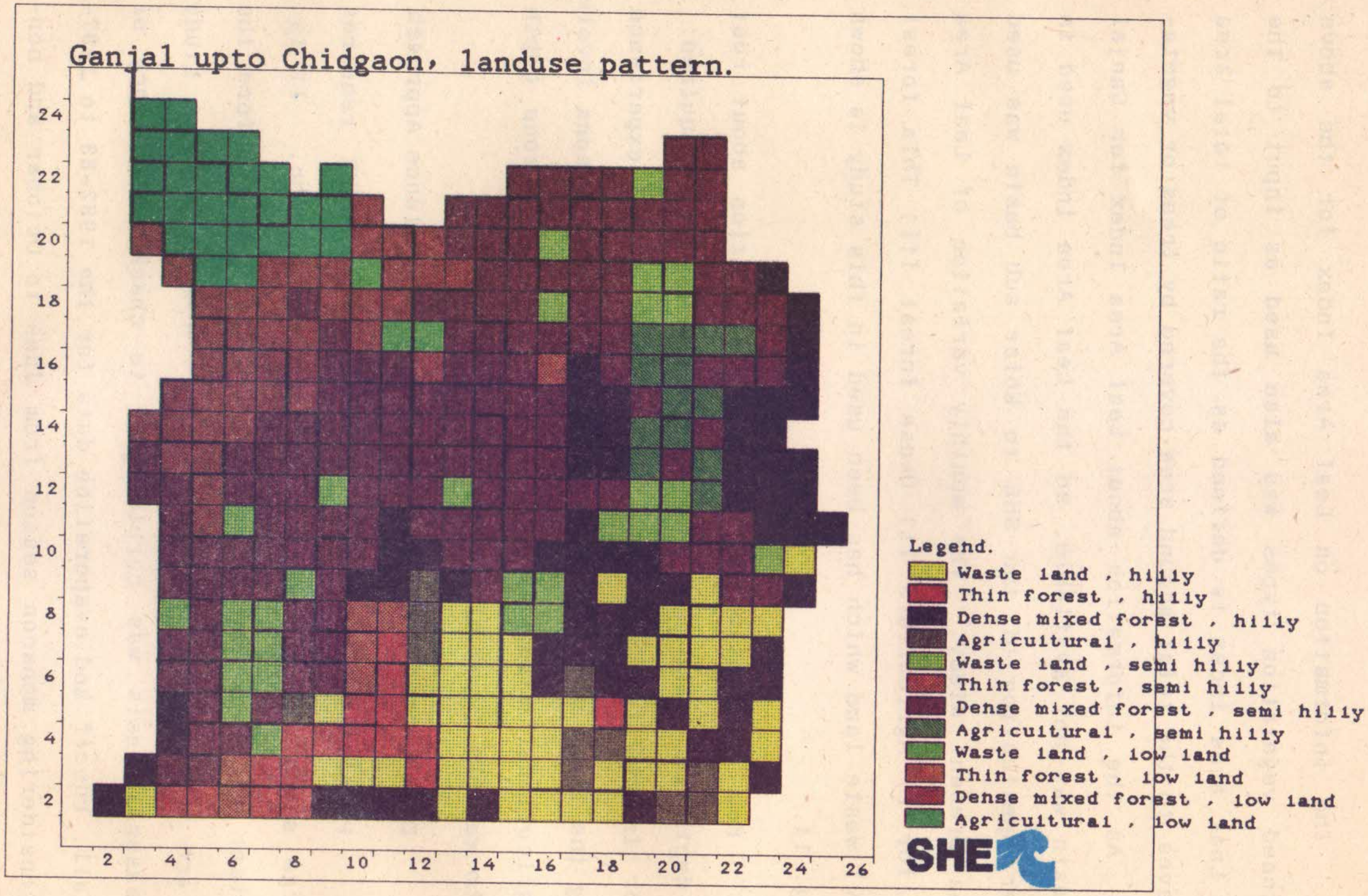


Fig. 13: Landuse pattern of the Ganjal sub basin in 2km x2km Grid size.

The information on Leaf Area Index for the above mentioned vegetation types was also used as input to the SHE. Leaf area index is defined as the ratio of total area of leaves to the total ground area covered by trees or vegetation. As the information about Leaf Area Index for Ganjal sub basin was not available, so the Leaf Area index used in earlier application of the SHE to Kolar sub basin was used in the present study. The monthly variation of Leaf Area Index for i) Agriculture ii) Dense forest iii) Thin forest and iv) waste land which has been used in this study is shown in fig. 14.

For application of the SHE, information about root zone depth for each type of vegetation is also required. As per information available in the literature, experience during the field visits and discussions with the persons involved in agricultural studies/research area, the root zone depth for the various types of vegetation was finalised.

4.9 Data Consistency Check - Using Water Balance Approach

Physically based, distributed model, SHE requires a large amount of input data for its application. It is improtant to check the consistency of field data before the same are used in the modelling study. A water balance study on seasonal basis was carried out to check consistency of rainfall, runoff and evaporation data for the 1982-83 to 1987-88, considering monsoon season from June to October and non-monsoon season from November to May. The details of study

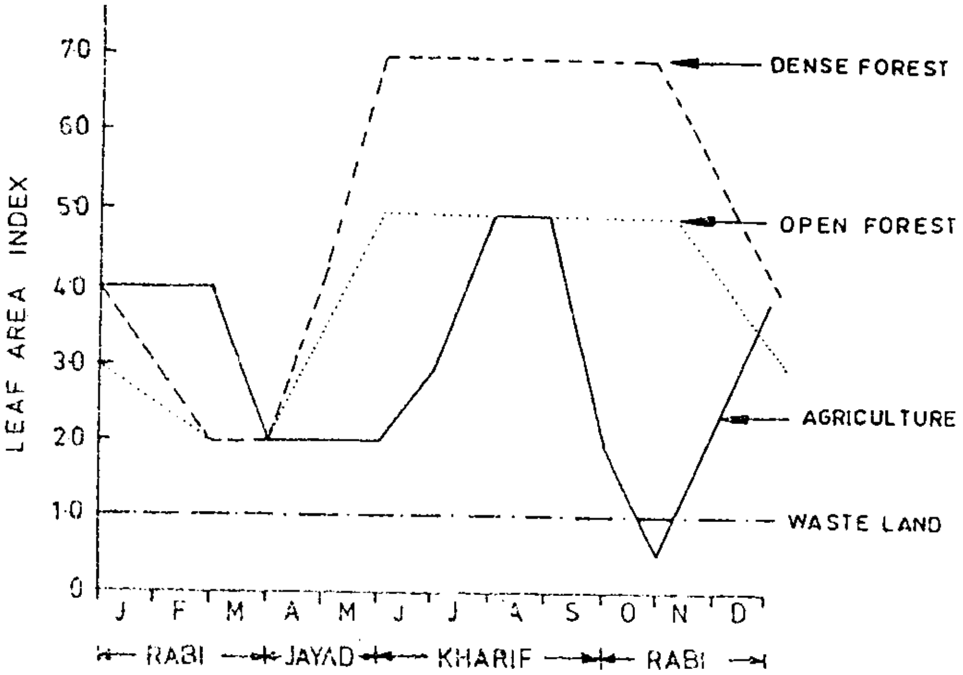


Fig. 14: Time variation of leaf area index for four landuse types used in the simulation.

are given below:

a) Runoff coefficients for monsoon seasons were computed and plot was made between monsoon season rainfall and runoff, to study its pattern. Fig. 15 shows rainfall-runoff relationship for monsoon season.

b) Relation between non-monsoon runoff (after subtracting baseflow) and non-monsoon rainfall was examined. Non monsoon runoff due to rainfall was estimated as:

$$Q_{nmR} = Q_{nm} - Q_{Bm}$$

where, Q_{nmR} = non-monsoon runoff due to non monsoon rainfall

Q_{nm} = non-monsoon runoff including baseflow

Q_{Bm} = non-monsoon baseflow

Fig. 16 shows variation of non-monsoon runoff with non-monsoon rainfall.

c) Variation of non-monsoon baseflow in non-monsoon season with estimated groundwater recharge (R_1) for monsoon season was studied. Non-monsoon baseflow was estimated from the observed discharge data. Monsoon groundwater recharge (R_1) was estimated assuming actual evapotranspiration as 70% of potential evapotranspiration, as follows:

$$R_1 = P_m - Q_m - 0.7PE_m$$

where,

R_1 = groundwater recharge during monsoon season

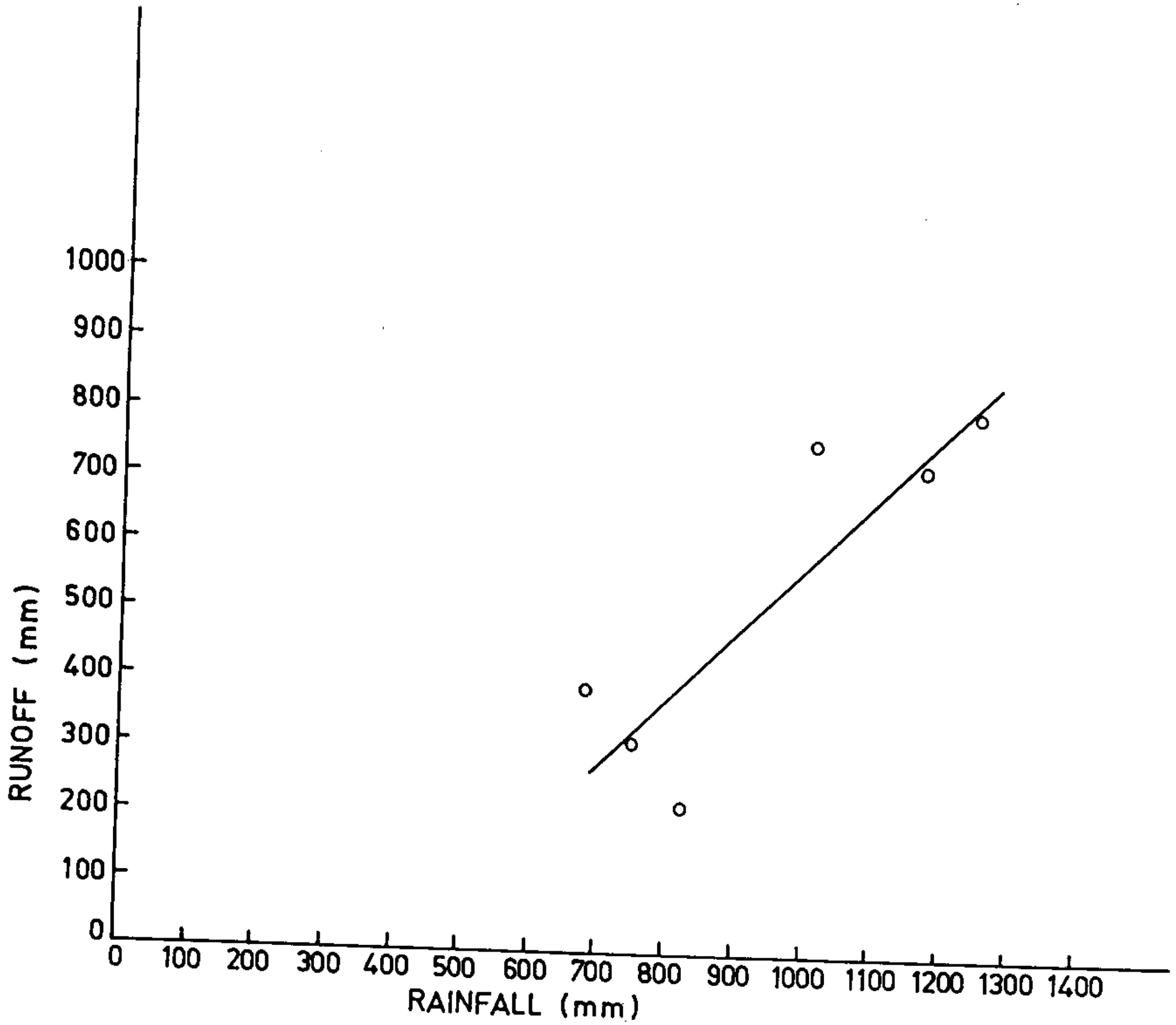


FIG. 15-RAINFALL RUNOFF RELATIONSHIP FOR MONSOON SEASON

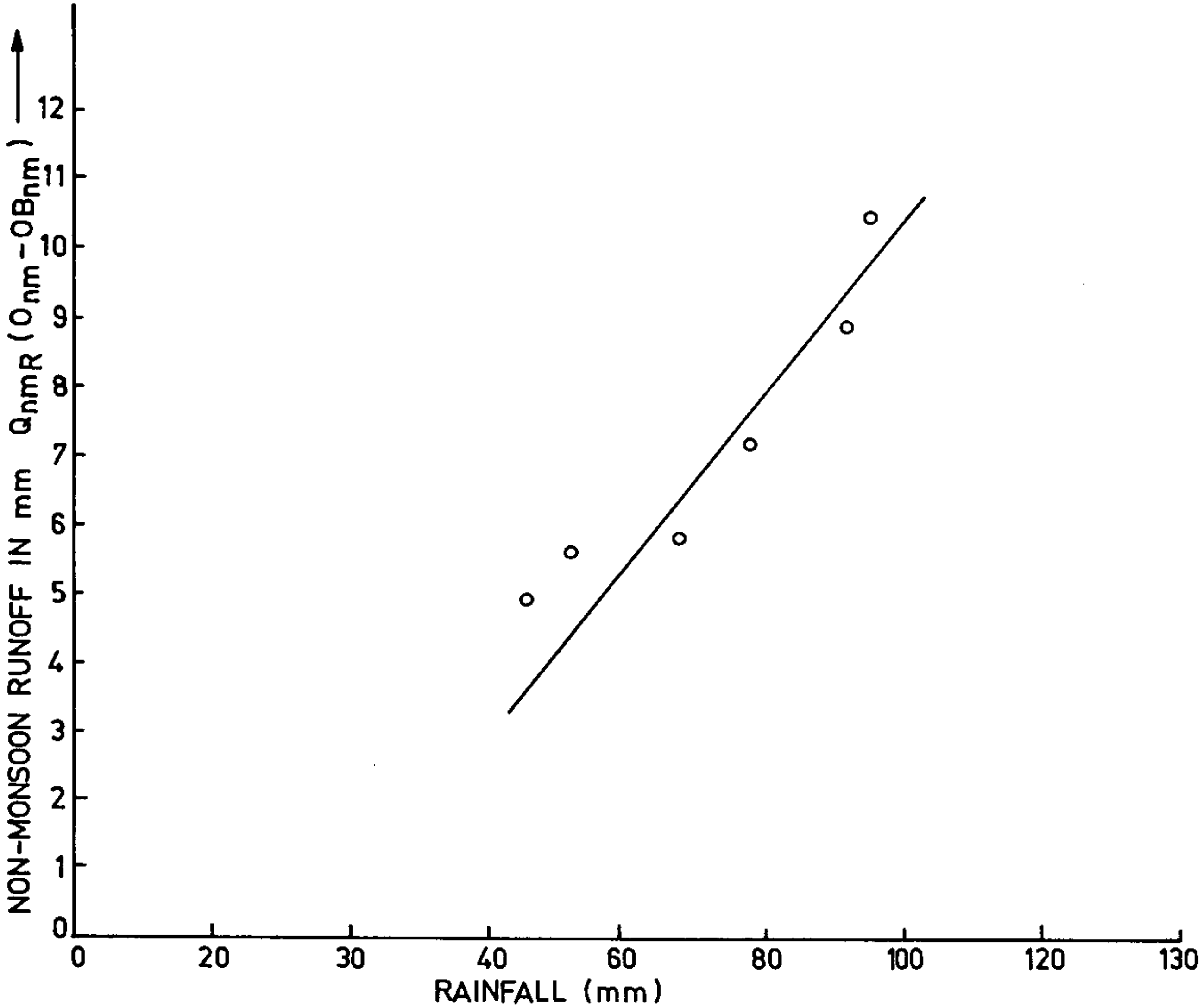


FIG. 16 - RAINFALL RUNOFF RELATIONSHIP FOR NON-MONSOON SEASON.

P_m = average rainfall during monsoon season

Q_m = average runoff during monsoon season

PE_m= potential evapotranspiration during monsoon season

Fig. 17 shows variation of non-monsoon baseflow with monsoon groundwater recharge (R_1)

d) Variation of non-monsoon baseflow with monsoon groundwater recharge (R_2) was also studied. Here, monsoon groundwater recharge (R_2) was assumed to be 12% of monsoon rainfalll $(R_2=0.12\ Pm)$. Fig. 18 shows variation of non-monsoon baseflow with groundwater recharge during monsoon season.

The rainfall runoff relationships for monsoon and non-monsoon seasons as well as pattern of variation of non-monsoon baseflow with monsoon recharge show that the data for the years 1982-83 to 1987-88 are reasonably consistent. Table 3 summarises the details about the above mentioned water balance study.

4.10 Model Setup for Ganjal Sub Basin

As mentioned in section 4.1, using the digitized topographic data, computational grids were initially set up in 500m x 500m size. The computational requirements for this size of grids were enormous and it was not possible to achieve the simulation results in the stipulated period. Hence, it was decided to set up the model for grid sizes of 1 km x 1 km, 2 km x 2 km for and 4 km x 4 km. The present study has been carried out using grid size of 2 km x 2 km.

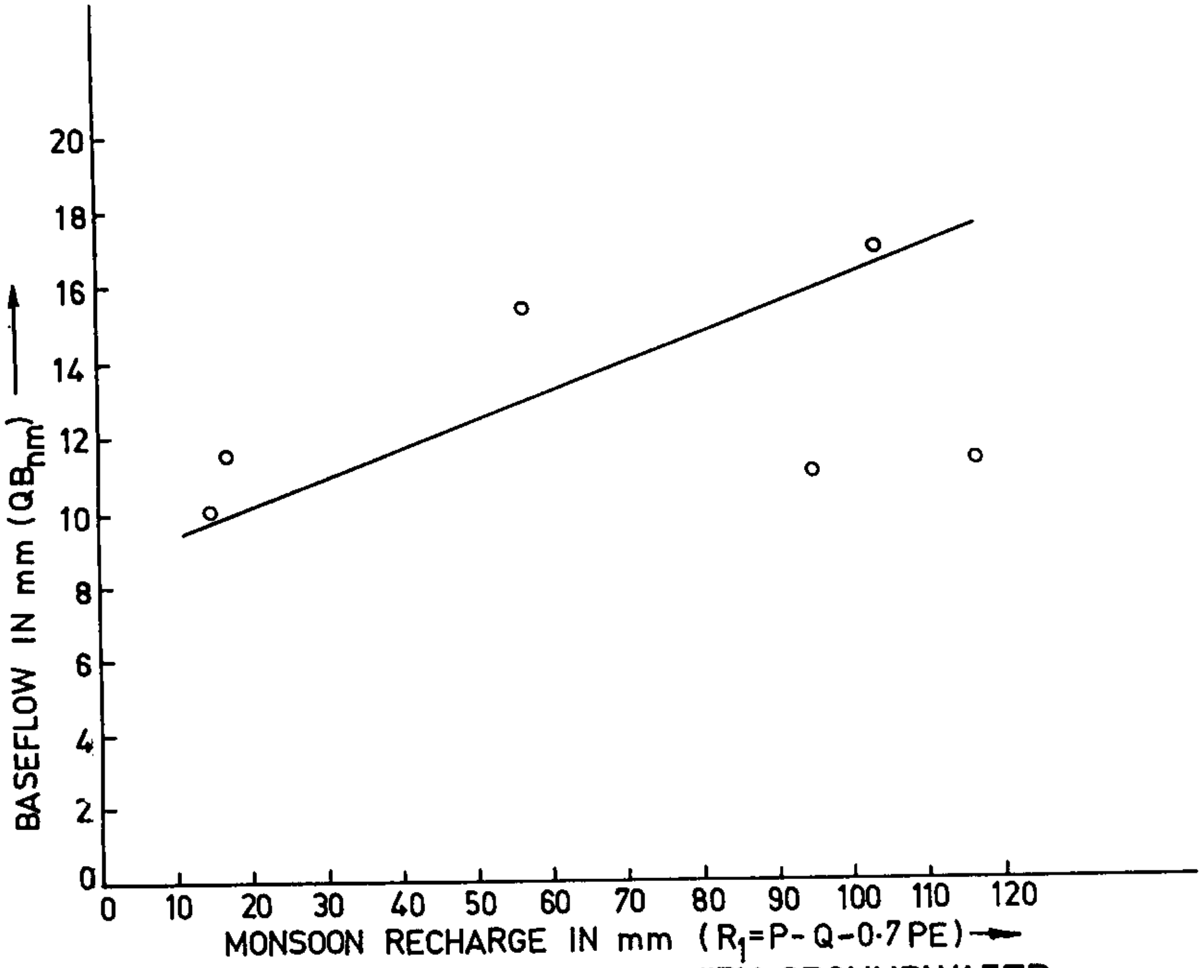


FIG.17–VARIATION OF BASEFLOW WITH GROUNDWATER RECHARGE (R_1)

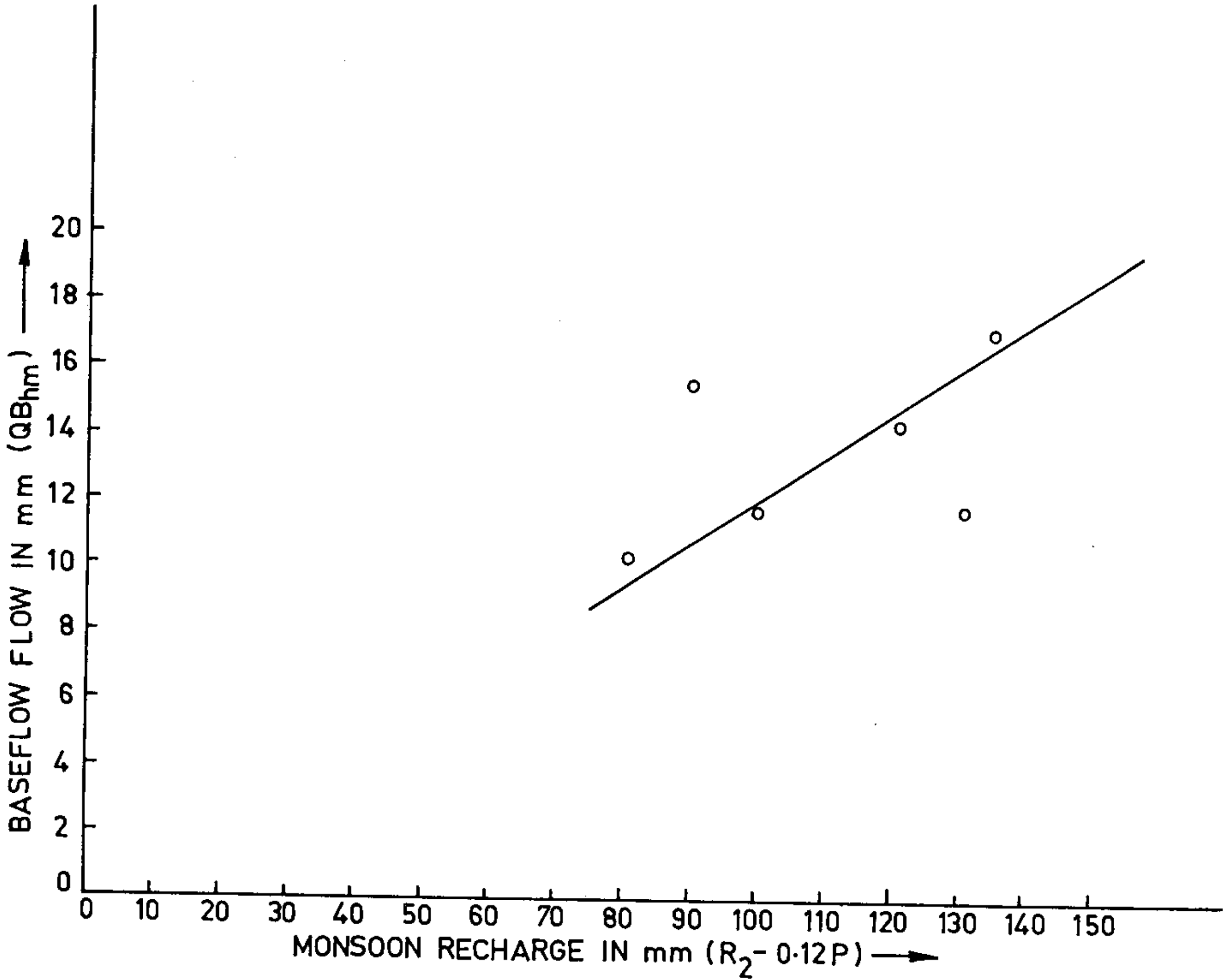


FIG.18 - VARIATION OF BASEFLOW WITH GROUNDWATER RECHARGE (R_2)

In the model, the rivers are set up along the grid boundaries; hence their course is approximated by straight lines. Since, it is very tedious to set up the rivers manually, in the SHE format. A service program, SHE. AF (array formating routine) was used to set up the rivers according to the format required in the model. The river setup for the Ganjal sub basin in 1 km x 1 km, 2 km x 2 km and 4 km x 4 km grid sizes are shown in fig. 19. The ratio between the number of river links and number of grid squares has an effect on the basin response. A small ratio signifies that in the model set up, overland shows predominance of the channel flow. The details of the basin area represented, number of grid squares representing the Ganjal sub basin, number of river links representing the sub basin and the ratio of number of rivers links to the number of grid squares for the grid sizes of 0.5 km x 0.5 km, 1km x 1km, 2km x 2km and 4km x 4km are given in table 4.

The unsaturated zone component computations required large CPU time. Within the SHE, there is a provision for a classification scheme, limiting the calculations to selected grid squares, each representing a domain of grid squares based on similar meteorological, soil, landuse characteristics and groundwater fluctuations, then transferring the computed results at each time step to the other grid squares in the domain. This saves considerable amount of CPU time. In the present study, for the grid size of 2 km x 2 km, unsat-

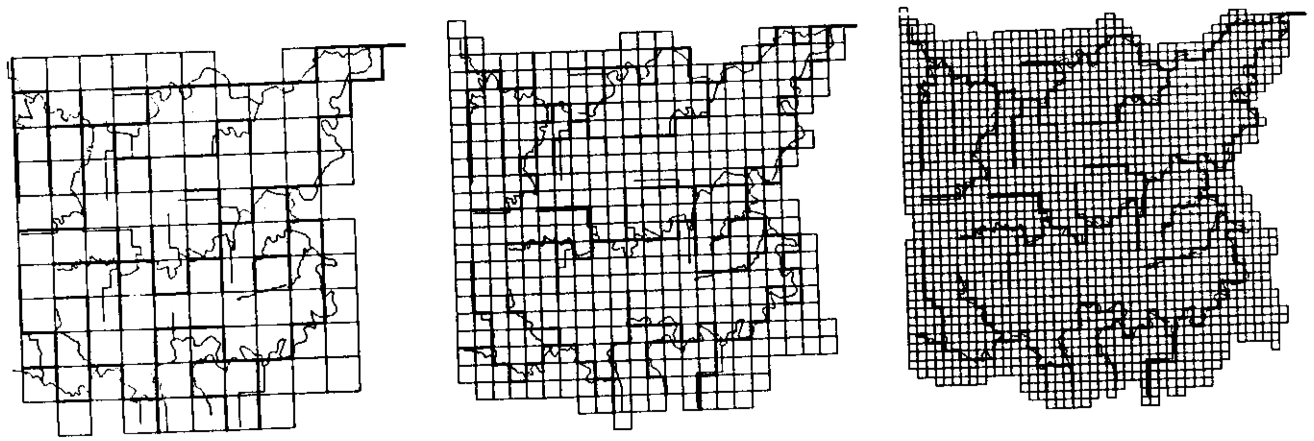


Fig. 19: River setup in different grid sizes.

TABLE-4:Grid and Channel network dimensions for the Ganjal basin for different grid scales.

Grid square size	Represented basin area	Number of grid squares representing the basin	Number of river links representing the river system	Ratio of number of links to number of squares
0.5x0.5	1721	6885	1090	0.16
1x1	1719	1719	497	0.29
2x2	1716	429	224	0.52
4x4	1664	104	95	0.91

urated zone computations were carried out in 14 grids. The data files corresponding to unsaturated and saturated zone component were also prepared in the SHE format, by the array formating routine, for which the information about soil types, landuse, soil depths, initial conditions etc. represented in the form of grids was utilised.

5.0 CALIBRATION AND VALIDATION OF SHE FOR GANJAL SUB BASIN

Split sample approach was used in this tudy. Data for the period March 1982 to February 1984 were used for calibration and March 1985 to December 1987 for validation.

5.1 Calibration of the Model

The model was calibrated by comparing and analysing the simulated discharge hydrographs, monthly runoff volumes, monsoon volumes and monsoon peaks at the outlet and phreatic surface levels at specific locations with the corresponding observed values.

From an overview of available literature and the experience gained from the useful discussions during the field visits; various trials were made during calibration to decide the model parameters which include Strickler roughness coefficient for overland and channel flow, soil hydraulic conductivities in saturated and unsaturated zones, representation of soil cracks, and surface detention storage. It may be stated that as SHE is a physically based model, theoretically, it should not require any calibration for the parameter values. However, in practice, some variation in parameter values is required because:

a) Some degree of lumping is done at the level of grid size and parameters in the SHE, which is considered to be fully distributed and physically based model.

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

In general, it has been observed that the Strickler coefficient has a strong influence on hydrograph peaks, the unsaturated zone hydraulic conductivity mainly affects the infiltration and thereby the volume of discharge hydrograph, the detention storage and soil crack model affect the hydrograph peaks and infiltration during the initial period of rainy season, saturated zone conductivity and depth of soil affect the baseflow. If the soil depth is more, the baseflow is more as hydraulic gradient for flow increases with increase in hydraulic head in terms of soil depth.

The range of values within which the parameters were allowed to vary was decided from information gathered from the literature and field visits. The calibration began with initial parameter values based on these sources. The comparison of observed and simulated volumes of runoff showed that there was lower simulation. The timings of the peaks were acceptable but not the magnitudes. In particular, the first few peaks during the monsoon were being overpredicted. The recession of the simulated hydrograph was also yielding less runoff as compared to the observed hydrograph.

In order to simulate the initial peaks in a realistic way, soil cracking and detention storage was applied in the simulation. It was achieved by specifying a fraction of the net rain which goes directly to the bottom of the root zone rather than contributing to overland flow. The cracks vanish when the cumulative rainfall exceeds a specified threshold. Detention storage in the model specifies a minimum threshold depth of water to be present on the surface of land before it contributes to over landflow. When a variation of parameter values was required to obtain a better fit, the strategy followed was first to take runs with extreme values to identify the feasible range. Then the concerned parameter was systematically varied to obtain the best fit.

The magnitudes of the observed and simulated peaks were matched by changing the Strickler roughness coefficient for overland flow. The conductivities in the saturated and unsaturated subsurface zones were varied to simulate ground water response according to well observations as well as to match the river baseflow. Water content at wilting point and residual water content i.e. inaccessible water content in soil due to adsorption and exponent appearing in Averjanous formula for calculation of unsaturated conductivity as a function of water content were varied to simulate runoff, groundwater response and river baseflow. Proceeding in this manner, the representative values of the parameters mentioned earlier were obtained. Strickler coefficient of 1.5 & 20 were adopted for overland flow and river system in the final run.

In the final run, good fits were obtained for monthly and monsoon seasonal volumes and peak values. Hydrological regime of the catchment was reasonably well represented.

Though, representation of groundwater regime of the catchment had some scope for improvement The final parameter values adopted are given in table-5. The observed and simulated hydrographs for the calibration period are given in fig. 20. The variation of groundwater table for the calibration period under different landuses of specific grids viz dense forest, agricultural area and waste land are given in fig. 21. Fig. 22 shows variation of moisture content with soil depth, potential evaporation and actual simulated evapotranspiration for a grid under dense mixed forest. A comparison of volumes and peaks, observed and simulated discharges is given in table 6. The water table depth of the Ganjal sub basin for each of the years (1982-84) in pre and post monsoon periods of the calibration run in shown in fig. 23 through fig. 28.

5.2 Validation of the Model

The data for the period March 1985 to December 1987 were used for validation of the model. Usually, in hydrology it is standard practice to split the sample in two parts and use one part for calibration and the other for validation. The main objective of validation is to reproduce the discharge hydrographs using the calibration parameter values for the periods not considered during the calibration and compare the observed ones on some objective criteria.

In the validation run, the model set up and parameters were kept the same as during the calibration runs. The initial

Table-5 : Soil and Vegetation parameters used in Simulation

S.No.	Landuse	Proportion of basin covered (%)	Soil depth (m)	Initial phreatic level (in march) (m)	Root zone depth (m)	Saturated soil conduc tivity (m/day)	
						Unsatura-ted zone	Saturated zone
1.	Agriculture - low land	5.8	10	3.0	0.6	0.1	7.5
2.	Dense mixed forest - low-land	10.3	10	3.0	2.0	0.1	7.5
3.	Thin forest - lowland	0	10	3.0	1.0	0.1	7.5
4.	Waste land - lowland	1.1	10	3.0	0.5	0.1	7.5
5.	Agriculture - semi hilly	3.6	3.0	2.4	0.6	0.1	7.5
6.	Dense mixed forest - semi hilly	35.1	3.0	2.4	2.0	0.1	7.5
7.	Thin forest - semi hilly	2.0	3.0	2.4	1.0	0.1	7.5
8.	Waste land - semi-hilly	7.6	3.0	2.4	0.5	0.1	7.5
9.	Agriculture - hilly	2.7	1.5	1.4	0.6	0.1	7.5
10.	Dense mixed forest - hilly	17.7	1.5	1.4	2.0	0.1	7.5
11.	Thin forest - hilly	3.8	1.5	1.4	1.0	0.1	7.5
12.	Waste land - hilly	10.6	1.5	1.4	0.5	0.1	7.5

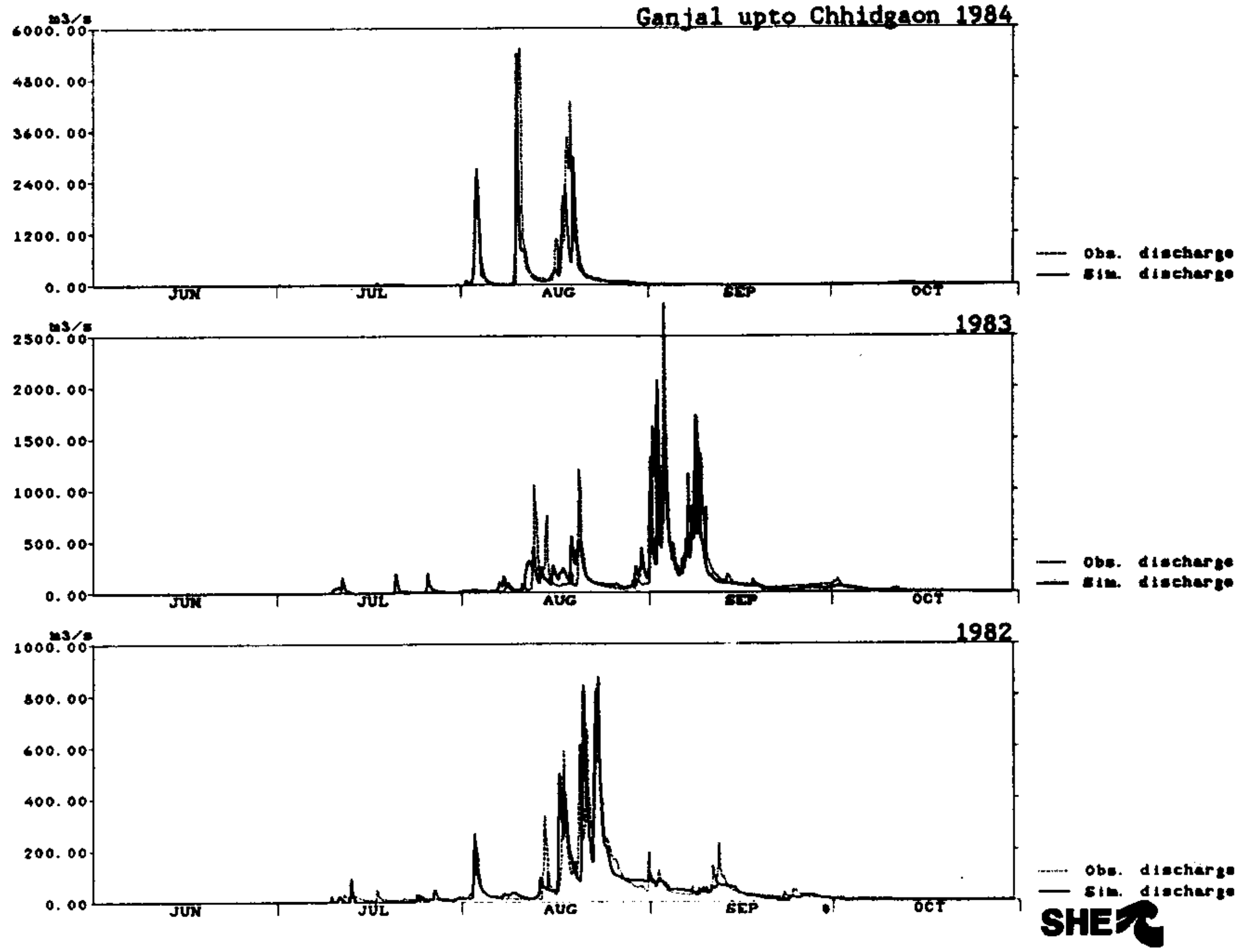


Fig. 20: Comparison of simulated and observed hydrographs at Chhidgaon gauging site for calibration run.

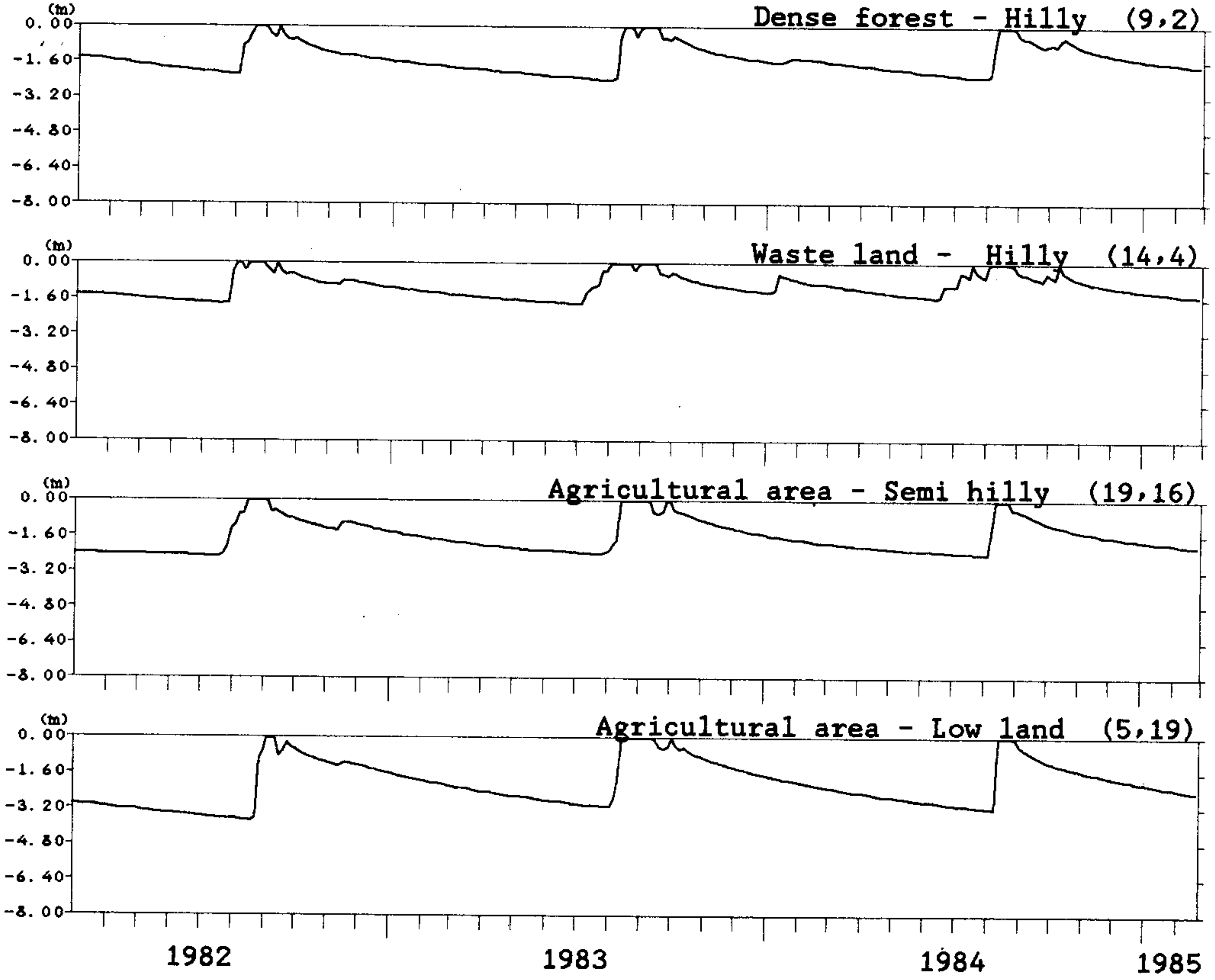


Fig. 21: Variation of groundwater table for grids under varous landuses for calibrtion run

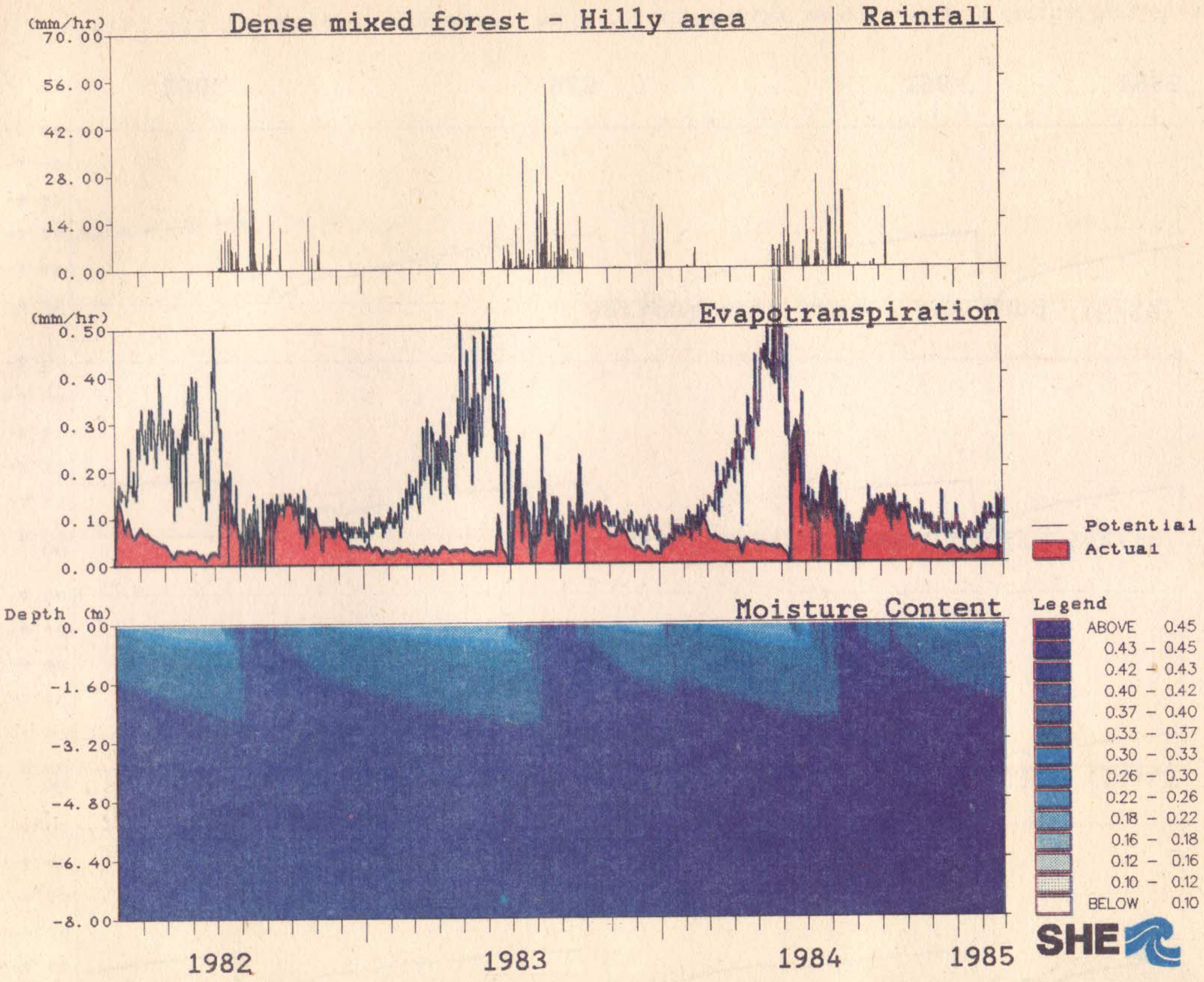


Fig. 22: Variation of moisture content, evapotranspiration and rainfall for a grid under dense forest for calibration run.

TABLE-6 Comparison of Volumes and Peaks of Observed and simulated Runoff for simulation period

Year	Month	Areal Rainfall(mm)	Runoff Observed (mm)	Runoff Simulated (mm)
1982	June	22.2	6.4	2.5
	July	248.3	18.3	10.9
	Aug.	357.0	204.1	203.4
	Sept.	94.4	60.5	53.1
	Oct.	26.4	21.9	9.3
	Sum	748.3	311.3	279.2
	Peak (m^3/s)		874.6	839.9
1983	June	96.8	21.4	2.0
	July	212.1	21.3	26.2
	Aug.	447.2	176.9	206.3
	Sept.	404.7	472.3	380.6
	Oct.	14.9	37.8	27.5
	Sum	1175.7	729.7	642.6
	Peak (m^3/s)		2832.5	2068.3
1984	June	19.9	8.0	2.3
	July	133.7	9.1	8.0
	Aug.	920.7	773.5	657.4
	Sept.	36.8	11.1	21.4
	Oct.	46.9	9.8	17.0
	Sum	1258.0	811.5	706.1
	Peak (m^3/s)		5544.9	5412.0

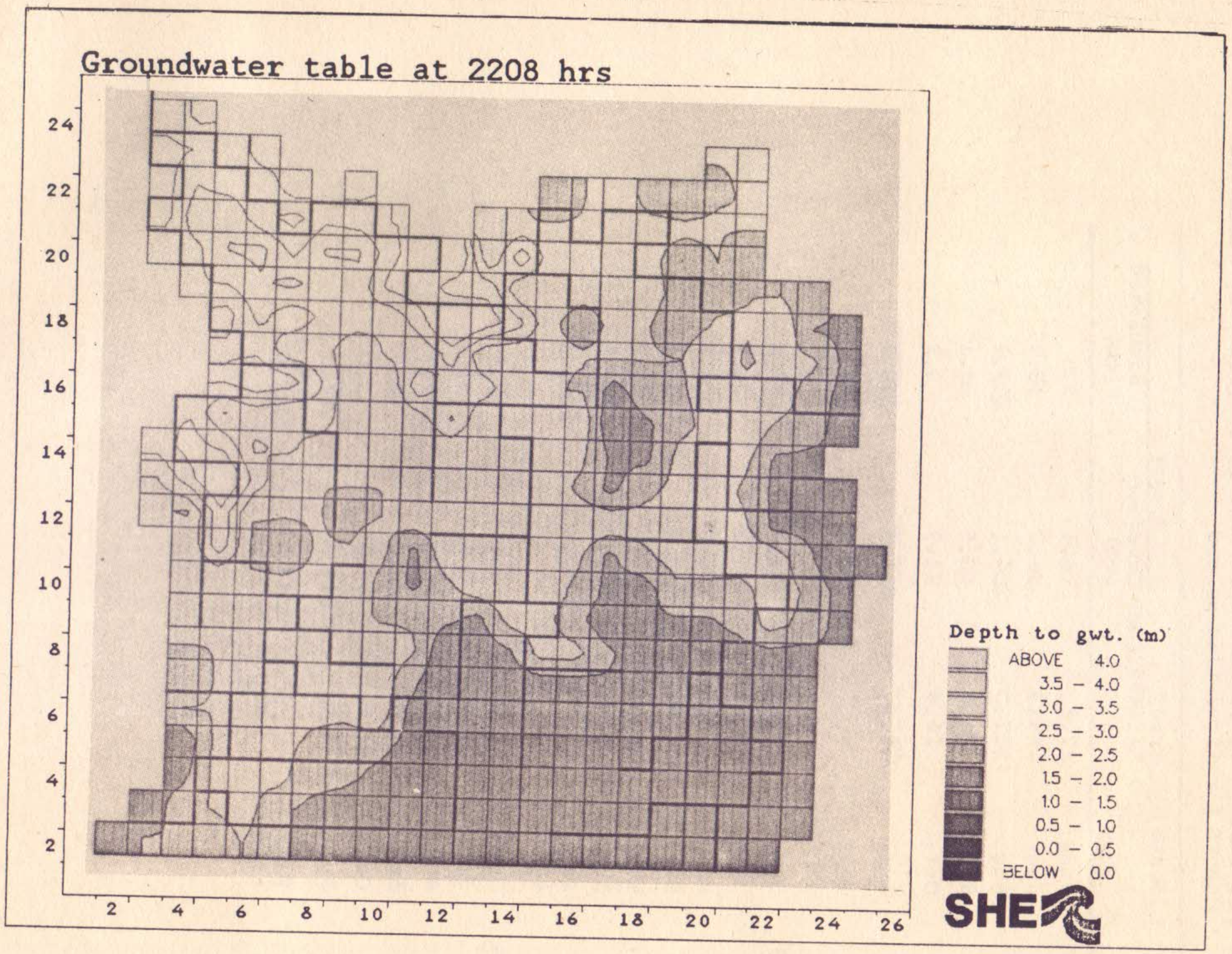


Fig. 23: Depth of groundwater table in Ganjal sub basin for premonsoon period of 198

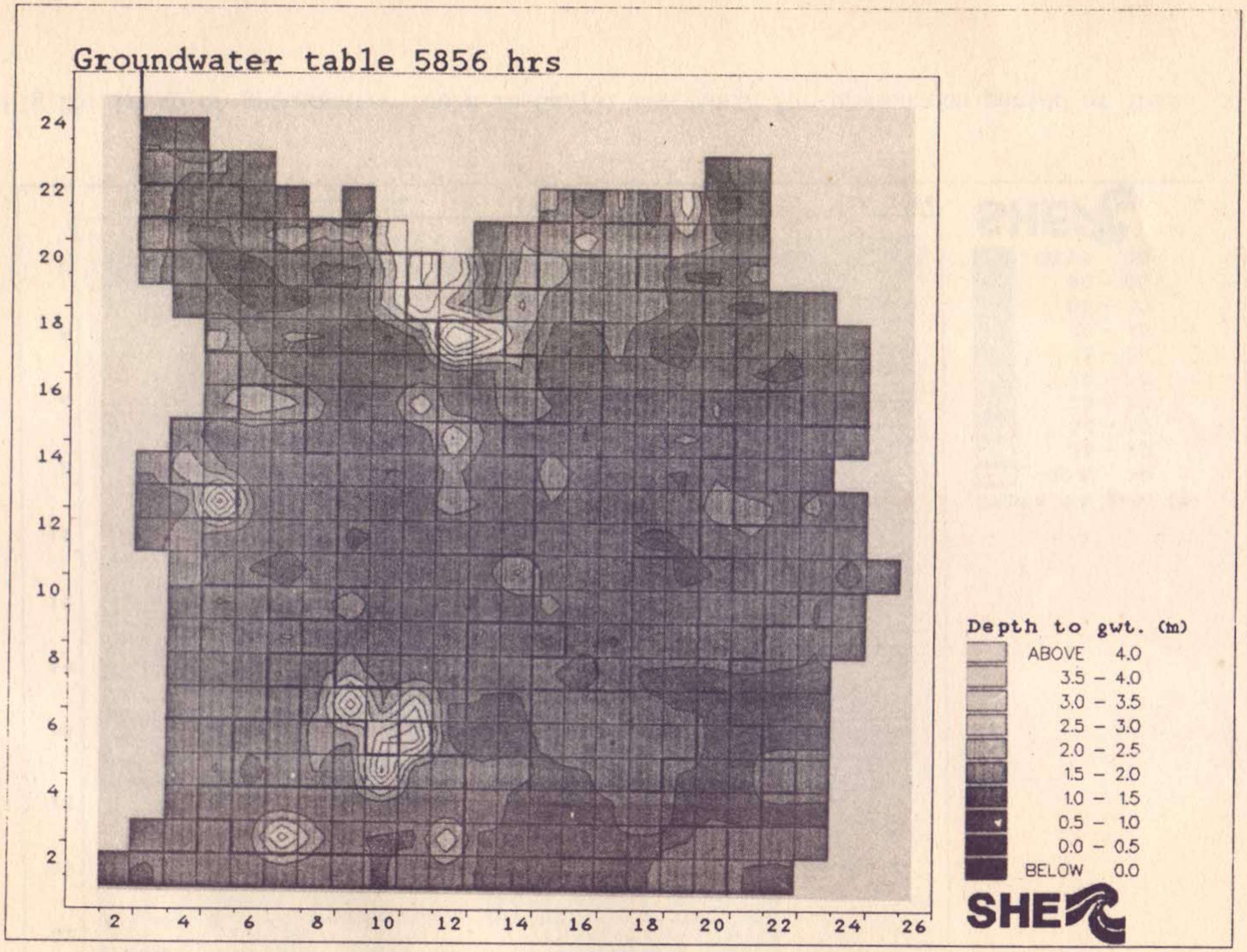


FIG.24: Depth of groundwater table in Ganjal sub basin for post monsoon period of 1982.

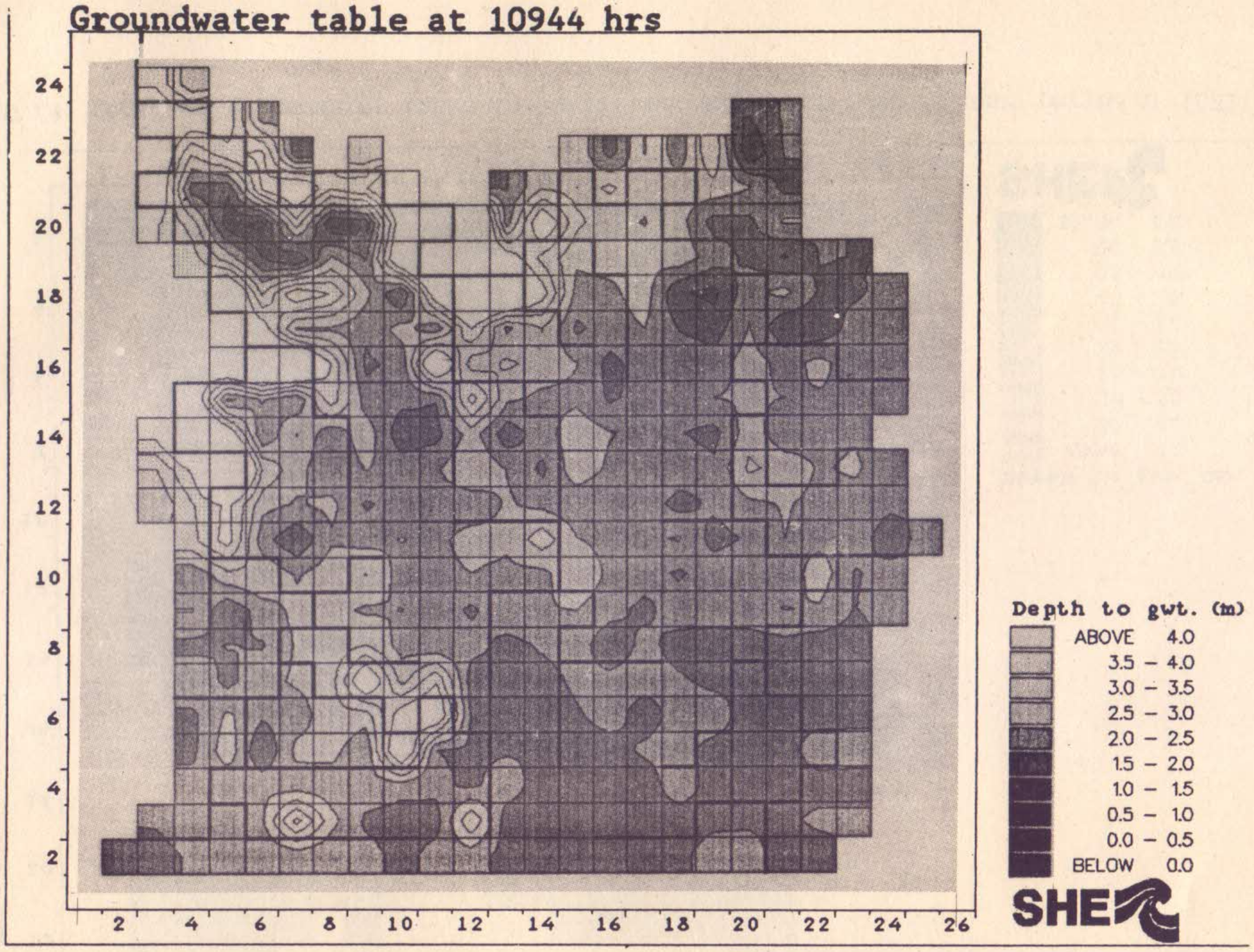


Fig.25: Depth of groundwater table in Ganjal sub basin for premonsoon period of 1983.

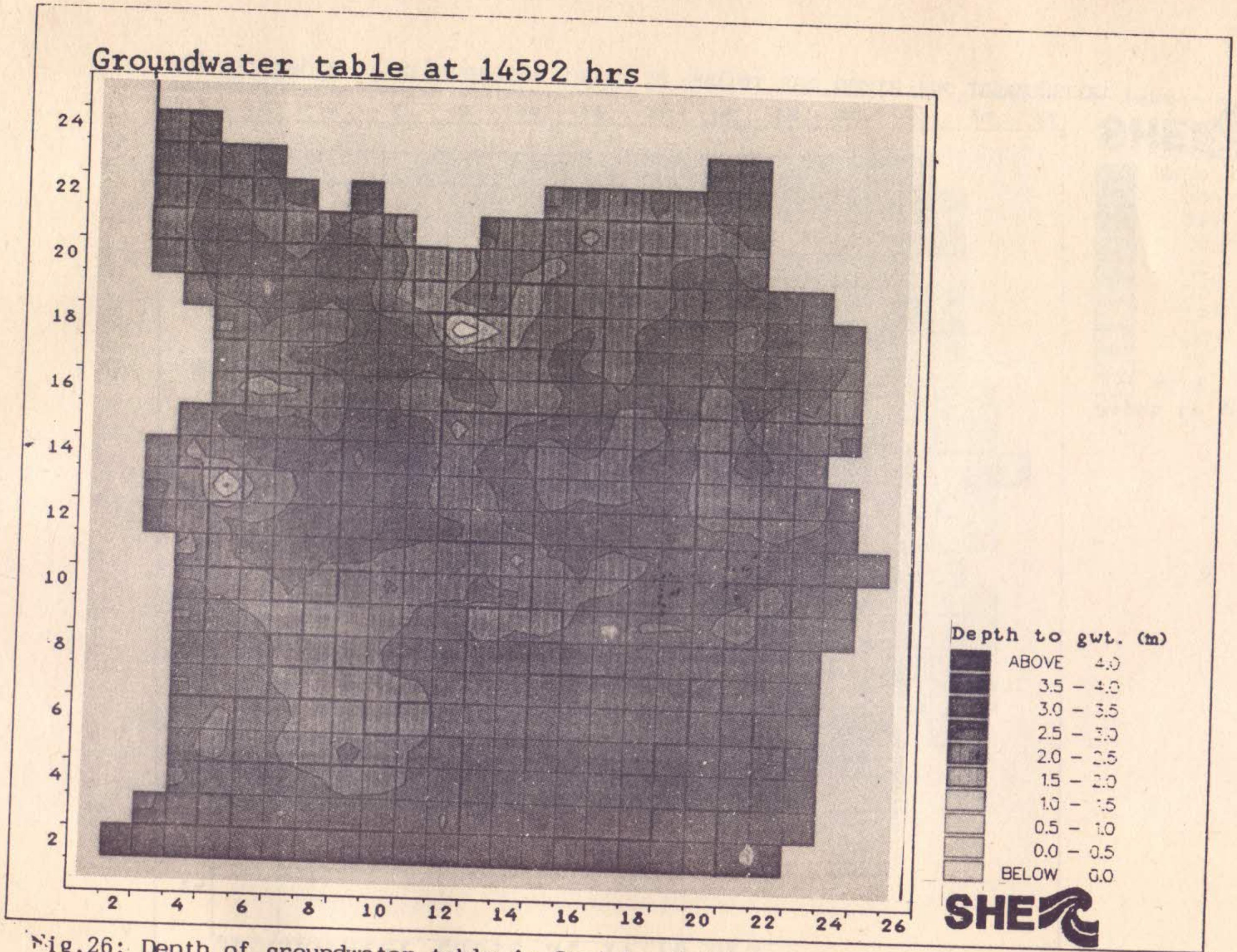
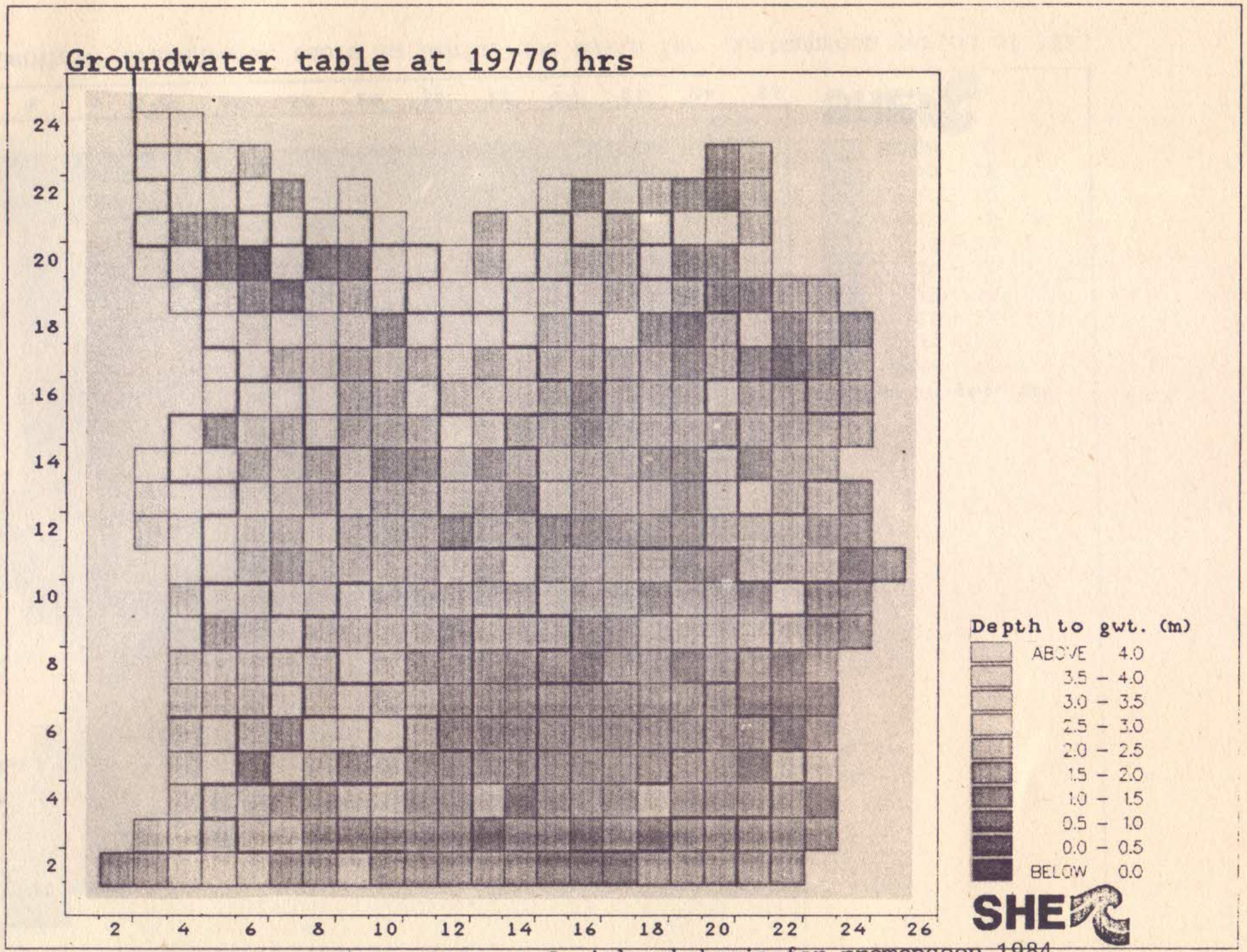


Fig.26: Depth of groundwater table in Ganjal sub basin for postmonsoon period of 1933.



Groundwater table at 19776 hrs

Fig.27: Depth of groundwater table in Ganjal sub basin for premonsoon 1984.

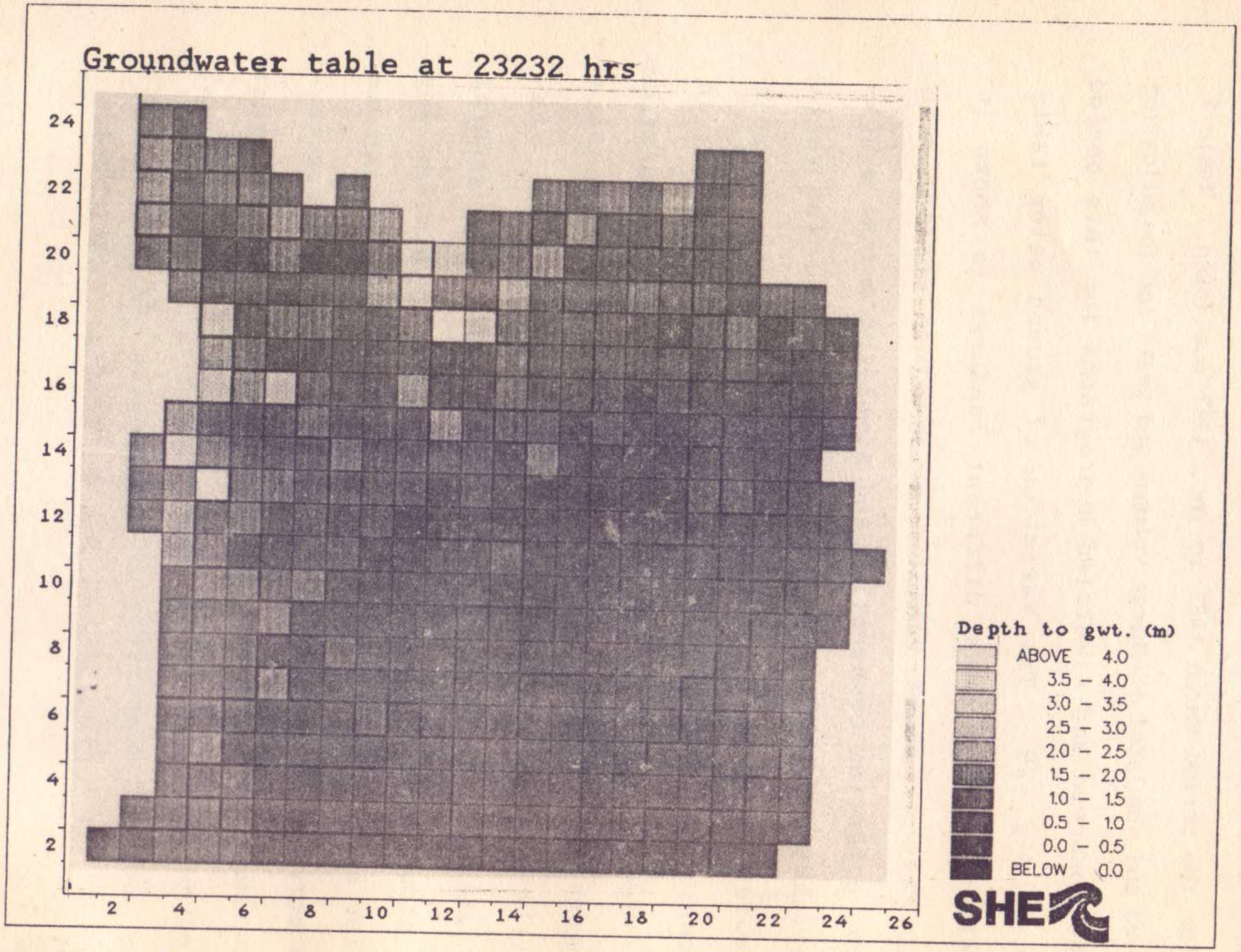


FIG.28: Depth of groundwater table in Ganjal sub basin for postmonsoon period of 1984.

conditions were also kept the same as in the calibration runs and a continuous run for the period March 1982 to Dec. 1987 was taken. Table 7 gives observed and simulated discharge volumes and peaks for the validation period. The observed and simulated hydrographs for this period are given in fig. 29. The variation of ground water table in the selected grids under different landuses is shown in fig. 30. Fig. 31 shows variatin of moisture content with soil depth, potential evaporation and simulated actual evapotranspiration for a grid under dense mixed forest. The variation of water table depth for the Ganjal sub basin in post monsoon period at the end of validation period is shown in fig. 32. The results show that there is some under simulation of discharge for the years 1985 and 1986, where as there is a little over simulation for the year 1987. The same trend is observed in case of peak discharges. The general trend of groundwater response is represented in similar way as that for calibration period, and it has a scope for improvement based on correct input rainfall data and catchment characteristics parameters. At the same time it is important that the observed data including hourly stage/discharge values which are used for comparison of the results are reliable.

Table-7 : Comparison of Volumes and Peaks of Observed and Simulated Runoff for Validation Period

Year	Month	Areal Rainfall	Runoff	
			Observed	Simulated
1985	June	98.8	15.4	2.6
	July	158.2	28.7	6.1
	August	246.5	202.1	105.6
	September	103.5	73.6	26.3
	October	71.6	76.3	29.3
	Sum	678.6	396.0	169.9
	Peak (m^3/s)		1226.0	932.9
1986	June	138.1	16.3	1.5
	July	601.1	431.2	298.4
	August	233.2	272.4	195.1
	September	38.8	34.7	14.0
	October	0.0	10.9	7.0
	Sum	1011.2	765.5	516.0
	Peak (m^3/s)		2004.9	1503.5
1987	June	135.7	10.9	1.8
	July	111.9	21.2	3.5
	August	449.6	99.4	179.0
	September	71.6	73.9	61.6
	October	55.6	13.3	6.6
	Sum	824.4	218.7	252.5
	Peak (m^3/s)		1088.0	1434.5

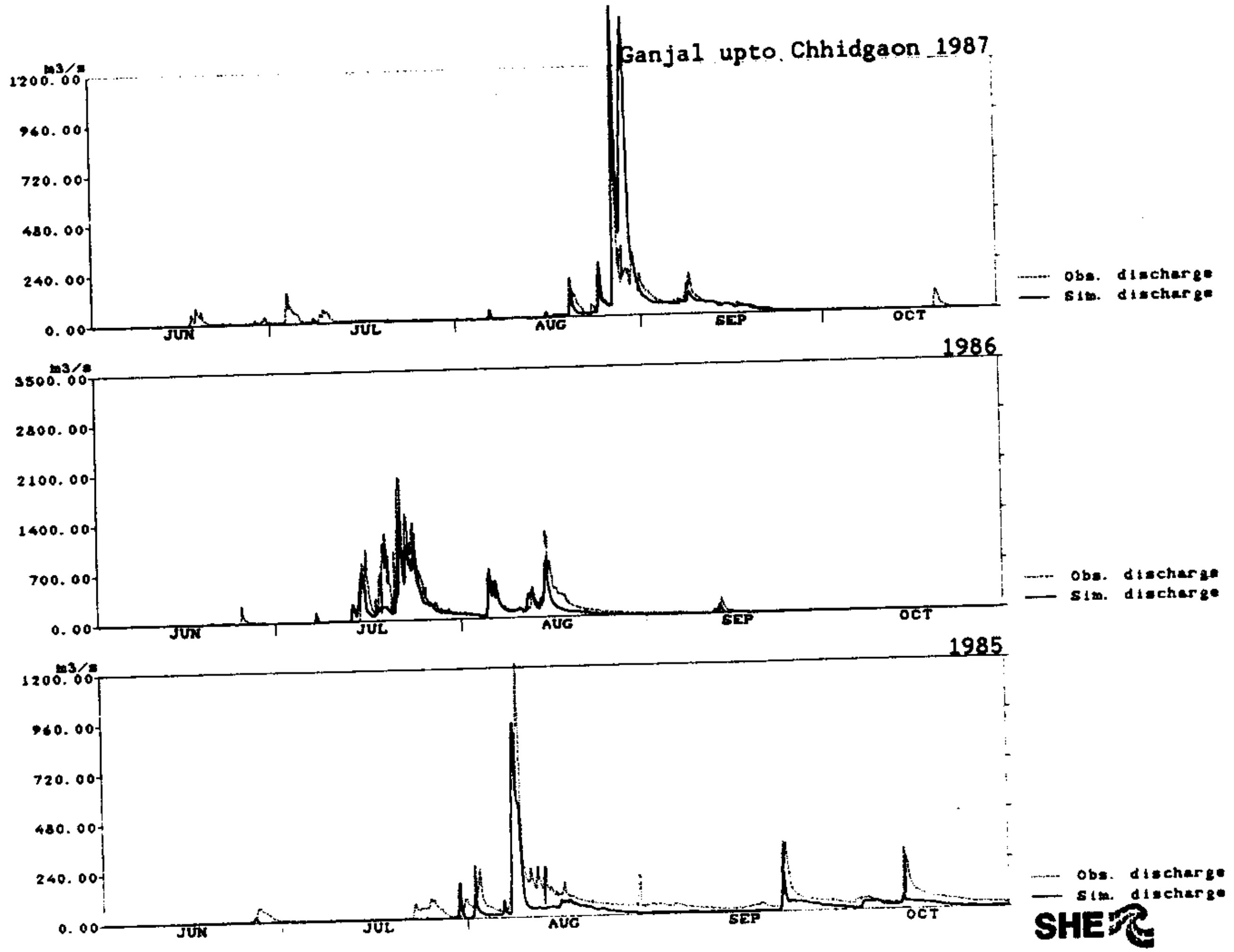


FIG. 29: Comparison of simulated and observed hydrographs at Chhidgaon gauging site for validation run.

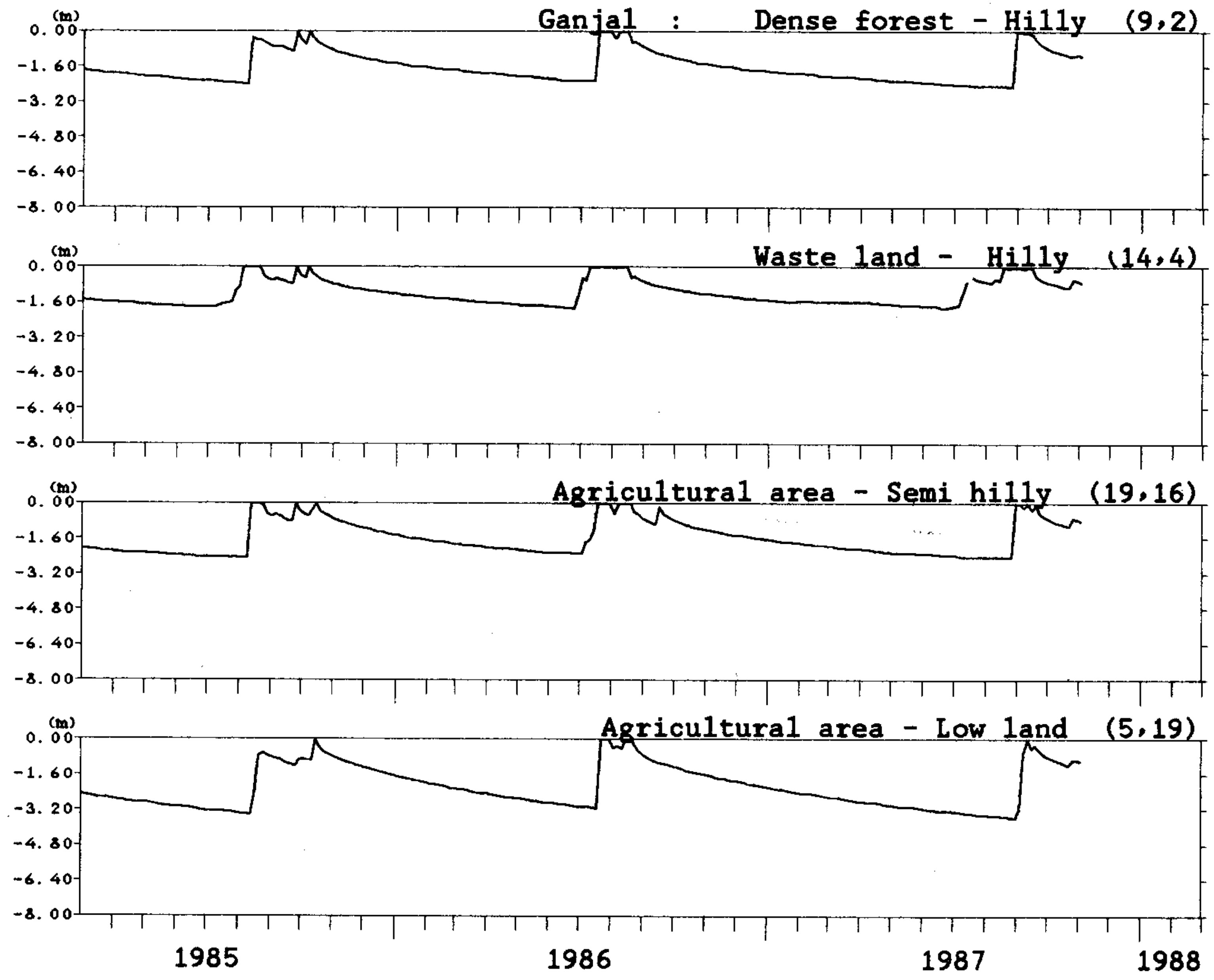


Fig. 30: Variation of groundwater table under various landuses for validation run.

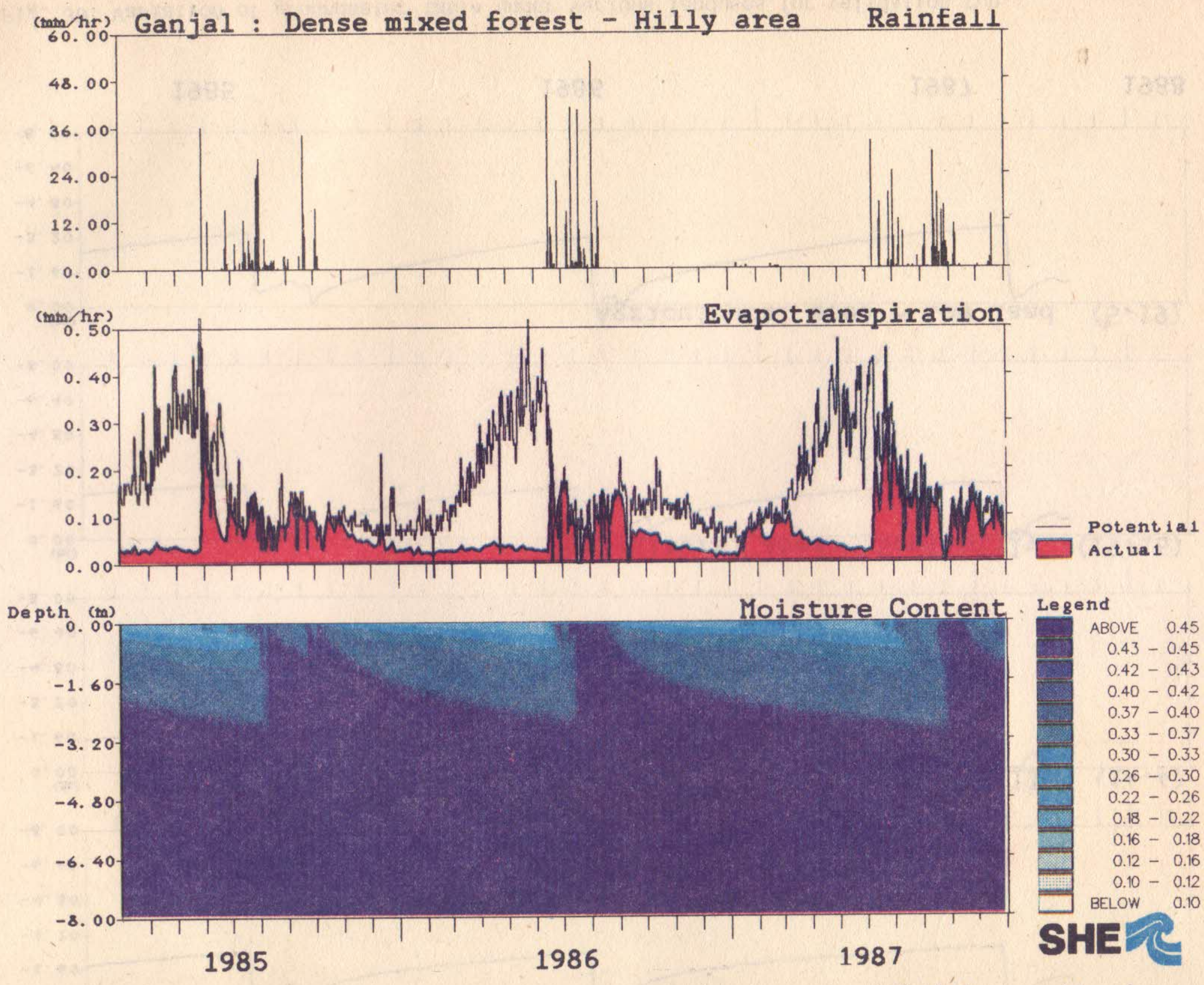


Fig. 31: Variation of moisture content, evapotranspiration and rainfall for a grid under dense forest for validation run.

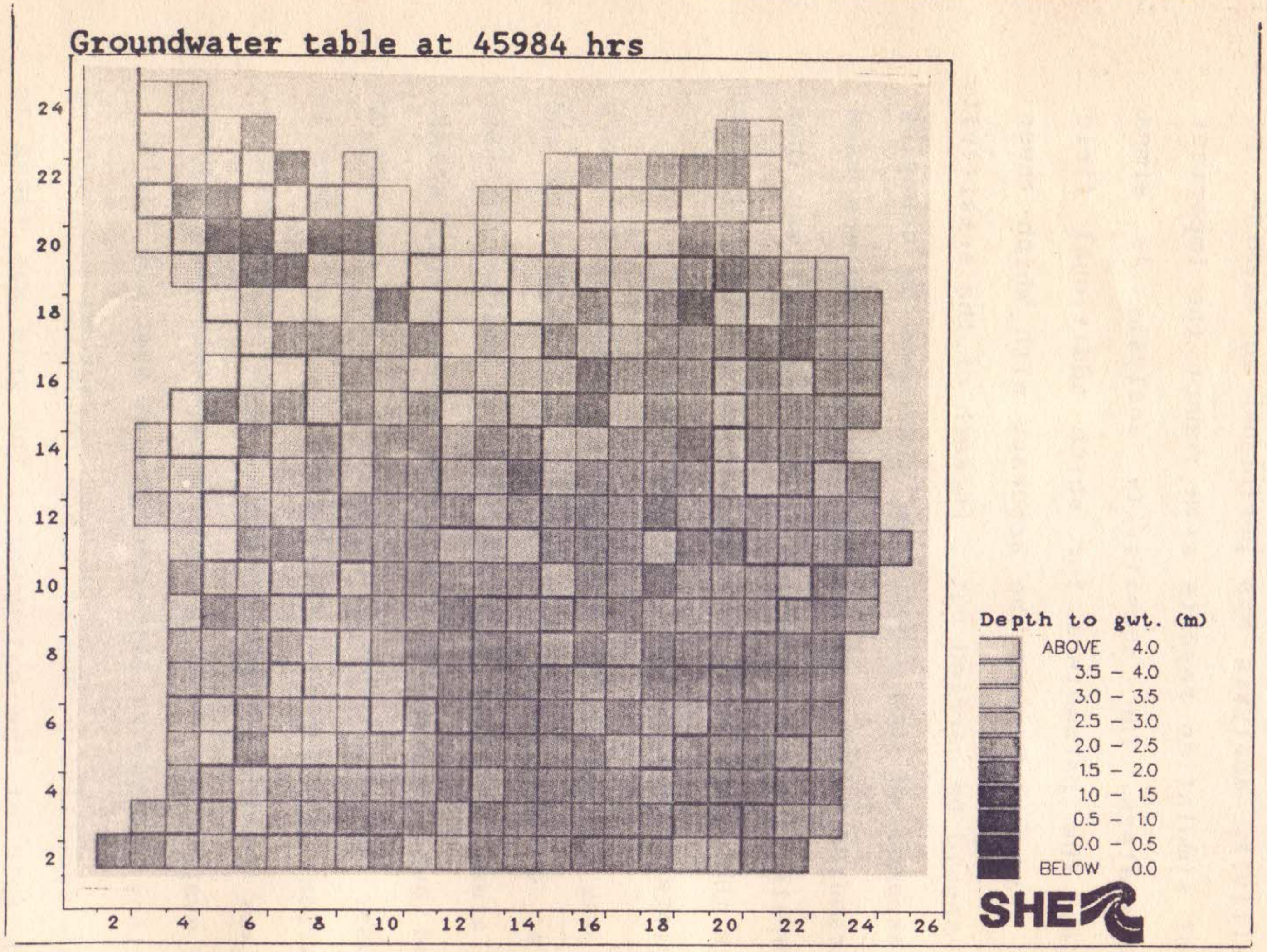


Fig. 32: Depth of groundwater table in the Ganjal sub-basin for post monsoon period of validation run.

6.0 SENSITIVITY ANALYSIS

Sensitivity analysis was performed to examine the sensitivity of simulation results with repect the important calibraton parameters. The sensitivity analysis is aimed at identifying the parameters for which additional field measurements are useful, and the accuracy with which these measurements should be carried out. In each of the sensitivity runs, the response of the basin was simulated by changing just one parameter value and keeping other parameters same as the calibrated parameter values. This response was then compared with the results of the best simulation run, referred to as the reference run in the remaining discussion.

It may be mentioned that the sensitivity analysis for Strickler coefficient, landuse changes, grid size and using mean areal rainfall instead of distributed rainfall were carried out during the simulation studies for Kolar, Barna and Sher basins, under this project. The network of pan evaporation measurement stations is relatively less in India. It was considered appropriate to examine the sensitivity of pan evaporation data of various pan evaporation measurement stations located at different places near the basin.

The sensitivity analysis was conducted considering one typical grid of the catchment. The grid was taken to be under dense forest and represented by Makrai raingauge station. Thus, by performing the sensitivity analysis on one grid the consumption of CPU time was emmensely reduced.

The following sensitivity runs were taken using the record for the period March 1983 to February 1985.

Run (a) Using calibration parameters (Reference run)

Run (b) Using Betul pan evaporation data

Run (c) Using Powarkheda pan evaporation data

Run (d) Using Pendra Road evaporation data

Run (e) Reducing the exponent appearing in Averjanov's formula (for calculation of unsaturated conductivity) from 14 to 10.

Run (f) Reducing water content at wilting point and residual water content from 0.21 and 0.21 to 0.12 and 0.12.

Run (g) Increasing saturated conductivity of unsaturated zone from 0.1 to 0.5.

The results of the above mentioned runs are discussed below:

Run (a) For calibration and validation of the model ,potential evaporation data of Jabalpur pan evaporation measurement station has been used. The results of sensitivity runs a), b), c) and d) are given in table 8 through table 11. It is seen from table 8 and 9 that Makrai raingauge station has an areal rainfall of 1845.5 mm and 1673.9mm and Jabalpur pan evaporation station reports potential evaporation of 1300.2 mm and 1377.6 mm for the year 1983-84 and 1984-85 respectively. The simulated actual evapotranspiration, is 591.9 mm and 494.6 mm and simulated runoff is 1351.8 and

Table-8 : Comparison of simulated actual evapotranspiration for sensitivity analysis of pan evaporation data of 1983-84

Month	Rainfall (Makrai)	Jabalpur		Betul		Powarkhed		Pendra Road	
		Potential m	Actual	Potential	Actual	Potential	Actual	Potential	Actual
March	0.0	149.55	71.28	93.7	57.68	152.52	72.46	125.76	65.98
April	0.0	177.42	42.40	121.8	42.69	241.46	46.87	146.64	41.62
May	0.0	245.88	29.30	153.8	29.36	368.16	31.16	152.88	25.83
June	71.9	208.80	46.15	138.6	49.95	231.77	64.38	124.32	43.71
July	515.8	79.08	75.48	116.7	110.43	125.57	115.63	62.88	60.72
August	609.9	76.92	72.72	105.6	105.52	86.53	86.53	64.08	60.48
September	606.9	56.94	56.94	82.47	82.4	86.70	87.59	58.08	58.32
October	40.9	78.66	78.16	89.6	88.17	112.02	103.83	66.48	66.71
November	0.0	62.73	47.11	85.3	52.06	90.75	47.26	58.32	49.14
December	0.0	55.53	29.65	79.7	32.34	70.37	27.23	49.44	28.85
January	0.0	44.88	20.62	66.6	22.33	53.20	18.43	43.68	22.13
February	0.0	63.78	22.91	64.8	17.29	89.92	23.07	55.44	21.17
Total	1845.4	1300.2	591.98	1198.7	690.2	1708.9	724.4	1008.0	554.7

Table 9 :Comparison of simulated actual evapotranspiration for sensitivity analysis of pan evaporation data of 1984-85.

MONTH	Areal Rainfall (Makrai)	Jabalpur		Betul		Powarkheda		Pendra Road	
		Potential	Actual	Potential	Actual	Potential	Actual	Potential	Actual
March	0.0	123.24	24.49	95.9	17.03	152.52	22.92	117.84	25.95
April	0.0	190.80	30.35	99.5	20.00	241.46	28.83	135.36	27.16
May	0.0	330.69	28.13	136.3	21.21	392.91	25.89	189.84	24.83
June	34.9	190.38	52.64	114.9	50.58	226.95	57.8	90.48	45.13
July	179.8	87.78	87.71	99.8	92.24	130.95	111.6	59.52	57.99
August	1436.0	51.09	50.64	97.4	96.24	69.97	69.9	56.40	55.44
September	17.8	72.57	72.57	84.7	86.16	80.24	81.9	66.24	66.70
October	5.4	86.97	62.98	90.0	57.40	103.93	65.6	66.96	56.85
November	0.0	68.82	30.10	88.2	33.02	86.26	31.9	60.00	33.04
December	0.0	56.70	20.77	88.9	24.83	78.00	22.8	60.00	24.72
January	0.0	49.53	15.84	66.6	16.58	82.11	20.6	35.04	12.97
February	0.0	69.06	18.40	62.2	12.66	91.35	17.4	66.72	19.81
Total	1673.9	1377.6	494.6	1124.6	527.9	1736.6	557.0	1004.5	450.6

and 1224.2 mm for 1983-84 and 1984-85 respectively (Table -10). Table - 11 shows a deficit of 44.9mm in groundwater storage for the year 1984-85. Fig. 33 shows moisture deficit, moisture content variation with depth, runoff, potential evaporation, simulated actual evapotranspiration and rainfall (Makrai raingauge station) for the period June 1983 to Nov. 1984 for this run.

Run (b) Potential evaporation data of Betul pan evaporation measusrement station have been used in this run. This station reports relatively lower potential evaporation of 1198.7mm and 1224.6mm for the years 1983-84 and 1984-85. The simulated actual evapotranspiration is 690.2mm and 527.9mm and simulated runoff is 1263.0 mm and 1190.8mm for the years 1983-84 and 1984-85 respectively (Tables 8,9 & 10). Table 11 shows deficit in groundwater storage of 44.8 mm for the year 1984-85. Fig. 34 shows soil moisture deficit, moisture content variation with depth of soil, runoff, potential evaporation, simulated actual evapotranspiration and rainfall for the period June 83 to Nov. 1984. It is observed that simulated actual evapotranspiration for this run is more, even though annual potential evaporation is relatively less. It can be stated that actual evapotranspiration depends largely on the potential

Table- 10: Comparison of simulated runoff for sensitivity analysis of pen evaporation data

Month	Areal Rainfall (Makrai) 1983-84	1984-85	Jabalpur 1983-84	1984-85	Betul 1983-84	1984-85	Powarkheda 1983-84	1984-85	Pendra Road 1983-84	1984-85
March	0.0	0.0	0.71	0.27	0.72	0.11	0.70	0.07	0.72	0.39
April	0.0	0.0	0.11	0.00	0.15	0.00	0.09	0.00	0.13	.00
May	0.0	0.0	.00	0.00	.00	0.00	0.00	0.00	0.00	.00
June	71.9	34.9	.00	0.00	.00	0.00	0.00	0.00	0.00	.00
July	515.8	179.8	173.09	27.43	153.66	23.43	116.42	19.38	199.98	28.25
August	609.9	1436.0	579.37	1156.42	539.77	1138.21	554.75	1111.83	592.45	1197.91
September	606.9	17.8	537.85	21.49	516.00	13.55	513.05	18.58	535.45	22.23
October	40.9	5.4	41.63	9.06	35.14	7.92	32.49	8.59	45.80	9.42
November	0.0	0.0	8.88	5.15	8.56	4.47	7.98	4.80	9.30	5.49
December	0.0	0.0	5.54	2.93	5.18	2.37	4.79	2.62	5.83	3.21
January	0.0	0.0	3.14	1.27	2.77	0.71	2.53	0.93	3.37	1.53
February	0.0	0.0	1.47	0.16	1.05	0.00	0.90	0.02	1.65	0.26
Total	1845.4	1673.9	1351.8	1224.2	1263.0	1190.8	1233.8	1166.8	1394.7	1268.7

TABLE-11: Comparison of change in groundwater storage for sensitivity analysis of pan evaporation data

Year	Jabalpur	Betul	Powarkheda	Pendra Road
1983-84				
Rainfall (Makrai)	1845.4	1845.4	1845.4	1845.4
Potential Evaporation	1300.2	1198.7	1708.9	1008.0
Simulated Runoff	1351.8	1263.0	1233.8	1394.7
Simulated Actual Evapotranspiration	591.9	690.2	724.4	554.7
Change in storage	-98.3	-107.8	-112.8	-104.0
1984-85				
Rainfall (Makai)	1673.9	1673.9	1673.9	1673.9
Potential Bvaporation	1377.6	1124.6	1736.6	1004.5
Simulated Runoff	1224.2	1190.8	1166.8	1268.7
Simulated Actual Evapotranspiration	494.6	527.9	557.0	450.6
Change in storage	-44.9	-44.8	-49.9	-45.4

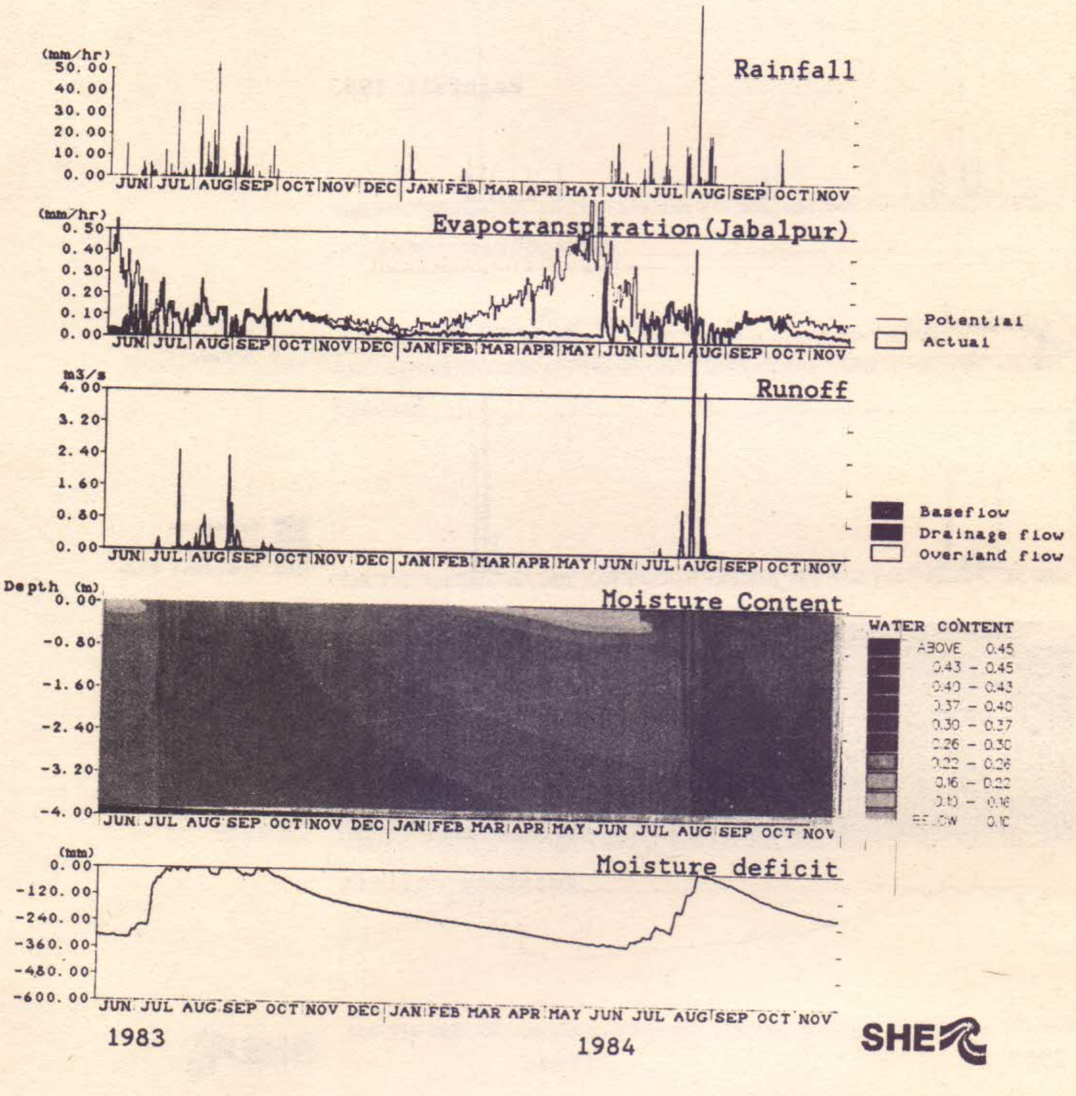


Fig. 33: Variation of soil moisture deficit, moisture content, runoff, evapotranspiration and rainfall for reference Run (a)of sensitivity analysis.

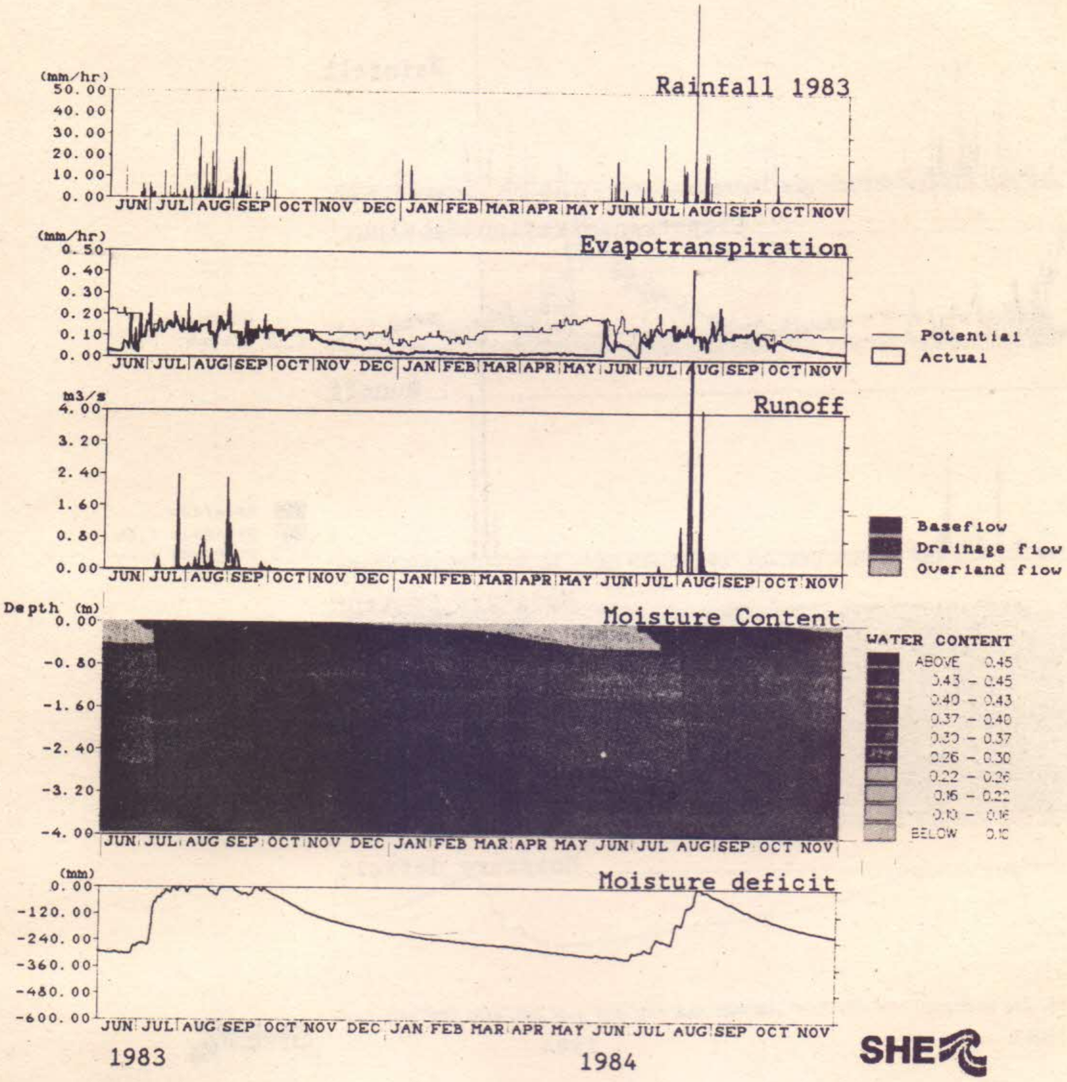


Fig. 34: Variation of soil moisture deficit, moisture content, runoff, evapotranspiration and rainfall for Run (b) of sensitivity analysis.

available for evaporation when water over the basin is available for evaporation and not on the evaporation potential without enough of water. However, tables 10, and 11 show annual runoff and change in groundwater storage are nearly same as those in reference run.

Run (c) Potential evaporation data of Powarkheda pan evaporation measurement station have been used in this run. This station reports highest observed potential evaporation of 1708.9mm and 1736.6mm among all the stations for the years 1983-84 and 1984-85. Fig. 35 shows soil moisture deficit, moisture content variation with depth of soil, runoff, potential evaporation, simulated actual evapotranspiration and rainfall for the period June 1983 to November 1984. The actual evapotranspiration of 724.4mm and 557.0mm and runoff of 1233.8mm and 1166.8mm have been simulated for 1983-84 and 1984-85 (Tables 8,9,& 10). A deficit of 49.9mm has been computed for the year 1984-85 (Table 11). The above referred values are quite comparable to those of reference run.

Run (d) Potential evaporation data of Pendra Road pan evaporation measurement station have been used in this run. This station reports the lowest potential evaporation of 1008.0 mm and 1004.5mm for the years 1983-84 and 1984-85. Fig. 36 shows soil moisture

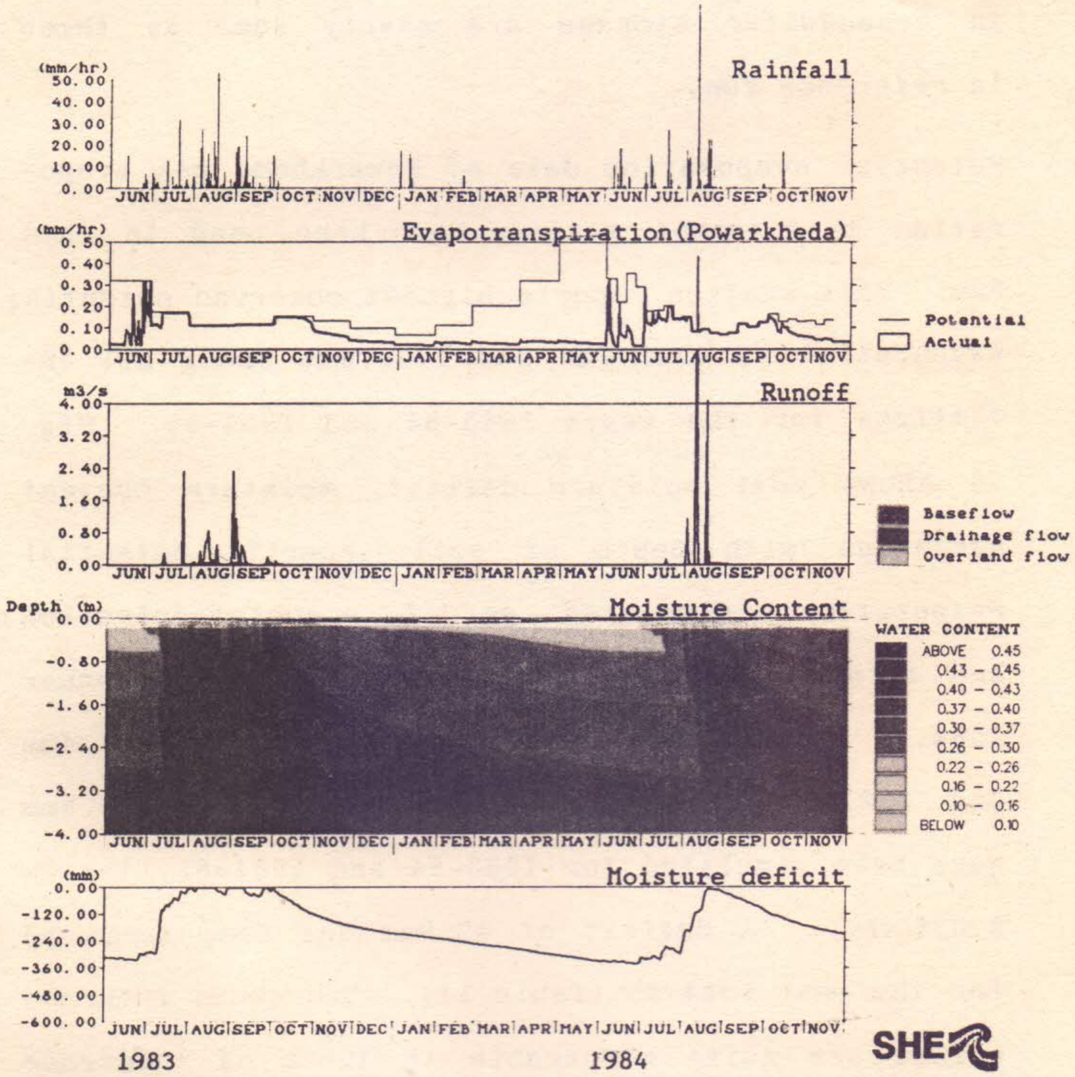


FIG. 35: Variation of soil moisture deficit, moisture content, runoff, evapotranspiration and rainfall for Run(c) of sensitivity analysis.

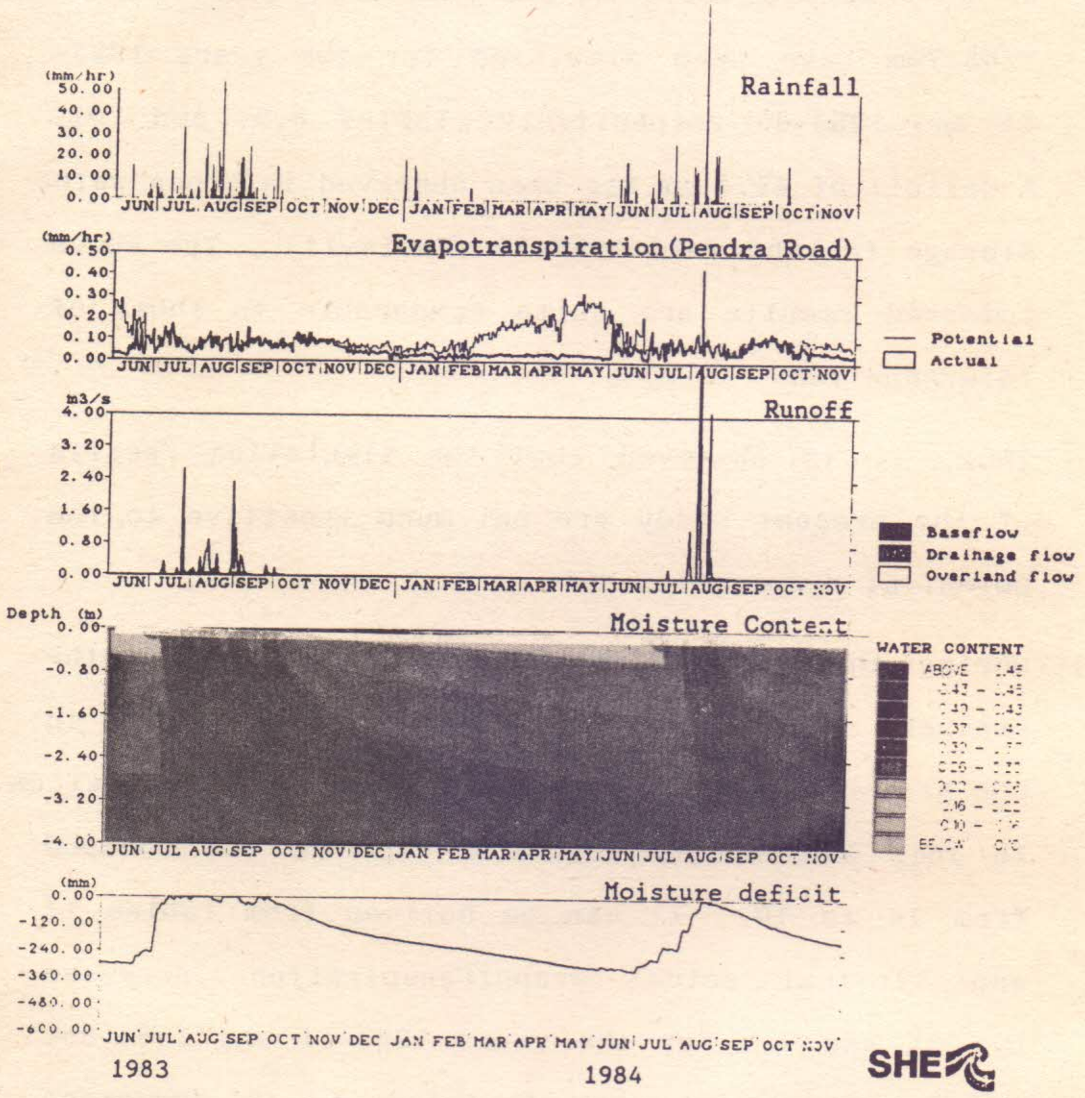


Fig. 36: Variation of soil moisture deficit, moisture content, runoff, evapotranspiration and rainfall for Run (d) of sensitivity analysis.

deficit, moisture content variation with depth of soil, runoff, potential evaporation, simulated actual evapotranspiration and rainfall for the period June 1983 to November 1984. The actual evapotranspiration of 554.7mm and 450.6 mm and runoff of 1394.7mm and 1268.7mm have been simulated for the years 1983-84 and 1984-85 respectively (Tables 8,9, and 10). A deficit of 45.4 mm has been observed in groundwater storage for the year 1984-85 (Table-11). The above referred results are quite comparable to those of reference run.

Thus, it is observed that the simulation results of the present study are not much sensitive to the potential evaporation data.

Run (e) During the calibration, it was observed that the exponent appearing in Averjanov's formula used in SHE has an immense effect on actual evapotranspiration. In this sensitivity run, this exponent was reduced from 14 to 10. It can be noticed from tables 12 and 13 that actual evapotranspiration increased by 33% and 41% for the years 1983-84 and 1984-85. At the same time the simulated runoff decreased by 8% and 14% for same years, respectively. Figure 37 shows that the soil moisture deficit has increased due to resulting higher evapotranspiration. The soil moisture content also shows a large depletion

TABLE:12 - Comparison of simulated runoff and actual evapotranspiration in sensitivity analysis for exponent in Averjanous formula (n), water content at wilting point (Q), and residual water content (Q_r), and saturated conductivity of UZ for 1983-84

Month	Reference Run		n reduced from 14 to 10		Q and Q_r reduced from .21, .21 to 0.12, 0.12		Kuz increased from 0.1 to 0.5	
	Evapotranspiration	Runoff	Evapotranspiration	Runoff	Evapotranspiration	Runoff	Evapotranspiration	Runoff
March	71.3	0.71	100.0	0.3	94.5	0.4	84.5	0.2
April	42.4	0.11	70.0	0.0	66.9	0.0	58.8	0.0
May	29.3	0.0	53.1	0.0	50.5	0.0	43.9	0.0
June	46.2	0.0	60.8	0.0	58.0	0.0	54.8	0.0
July	75.5	173.1	77.9	84.8	76.2	96.4	76.7	119.3
August	72.7	579.4	72.7	570.3	72.7	573.8	72.7	578.1
Sept.	56.9	537.9	60.0	538.5	60.0	538.3	60.0	538.9
October	78.2	41.6	78.2	40.2	78.2	40.5	78.2	39.9
November	47.1	8.9	61.9	5.6	61.9	6.3	61.9	5.6
Dec.	29.7	5.5	54.2	0.6	54.2	1.47	54.1	0.7
January	20.6	3.1	44.4	0.0	44.9	0.0	40.4	0.0
Feb.	22.9	1.5	57.6	0.0	42.8	0.0	36.6	0.0
Total:	592.8	1351.8	789.9	1240.5	760.8	1257.7	722.6	1281.9

TABLE- 13: Comparison of simulated runoff and actual evapotranspiration in sensitivity analysis for exponent in Averjanous formula (n), water content at wilting point Q_w and residual water content (Q_r) and saturated conductivity of UZ for 1984-85

Month	Reference Run		n reduced from 14 to 10		Q and Qr reduced from .21, .31 to 0.12, 0.12		Kuz increased from 0.1 to 0.5	
	Evapotra-nspiration	Runoff	Evapotra-nspiration	Runoff	Evapotrans-piration	Runoff	Evapotrans-piration	Runoff
March	24.5	0.27	47.6	0.0	42.3	0.0	36.7	0.0
April	30.4	0.0	50.3	0.0	48.9	0.0	41.4	0.0
May	28.1	0.0	41.8	0.0	42.8	0.0	35.6	0.0
June	52.6	0.0	61.3	0.0	59.9	0.0	56.5	0.0
July	87.7	27.4	91.0	16.1	88.3	16.6	89.4	7.6
August	50.6	1156.4	50.6	1016.4	50.6	1043.4	50.6	1040.2
Sept.	73.8	21.5	73.9	17.5	73.9	16.6	73.9	19.7
Oct.	62.9	9.1	86.8	5.3	86.6	6.1	86.5	6.4
Nov.	30.1	5.2	66.8	0.2	58.5	0.9	52.4	0.4
Dec.	20.8	2.9	54.4	0.0	38.3	0.0	36.4	0.0
Jan.	15.8	1.3	37.5	0.0	30.6	0.0	27.1	0.0
Feb.	18.4	0.2	37.9	0.0	34.2	0.0	30.5	0.0
Total:	494.6	1224.2	699.9	1055.5	654.9	1083.6	617.0	1113.3

specially during the non monsoon period of January 1984 to mid of August 1984. This occurs because of loss of water from soil through transpiration by capillary rise is more during the dry season.

Run (f) In this sensitivity run, water content at wilting point and residual water content of soil i.e. inaccessible water content in soil due to adsorption, both were reduced from 0.21 to 0.12. From tables 12 and 13, it is observed that actual evapotranspiration increases by 28% and 32% and runoff reduces by 7% and 11% for the years 1983-84 and 1984-85 respectively. Figure 38 shows that groundwater table goes much down. Decrease in water content at wilting point and residual water content of soil leads to larger evapotranspiration from soil and reduced runoff.

Run (g) In this run, saturated conductivity of unsaturated zone was increased from 0.1 to 0.5. From tables 12 and 13, it is observed that evapotranspiration increases by 22% and 25% and runoff decreases by 5% and 9% for the years 1983-84 and 1984-85. Figure 39 shows that the groundwater table goes much down in dry season. Initial peaks disappear or decrease due to high infiltration. Later peaks are higher due to filling up of groundwater storage in the early rainfall period. Higher actual evapotrans-

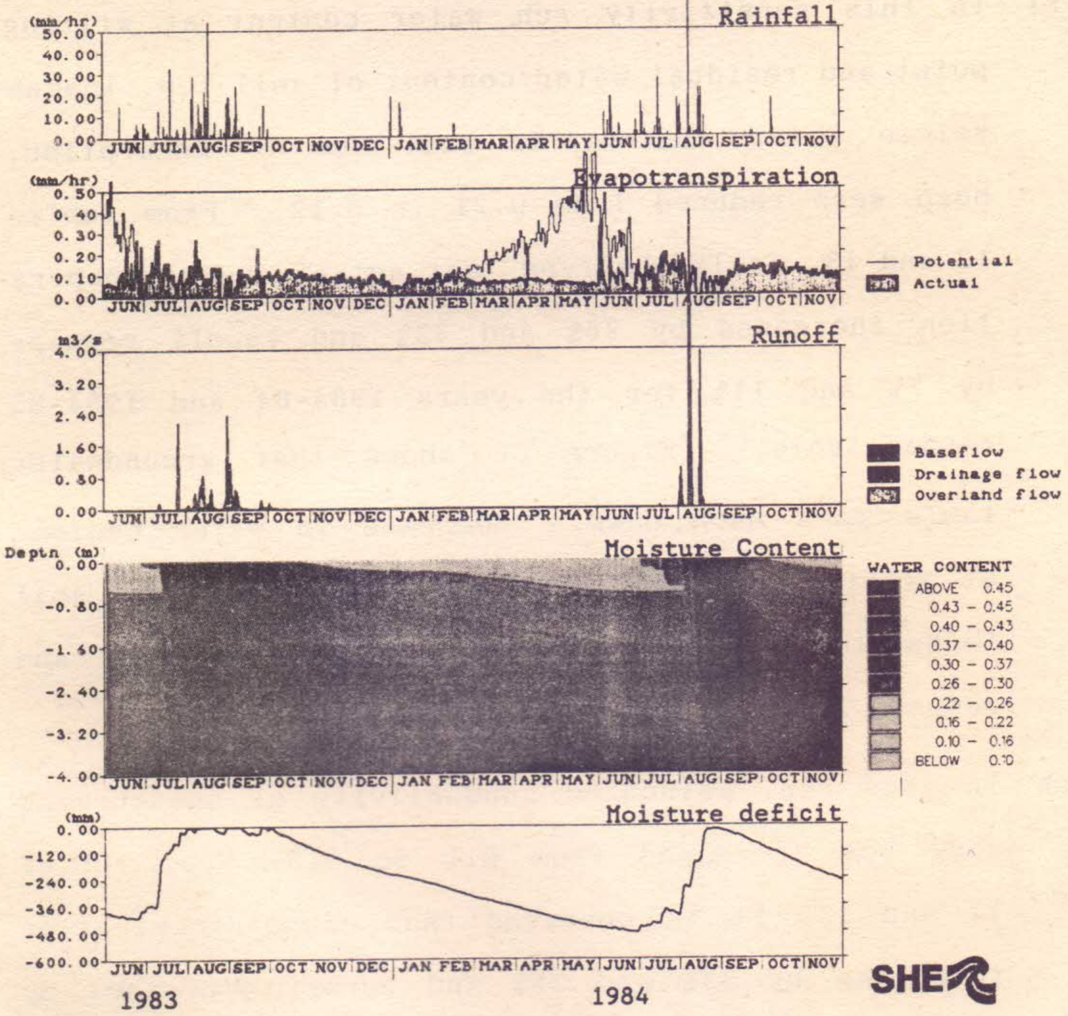


Fig. 37: Variationof soil moisture deficit, moisture content, runoff, evapotranspiration & rainfall for Run (e) of sensitivity analysis.

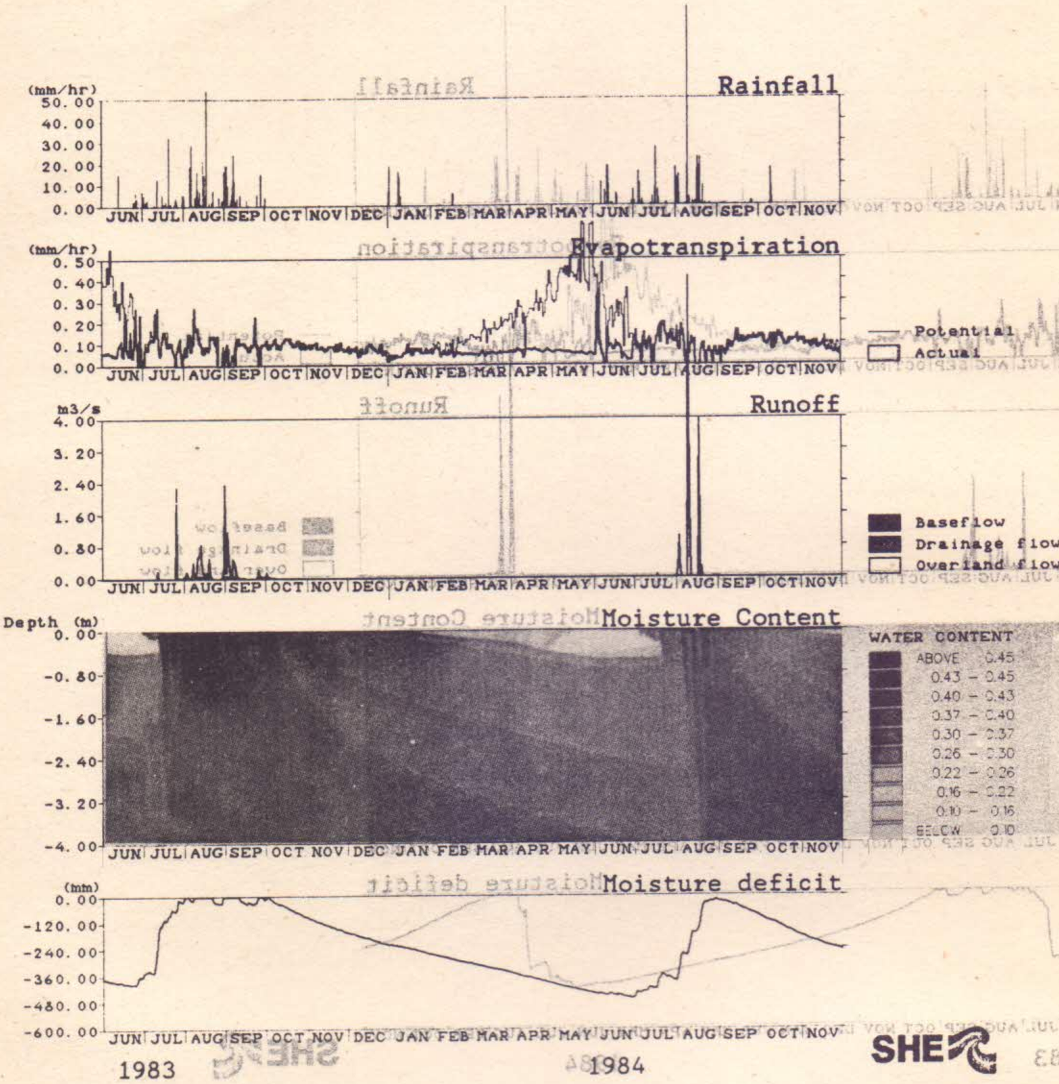


Fig. 38: Variation of soil moisture deficit, moisture content, runoff, evapotranspiration & rainfall for Run(f) of sensitivity analysis.

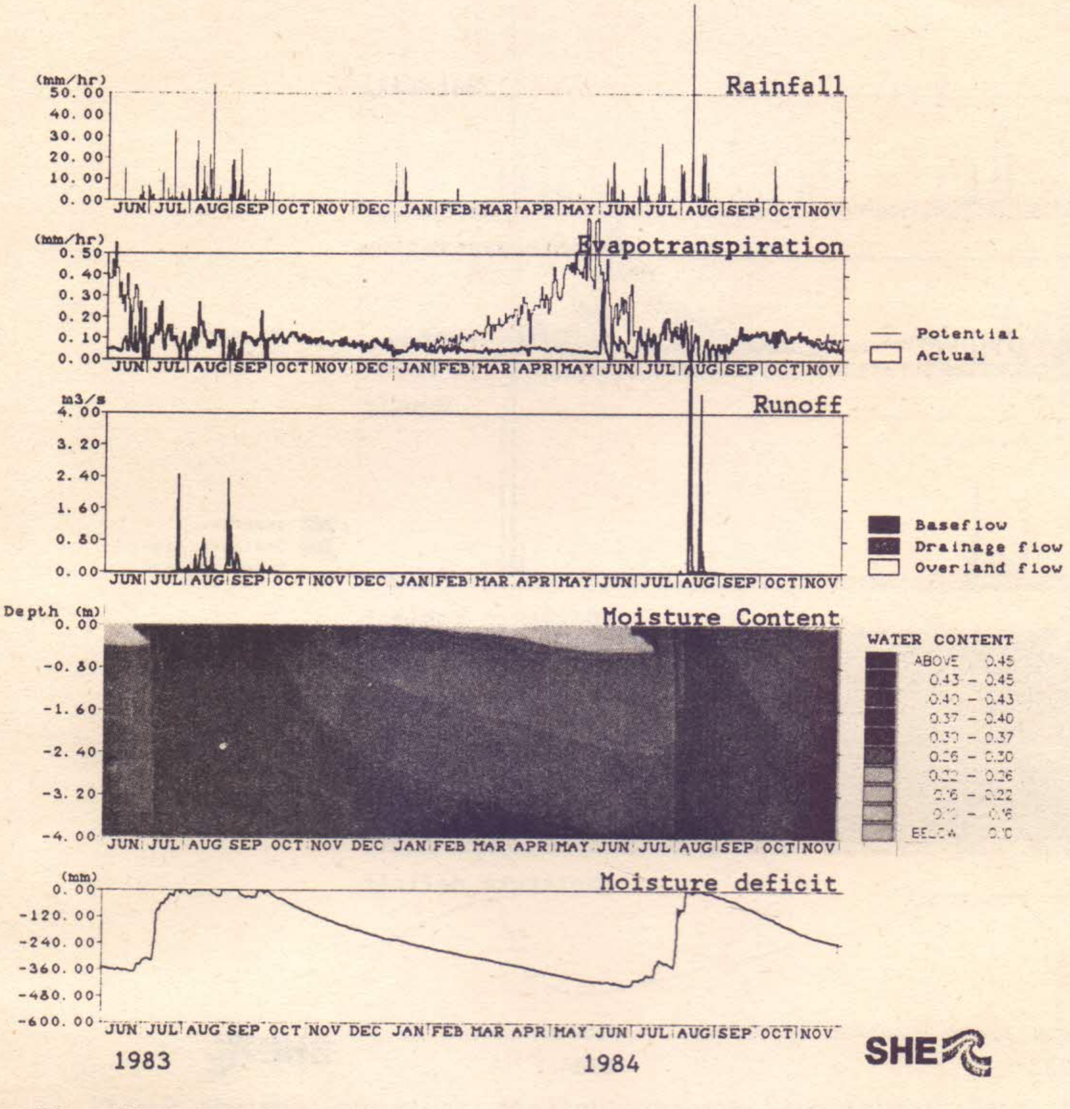


Fig. 39: Variation of soil moisture deficit, moisture content, runoff, evapotranspiration & rainfall for Run (g) of sensitivity.

piration in dry season is due to loss of moisture by capillary rise resulting from higher soil conductivity. Reduction in runoff is on account of higher infiltration as a result of higher soil conductivity.

7.0 CONCLUSIONS

The SHE model has been successfully used for modelling the entire landphase of hydrological cycle for Ganjal sub-basin, within the constraints of availability of data, time, and assumptions made. Conventional hydrological data of daily and hourly rainfall for some stations (inside/outside the basin) and hourly stages and daily stage-discharge at basin outlet were available. Pan evaporation data of Jabalpur station lying outside the basin have been used. Split sample approach has been used for simulation using 2km x 2km grid size. Data for the period March 1982 to February 1985 have been used for calibration of the model and data from March 1985 to December 1987 have been used for validation of the model. Sensitivity analysis has been carried for potential evapotranspiration data of four pan evaporation measurement stations as well as for the important parameters such as exponent in Averjaneovs formula used in the SHE, water content at wilting point and residual water content as well as saturated conductivity of unsaturated zone. On the basis of the present study, the following concluding remarks can be made:

a) The raingauge stations available in the sub-basin do not adequately represent the spatial and temporal distribution of rainfall. The simulation results are, therefore subject to uncertainties associated with the rainfall data.

b) The value of soil and vegetation parameters, which play a significant role in the simulation; in the absence of their availability for the basin, have been taken from indirect sources and available literature. Simulation runs have been made assuming uniform soil all over the basin. The spatial distribution of soil depth and root zone depth for various types of vegetation have been assumed on the basis of information gathered from field visits and general experience. Simulation results are therefore affected by these assumptions.

c) Inspite of data limitations and assumptions made, the calibration results show reasonably good reproduction of streamflow volumes, peaks and hydrographs. However, the performance of the model in simulating groundwater response was not of the desired level. Further, in the absence of observed values, the simulated soil moisture conditions and actual evapotranspiration could not be compared with the actual values.

d) The validation results using independent data set also show reasonable simulation of streamflow volumes, peaks and hydrographs. The groundwater and soil moisture resonse similar to calibration results is observed.

e) It is observed from sensitivity analysis, that simulation results are not much sensitive to potential evaporation data. Actual simulated evapotranspiration and runoff are very sensitive to the exponent appearing in Averjanov's formula as well as water content value at wilting point and residual water content. An increase in the value of saturated conductivity of unsaturated zone results in higher actual evapotranspiration in dry season due to loss of moisture by capillary rise.

f) As such, though the SHE model structure in its present form simulates the vertical movement of water, both upward and downward; the physical relevance of overland and channel flow component is somewhat affected by grid sizes. The present SHE code does not allow consideration of water bodies such as reservoirs, lakes, irrigation canal systems etc; existing in the basin and their interaction with hydrological processes of runoff generation and groundwater recharge. River network in the model has to follow grid boundaries; as a result coarser grid scale leads to distortion in the river network. 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 generally available

However, for dealing with situations such as conjuctive use of water and evaluation of effects of landuse/landcover changes on hydrological regime; distributed models like SHE are very much useful. This study has also indicated that besides soil type and landuse type distribution in a basin; it is also desirable to have information about soil depth and soil moisture observations, for better simulation.

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DIRECTOR : SATISH CHANDRA

PROJECT COORDINATOR : S M SETH

SCIENTIST : RAKESH KUMAR

SCIENTIFIC STAFF : PANKAJ KUMAR GARG
T. VIJAY
DIGAMBAR SINGH
MUKESH KUMAR SHARMA

OFFICE STAFF : PRABHAKARA PANICKER T
SANDEEP KUMAR
RAM KUMAR

DOCUMENTATION STAFF : MRS. NISHA KICHLU