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APPLICATION OF SHE MODEL TO NARMADA (UPTO MANOT) BASIN

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PREFACE

The way the development of the Narmada basin is affecting the hydrological regime, is difficult to quantify by conventional methods. The conventional rainfall/runoff models are inappropriate to many pressing hydrological problems, especially those related to the impact of man's activities on land-use change and water quality. Only through the use of models which have a physical basis and allow for spatial variations within a catchment can these problems be tackled. Through its foundation on physical principles and a distributed structure, the SHE is able to tackle issues denied to conventional rainfall/runoff models, especially the consequences of man-made changes in a catchment. It is therefore appropriate for use in the Narmada basin where the assessment of land-use change impacts, water-logging risks from irrigation and other problems is hampered by the lack of extensive hydrometeorological records and can not easily be carried out by simpler models.

The present study is a part of the project concerned with the transfer of the Systeme 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 (CEC) and the Government of India. Under the project, six NIH Scientists have been trained in theoretical and practical aspects of SHE, at Danish Hydraulic Institute, Denmark.

Narmada (upto Manot) is one of the six sub-basins selected for model application in the Narmada basin. The present study consists of data assembly and processing, evaluation of model parameters, assessment of uncertainty in input quantities, carrying out simulation runs, including formulating the approach to calibration, validation and sensitivity analysis and interpreting the results. The study has been carried out by Shri Chandra Prakash Kumar, Scientist 'B' under the guidance of Dr. S.M. Seth, Scientist 'F' and Coordinator, SHE Model Studies and in close interaction with consultants from the Danish Hydraulic Institute (Denmark), the University of Newcastle upon Tyne (U.K.) and SOGREAH (France).

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ABSTRACT

The Systeme Hydrologique Europeen (SHE), a physically-based, distributed, catchment model has been implemented for Narmada (upto Manot) basin in Madhya Pradesh, India. The SHE is physically based in the sense that it is derived directly from equations of flow and mass conservation for the hydrologic processes it aims to represent, and it is distributed by describing the catchment on a rectangular grid system. The capacity of SHE to account for spatial variations in meteorologic and hydrologic inputs represents an important advantage over traditional lumped catchment models.

The computational grid network and channel system was set up for the basin, forming the basis for the spatial distribution of topographic elevation, soil type, land use and rainfall stations in the data files. The basic network was composed of grid squares of 1 km x 1 km, but in view of the heavy computing requirements associated with such densely defined systems, this was converted to arrays with grid squares of 2 km x 2 km for the simulation work. Since direct measurements of soil and vegetation properties for the basin were not available, the model parameters were evaluated using information taken from the literature on neighbouring areas. Four land uses were identified (agricultural land, dense mixed forest, thin forest and waste land). Three categories of soil depth were defined

for low land, semi-hilly and hilly areas, the distributions obtained from the topographic maps. However, the same soil retention curve, typical of black cotton clays, was used throughout.

The calibration and validation of the model was achieved on the basis of physical reasoning and through consideration of the variation of runoff response from the basin. The calibration was carried out for the period 1982-84 by varying only a few of the parameters and was then validated against 1985 and 1987 hydrographs, on the basis of changes in the initial level of the phreatic surface. Some deficiencies in the simulations were noted but, in general, there were good agreement between observed and simulated responses. Sensitivity analysis was also carried out for the basin to study the sensitivity of model grid spacing and flow resistance coefficients to the simulated hydrological regime.

1.0 INTRODUCTION

1.1 Water Resources Development - Man's Influence on River Basin

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

1.2 Modelling as a Tool - Suitability of Distributed Approach

A model represents the physical/chemical/biological characteristics of the catchment and simulates the natural hydrological processes. It is not an end in itself but is a tool in a larger process which is usually a decision problem. A model aids in making decisions, particularly where data or information are scarce or there are large numbers of options to choose from. It is not a replacement for field observations. Its value lies in its ability, when correctly chosen and adjusted, to extract the maximum amount of information from the available data, so as to aid in decision making process.

In classifying hydrological models the following terms are widely used :

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

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

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

A **distributed model** includes spatial variations in all variables and parameters. A probability - distributed model describes spatial variability without reference to the geometrical configuration of the points in the network at which inputs, variables and parameters are determined. A geometrically - distributed model expresses spatial variability in terms of the orientation of the network points one to another, and their distances apart.

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

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

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

It is considered that the further development or enhancement of the conventional hydrological models can not provide a sound scientific basis for tackling many of the problems concerned with the effects of land-use change related to agricultural and forestry practices, hazards of pollution and toxic waste disposal and general problems arising from conjunctive uses of water. These lumped parameter, rainfall-runoff models depend essentially on the availability of sufficiently long meteorological and hydrological records for their calibration and such records are not always available. Their calibration also involves a significant element of curve fitting, thus making any physical interpretation of the fitted parameter values extremely difficult. Under these circumstances, prediction of the effects of land-use changes on the hydrological regime of a catchment, particularly where only part of the catchment is affected, can not be undertaken with any confidence. There is no reliable means of altering the model parameters to reflect the changes, since the parameters are not physically based.

Because of their inherent structure these models also make very little use of contour, soil and vegetation maps, or of the increasing body of information in such areas as soil physics and plant physiology. Similarly, much historical information frequently consulted during project planning, for example crop yields over specific periods, survival patterns of particular types of vegetation and characteristic events occurring during floods and droughts, is not used directly. A considerable improvement in project planning could therefore be derived from the integration of such information into the modelling process. In particular physically-based, distributed models can in principle overcome many of the above deficiencies through their use of parameters which have a physical interpretation and through their representation of spatial variability in the parameter values.

1.3 Narmada Basin - Water Resources Development

The Narmada is one of the twin rivers of Central India which drains peninsular part of India. It flows from east to west. Out of its total length of 1,312 km it flows 1,079 km through Madhya Pradesh; 35 km as boundary between Madhya Pradesh and Maharashtra; 39 km between Maharashtra and Gujarat. The lower reaches of about 159 km are in the state of Gujarat. The total area of the basin is 98,796 km². It rises in Amarkantak (1,057 m),one of the highest spots of Maikala range and joins the Arabian Sea. The magnitude of water resources may be realised by the fact that the Narmada brings water almost equal to Sutlej and Beas combined and its average annual flow at Gardeshwar, the lowermost discharge site is 38,670 million cubic metres.

The gross cultivated area is 4.8 million ha. The gross sown area is 80% of the cultivable area but the irrigated area is only 16%. The soils are mainly black and in the coastal plains of Gujarat they are clayey, alluvial soils, black on the surface. Inspite of excellent water resources in the basin, it is one of the poorly irrigated valleys. There is an excellent potential for developing ground water in the Narmada valley. The alluvial soils comprise alternating beds of sand and clay with lateric soil as cover. The ground water occurs both under water table and confined conditions, and perched water table conditions also occur at a few places.

The Narmada basin was not subject to any serious famines so that no ancient irrigation works exist on the Narmada and its tributaries. Only recently the Tawa, the Barna and the Chandrakeshar projects have been taken up in Madhya Pradesh. A total area of a million hectares will be developed when the projects are completed. The Narmada is yet to be developed on a large scale.

Compared with black box and lumped models, physically-based, distributed models have large appetites for data. Because of the physical significance of the parameters, it is possible to measure the parameters in the field. For some of the sub-basins of Narmada river, reasonable amount of data was available for carrying out studies for application of models such as SHE.

1.4 SHE Model Project at NIH funded by CEC

In 1987, a collaboration was initiated between National Institute of Hydrology (NIH), Roorkee, India and Danish Hydraulic Institute (DHI), Denmark in association with its European SHE partners. The project is concerned with the transfer of the Systeme Hydrologique Europeen (SHE) hydrological modelling system to the National Institute of Hydrology, 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 ALA 86/19, 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 Consultant, a group headed by the Danish Hydraulic Institute (DHI), Denmark and composed also of SOGREAH (France) and the U.K. Natural Environment Research Council's Water Resource Systems Research Unit at the University of Newcastle upon Tyne (UON).

The project commenced on the arrival of the Consultant's Project Manager at National Institute of Hydrology, Roorkee on November 18,1987. The project has a duration of 38 months. 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 scientists in the use of the SHE at both NIH and DHI. Data collection from central and state agencies, training courses and model studies are the key elements of the project.

The Narmada basin in the state of Madhya Pradesh, India has been selected for model applications since this basin is undergoing large-scale water resources development with complex environmental repercussions which SHE is designed to model. The following six tributary basins were chosen as the basis for focus applications.

1. Narmada upstream from Manot (area 4980 km^2)
2. Hiran upstream from Patan (area 4064 km^2)
3. Sher upstream from Belkheri (area 1345 km^2)
4. Barna upstream from Bareli (area 1530 km^2)
5. Kolar upstream from Satrana (area 820 km^2)
6. Ganjal upstream from Chhidgaon (area 1730 km^2)

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

In addition to the four months intensive training courses in Europe, on-the-job training is carried out in connection with the project work at NIH. Subsequent model applications encompassing e.g. simulation of irrigation command areas and scenario studies of the impact of land use change in the basins are planned.

The present report deals with the SHE model application study involving calibration, validation and sensitivity runs for the Narmada (upto Manot) basin.

2.0 SHE MODEL

2.1 General

The SHE is a physically-based, distributed, catchment modelling system produced jointly by the Danish Hydraulic Institute, the British Institute of Hydrology and SOGREAH (France) with the financial support of the Commission of the European Communities. The SHE developed from the perception that conventional rainfall/runoff models are inappropriate to many pressing hydrological problems, especially those related to the impact of man's activities on land-use change and water quality. Only through the use of models which have a physical basis and allow for spatial variations within a catchment can these problems be tackled. The physical basis and flexible operating structure of the SHE allows the model to use as many or as few data as are available and also to incorporate data on topography, vegetation and soil properties not normally included in catchment models. It does not require a lengthy hydrometeorological record for its calibration and its distributed nature enables the spatial variability in catchment inputs and outputs to be simulated. However, the large amount of data required by the model means that new operation methodologies must be evolved. Thus spatial scale effects or simply a lack of data may create significant uncertainties in the values of the catchment parameters used in a simulation. These uncertainties will give rise to corresponding uncertainties in the predictions. However, the SHE is able to quantify these uncertainties by carrying out sensitivity analyses 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".

2.2 Salient Features

It is envisaged that the SHE will be applicable to almost any kind of hydrological problem, although extensive further development and refinement is still needed to realise this vision. The flexible model structure combined with the distributed structure and the physical interpretation of the hydrological processes, is expected to provide significant advantages over existing hydrological models for a wide range of applications. Obviously there are many problems for which the necessary solutions can be obtained using cheaper, conventional rainfall/runoff models. However, for the more complicated problems there may be little alternative but to use a system such as the SHE. Some examples are as follows:

(1) Catchment changes

These include both natural and man-made changes in land-use, such as the effects of forest fires, urbanisation and forest clearance for agricultural purposes. The parameters of a physically-based, distributed model have a direct physical interpretation, which means that they can be evaluated for the new state of catchment before the change actually occurs. This enables the effects of changes to be examined in advance of such changes. In addition, the characteristically localised nature of catchment changes can easily be accounted for within the spatially distributed model structure.

(2) Ungauged catchments

An application in a previously ungauged catchment requires the initiation of a programme of field work to provide data and parameters for calibration. The physical significance of its model parameters enables the SHE to be applied on the basis of a much shorter, and therefore more cheaply obtained, hydrometeorological record than is necessary for more conventional models. Similarly, the catchment parameters can be estimated from intensive, short-term field investigations.

(3) Spatial variability in catchment inputs and outputs

Distributed models can be used to examine the effects on flood flows of different directions of storm propagation across a catchment and also the effects of localised river and ground water abstractions and recharge. This facility is beyond the capability of lumped catchment models which can deal only with quantities averaged across the catchment.

(4) Movement of pollutants and sediments

In order to model the movement of pollutants and sediments, it is first necessary to model the water flows which provide the basic dispersion mechanism. Most water quality and sediment problems are distributed in nature, so distributed models are the most suitable for supplying the basic information on water flows.

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 SHE is physically based 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 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 through the representation of the catchment by an orthogonal grid network and in the vertical by a column of horizontal layers at each grid square (figure 1). The channel system is represented on the boundaries of the grid squares. Grid

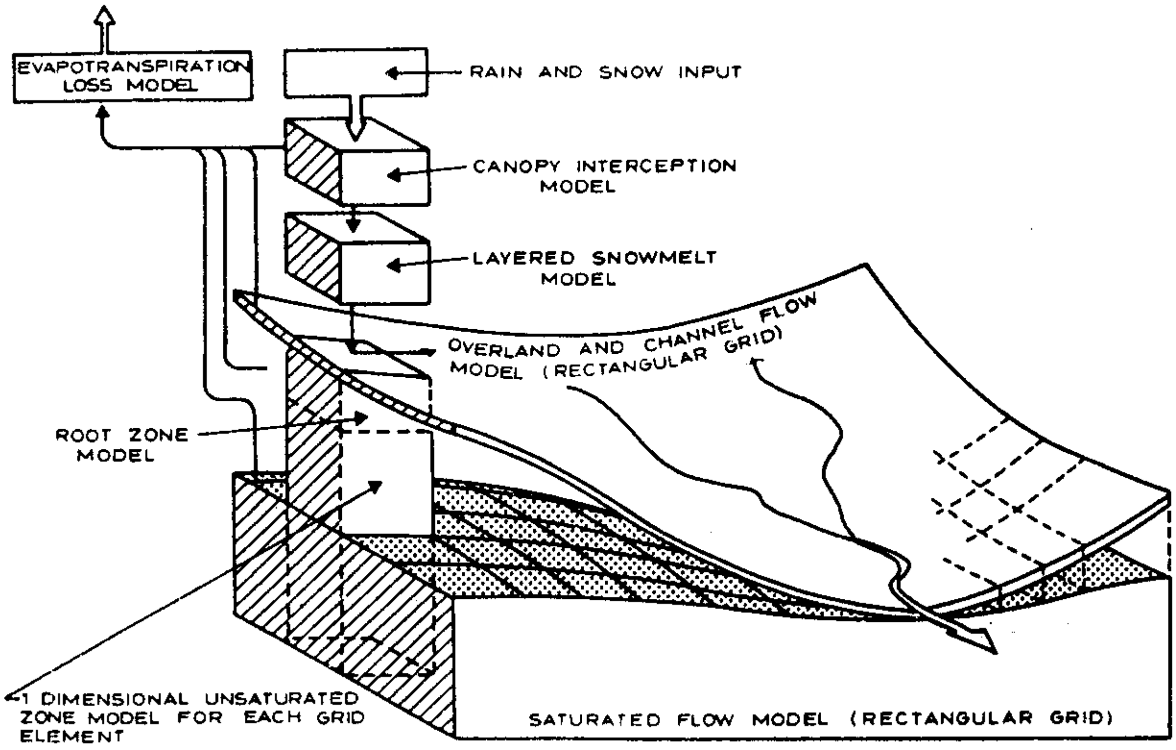


FIGURE 1 - STRUCTURE OF THE EUROPEAN HYDROLOGIC SYSTEM (SHE)

spacing in the horizontal can vary across the network but must be the same for a given row or column within the network array. Node spacing in the vertical is a function of the vegetation type which characterizes a given grid square and can vary between the root zone and the soil layer below the root zone.

Only the primary components of the land phase of the hydrological cycle are modelled - snowmelt, canopy interception, evapotranspiration, overland and channel flow and unsaturated and saturated subsurface flow. It is assumed that, for most slopes, flow in the unsaturated subsurface zone is essentially vertical and flow in the saturated subsurface zone is essentially horizontal. The result is a model structure in which independent, one-dimensional, unsaturated flow columns of variable depths link a two-dimensional overland flow component with a two-dimensional saturated flow component. Such an arrangement ensures acceptable computing costs at an acceptable level of approximation of the catchment processes. However, it also poses the numerical problem of linking one-dimensional and two-dimensional subsurface models at a time-varying interface (the phreatic surface). It also means that, in a simulation, runoff can reach the river system only as overland flow or as saturated flow.

In water resources projects the level of complexity at which modelling can be carried out varies according to data availability, type of problem, scale of operation, required accuracy, computer facilities and economic considerations. The SHE has therefore been designed as a flexible modelling system, encompassing several levels of complexity. This has been achieved through the use of structured programming, modular design and incorporation of various levels of sophistication for the process models. Within the computer software each hydrological process is allocated its own component and the simultaneous operation of all the components is controlled by the central FRAME component. These components can be modified or omitted in any given application, depending on the hydrological conditions and availability of data. Each component can also be used with different time steps, in order to accommodate the variations in time scales which characterize hydrological processes. Additional flexibility is assured through the ability of the SHE to use as few or as many data as are available, either from field measurements or from the scientific literature.

2.3 Typical Approaches for Modelling of Different Processes

To model each of the major hydrological processes of water movement, the following components are structured within the SHE.

1. FRAME (central control) component
2. Interception and evapotranspiration component

3. Overland and channel flow component
4. Unsaturated zone component
5. Saturated zone component
6. Snowmelt component

A detailed description of the above components is given by Abbott et al.(1986). In the following, the components in SHE will briefly be discussed.

1. FRAME (Central Control) Component

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

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

2. Interception and Evapotranspiration Component

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

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

Net rainfall, transpiration and soil evaporation rates are supplied to the unsaturated zone component, which in return provides information on soil moisture conditions in the root zone. Because interception can significantly affect evapotranspiration, the two processes are modelled within the one overall component.

Interception

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

Evapotranspiration

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

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

3. Overland and Channel Flow Component

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

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

4. Unsaturated Zone Component

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

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

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

where,

Ψ = soil moisture tension or pressure head;

t = time;

z = vertical space coordinate (positive upwards);

$C = \frac{\partial \theta}{\partial \Psi}$ = soil water capacity;

θ = volumetric water content;

$K(\theta, z)$ = hydraulic conductivity;

$S(z)$ = source/sink term for root extraction and soil evaporation.

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

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

5. Saturated Zone Component

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

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

$$S \frac{\partial h}{\partial t} = \frac{\partial}{\partial x}\left(K_x H \frac{\partial h}{\partial x}\right) + \frac{\partial}{\partial y}\left(K_y H \frac{\partial h}{\partial y}\right) + R \qquad \ldots(2)$$

where,

$S(x,y)$ = specific yield;

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

$K_x(x,y), K_y(x,y)$ = saturated hydraulic conductivities in the x and y directions respectively;

$H(x,y,t)$ = saturated thickness;

t = time;

x,y = horizontal cartesian coordinates;

$R(x,y,t)$ = instantaneous vertical recharge into the saturated zone.

This can be expressed by :

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

where,

Σq = transpiration + soil evaporation + infiltration + stream/aquifer exchange + external boundary flows;

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

gs = ground surface level.

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

6. Snowmelt Component

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

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

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

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

2.4 Data Required for SHE Model Application

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

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

FRAME Component

Model parameters	(i)	Ground surface elevation
	(ii)	Impermeable bed elevation
	(iii)	Distribution codes for rainfall and meteorological source stations
	(iv)	Distribution codes for soil and vegetation types

Interception Component

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

Evapotranspiration Component

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

Overland and Channel Flow Component

Input data	(i)	Specified flows or water levels at boundaries
	(ii)	Man-controlled diversions and discharges
	(iii)	Topography of overland flow plane and channel cross-sections
Model parameters	(i)	Strickler roughness coefficients for overland and river flows
	(ii)	Coefficients of discharge for weir formulae

Unsaturated Zone Component

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

Saturated Zone Component

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

Snowmelt Component

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

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

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

2.5 Studies Elsewhere using SHE Model

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

(i) a study of the effects of land use changes on floods and sediment loads (Thailand),

(ii) a study of the environmental impact of the use of fertilizers (Denmark),

(iii) a water supply planning project for the city of Aarhus (Denmark),

(iv) a comparative study of different models to simulate runoff from medium size catchments (Zimbabwe and Denmark),

(v) a study of the effects of irrigation development (India)

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

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

3.0 GENERAL DESCRIPTION OF STUDY AREA AND DATA AVAILABILITY

3.1 General

The Narmada is a major west-flowing river in Central India running through the states of Madhya Pradesh, Gujarat and Maharashtra. The basin is bounded on the north by the Vindhyas, on the east by the Maikala range, on the south by the Satpuras and on the west by the Arabian Sea and has a catchment area of 98,796 Km^2 (figure 2). From its source to its outflow in the Arabian Sea the mainstream stretches 1312 Km and is joined by 41 tributaries, oriented in the north-south direction.

The climate is generally humid tropical but ranges from subhumid in the east to semi-arid in the west. The average annual rainfall is 1200 mm. The south-west monsoon is the main source accounting for 90 percent of the annual rainfall, of which 60 percent falls during the months of July and August.

Soil surveys indicate that the major part of the Narmada basin consists of a variety of black soils with a large content of clay. Mixed red and black soils, red and yellow soils and skeletal soils are observed at isolated areas. The soils are generally deep in the plain areas along the Narmada river, whereas shallow soils, less than one metre deep, are found in the upland catchment areas of the tributaries.

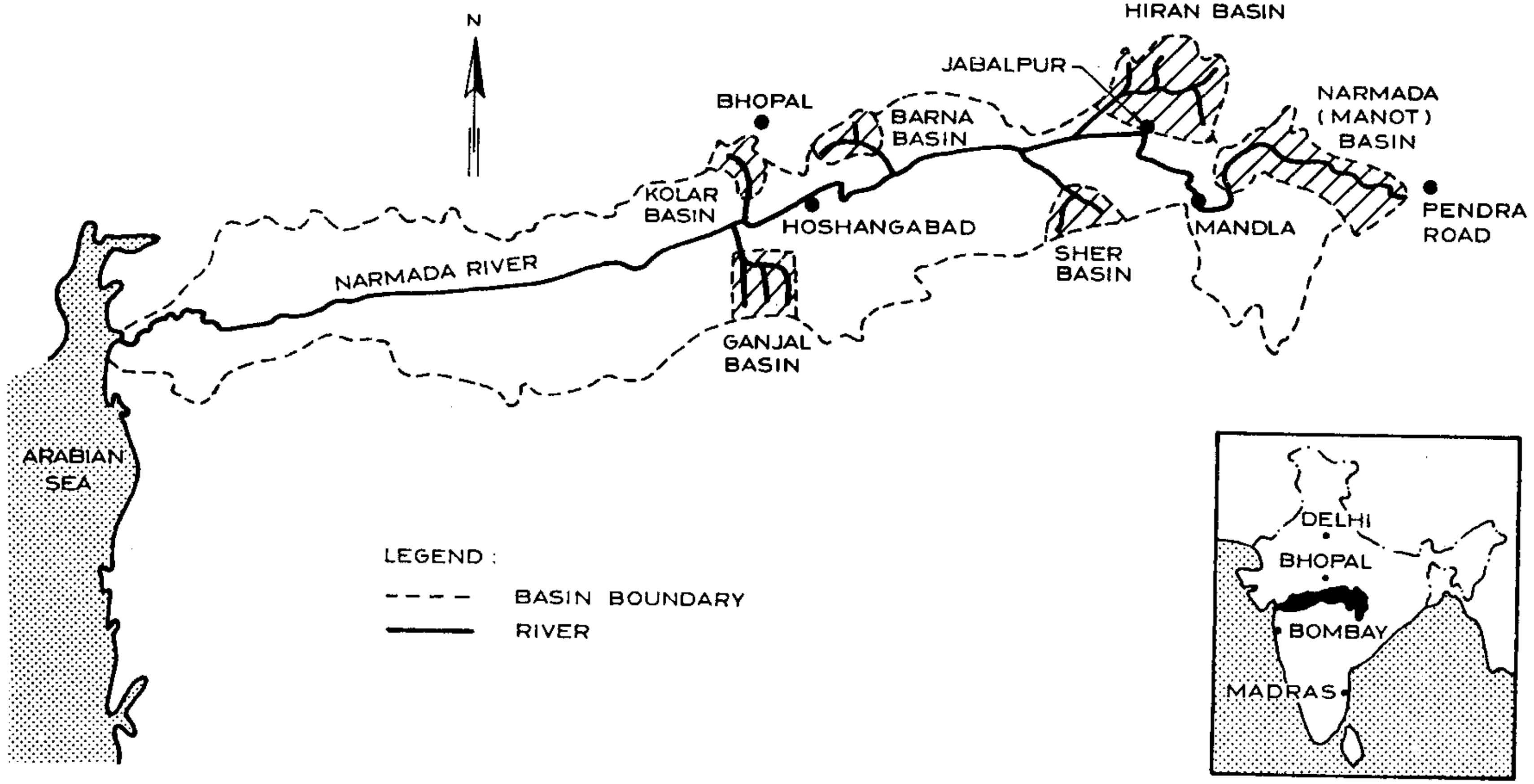


FIGURE 2 - INDEX MAP OF THE NARMADA RIVER BASIN

The vegetation in the Narmada catchment includes a variety of agricultural crops in the plains and forest of varying density in the upland areas. Areas of scrub land and bare soils are also widely observed.

The Narmada river has a huge potential for water resources development and presently 29 major, 135 medium and approximately 3000 minor irrigation projects have been proposed. Some of these are already in operation and several major schemes are under construction including the Sardar Sarovar dam (catchment area 88,000 km^2), the Indira Sagar (formerly Narmada Sagar) dam near Punasa (61,000 km^2) and the Bargi dam (15,000 km^2) on the Narmada river. The Kolar dam is under construction on the Kolar river and two schemes are already operating on the Barna and Tawa rivers.

The hydrological problems associated with the existing and proposed development are complex. Water resources studies will therefore be required on a variety of aspects such as :

* Estimation of runoff from ungauged catchments
* Surface water - ground water interaction
* Conjunctive use
* Predictions of effects of land use change on water yields, floods, low flows, soil erosion etc.

All these types of problems require hydrological modelling studies and in some cases distributed approach is necessary.

3.2 Location of Narmada (upto Manot) Basin

The Narmada basin (upto Manot) lies between east longitudes 80°24' to 81°47' and north latitudes 22°26' to 23°18', most of the part lying in Mandla district and some part in Shahdol district of Madhya Pradesh. The basin comprises the 4980 km^2 head water catchment of the Narmada defined by the Central Water Commission gauging site at Manot, where the river length is about 269 km (figure 3). The river rises in the Maikala range near Amarkantak in the Shahdol district of Madhya Pradesh, at an elevation of 1,057 m at north latitude 22°40' and east longitude 81°45'. It flows in a generally northwesterly direction but turns in a loop to the south upstream of Manot. At present the upper Narmada is not subject to any major development.

3.3 Climate and Rainfall

The tropic of Cancer crosses the basin in the upper plains area and a major part of the basin lies just below this line. The climate of the basin is humid and tropical, although at places extremes of heat and cold are often encountered. In the year, four distinct seasons occur in the basin. They are (i) cold weather, (ii) hot weather, (iii) south-west monsoon and (iv) post-monsoon.

The cold weather season which commences in December and continues till the end of February, is characterised by bright cloudless days, clean nights and piercing winds.

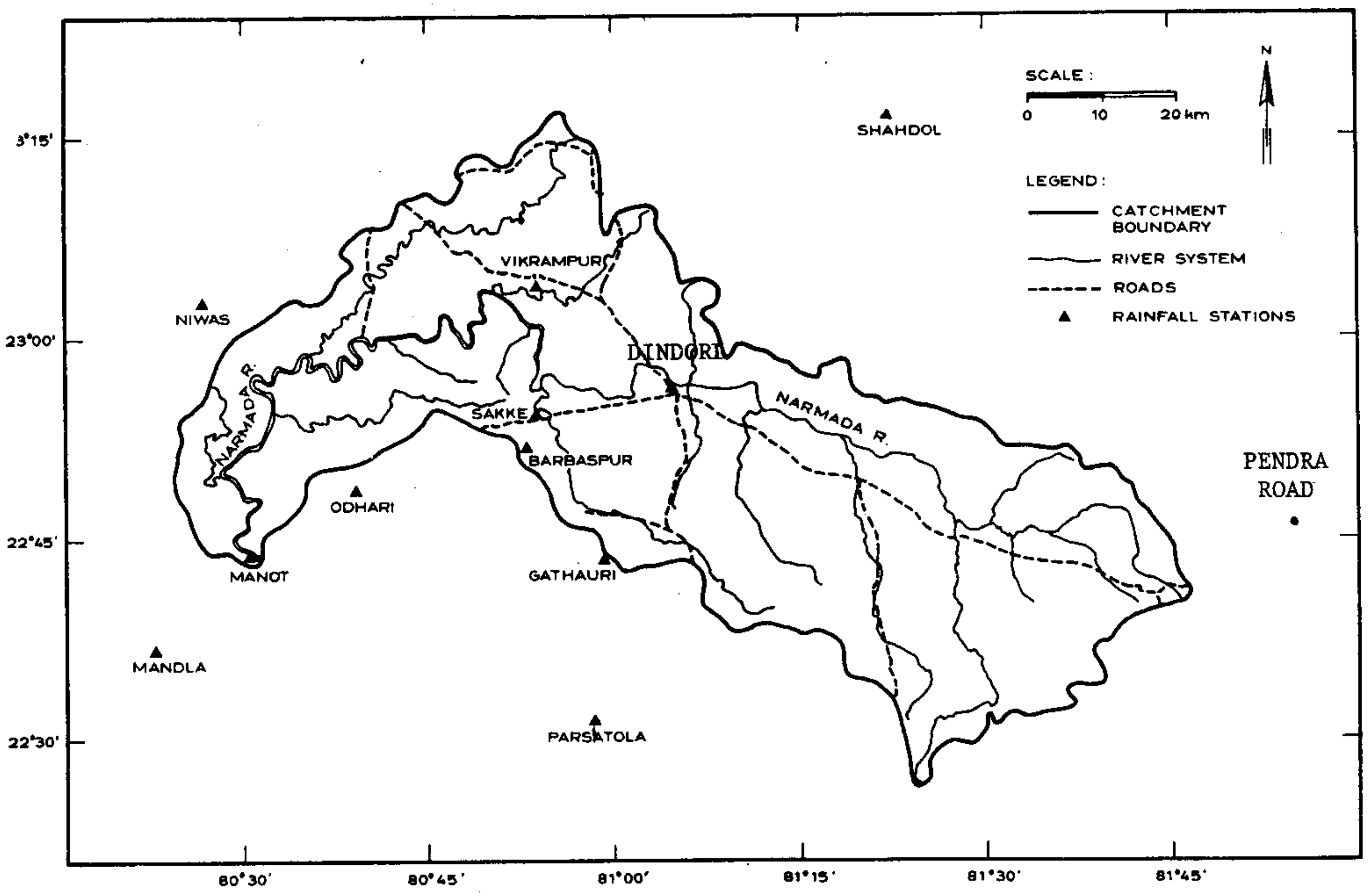


FIGURE 3 - THE NARMADA BASIN UPSTREAM OF THE MANOT GAUGING SITE

Frost is known to occur occasionally, hail too is not uncommon. There is slight precipitation in the basin during this season. The hot weather starts in March and continues upto the middle of June. May is usually the hottest month. This season is generally dry except for occasional thunder-storms. The south-west monsoon sets in by the middle of June and withdraws by the first week of October. June to September are the rainy months. During this season, the weather is somewhat sultry and oppresive, especially in areas adjoining the Narmada river. In the post-monsoon season, a few thunder-storms occur, especially in October. Thereafter, the weather clears up and dry pleasant weather prevails throughout the valley.

In the cold weather, the mean annual temperature varies from 17.5°C to 20°C and in the hot weather from 30°C to 32.5°C. In the south-west monsoon, the temperature ranges from 27.5°C to 30°C. In the post-monsoon season, temperatures between 25°C to 27.5°C are experienced. The maximum and minimum temperatures for Mandla town, very near to the basin, are given in table 1, which clearly indicate the extent of variations.

Nearly 90 percent of the total rainfall is received during the five monsoon months from June to October. The monthly and annual normals of rainfall in Mandla district are shown in table 2.

Table 1 - Maximum and Minimum Temperatures in Mandla

Period	Maximum (°C)	Minimum (°C)
January - March	34.9	9.0
April - June	40.2	19.6
July - September	29.1	21.7
October - December	29.4	6.8

3.4 Topography

Topography of the Narmada basin above Manot is hilly with forest cover, especially in the upper reaches. Flat farmland is more evident in the lower reaches. Flat agricultural areas containing bunded fields are interrupted by low hills with a medium to dense forest cover. Topographically, the basin can be divided into three distinct levels - low land areas, hill slopes or semi-hilly areas, and upland or hilly areas (figure 4). The topographic elevations in the basin ranges from 450 m near the Manot gauging site to 1110 m in the upper part of the basin. Figures 5,6 and 7 present the topography of the basin with the following observations -

Figure No.	**Grid Size**	**Topography based upon**	**Remarks**
5	1 km x 1 km	Point values	contours shown
6	2 km x 2 km	Average grid values	river network shown
7	2 km x 2 km	Average grid value	contours and river network shown

Table 2 - Monthly and Annual Normal Rainfall in Mandla District

Month	Normal Rainfall in mm
January	27.8
February	34.7
March	24.5
April	17.2
May	16.4
June	196.2
July	492.7
August	447.8
September	226.5
October	59.7
November	18.4
December	7.7
Annual Normal Rainfall in mm	1569.6

[Source : Memoirs of the India Meteorological Department, Vol.XXXI, Part III]

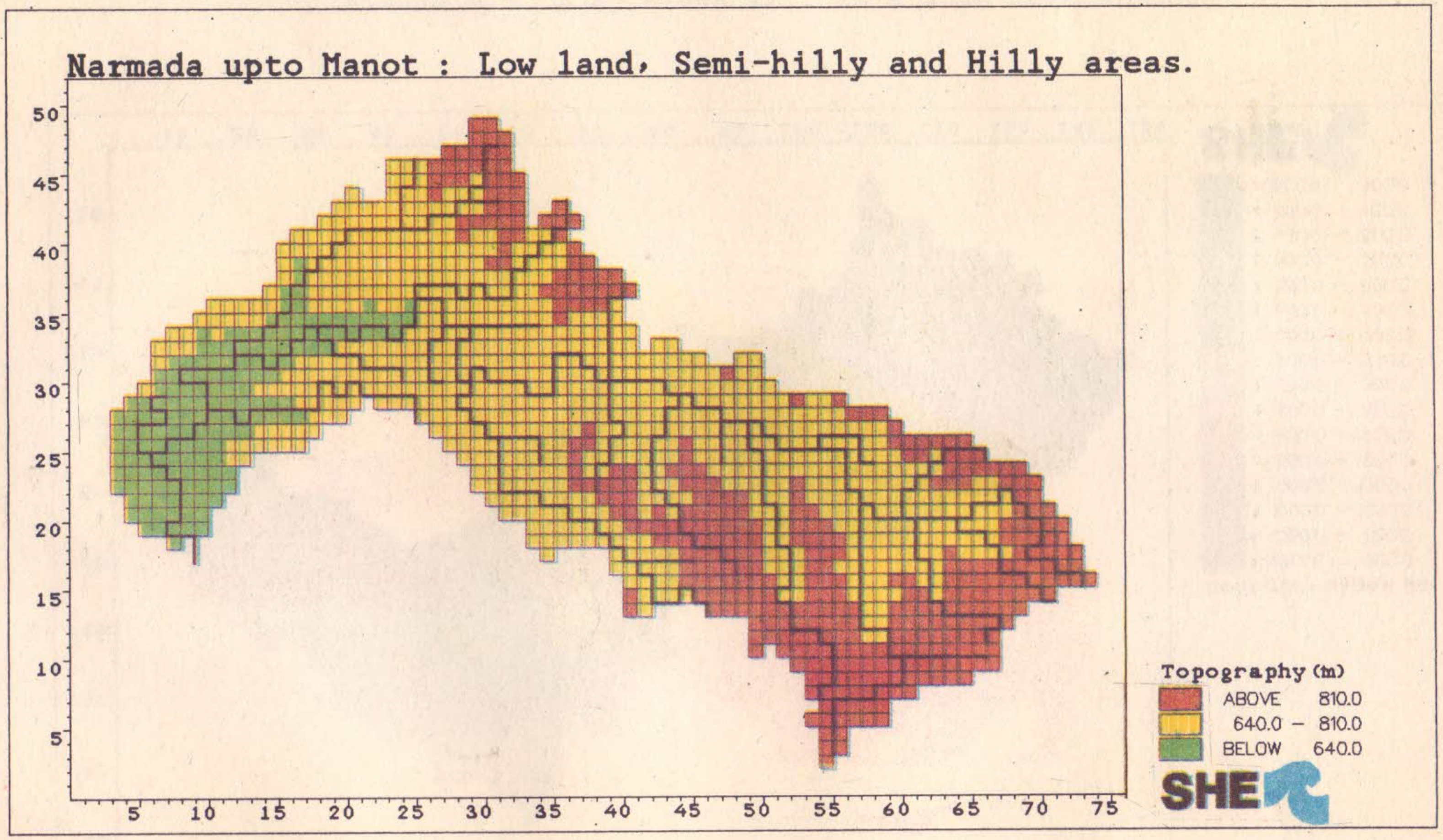
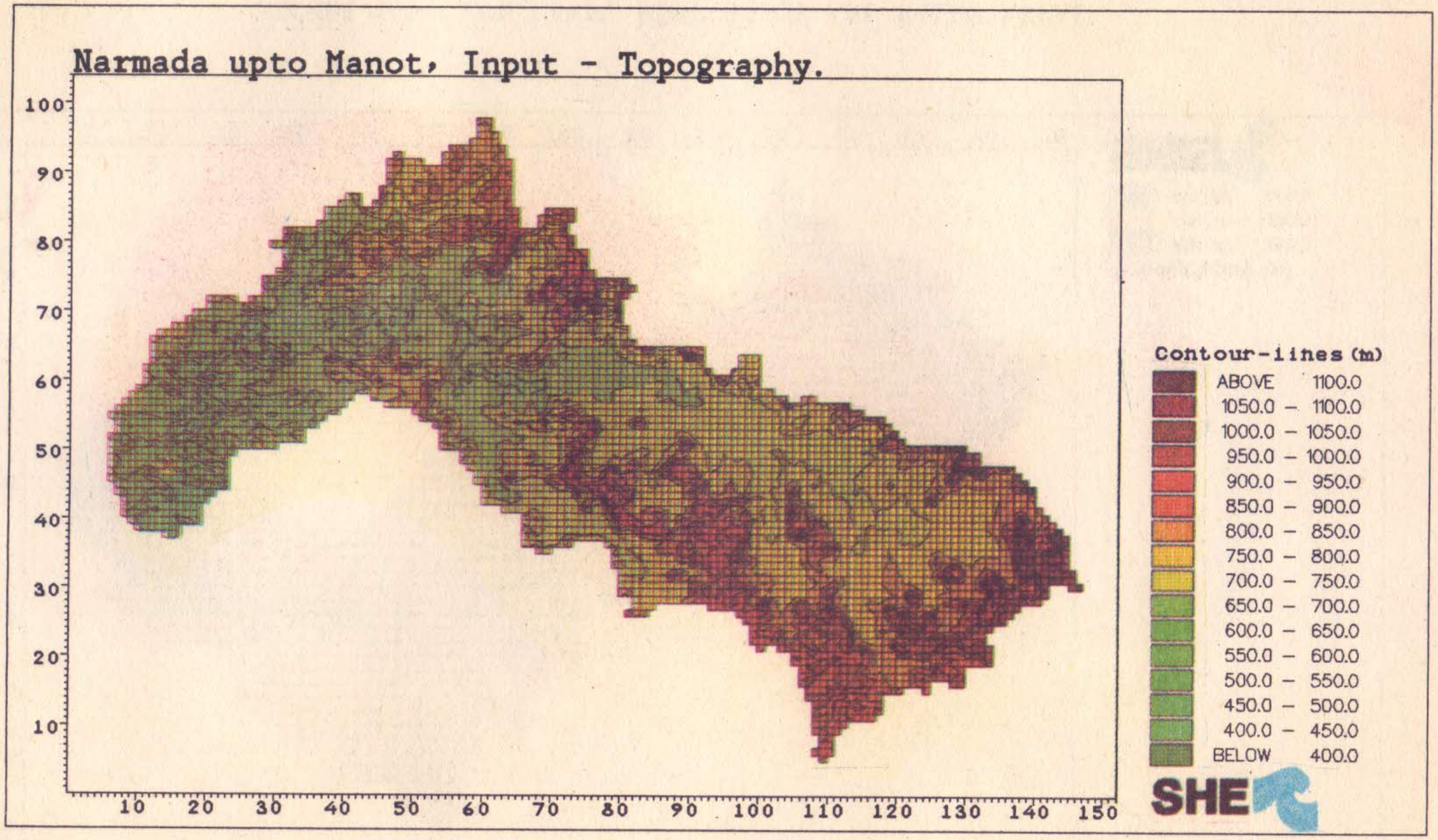


FIGURE 4 - LOW LAND, SEMI-HILLY AND HILLY AREAS



Narmada upto Manot, Input - Topography.

FIGURE 5 - TOPOGRAPHY IN 1 KM X 1 KM GRID NETWORK

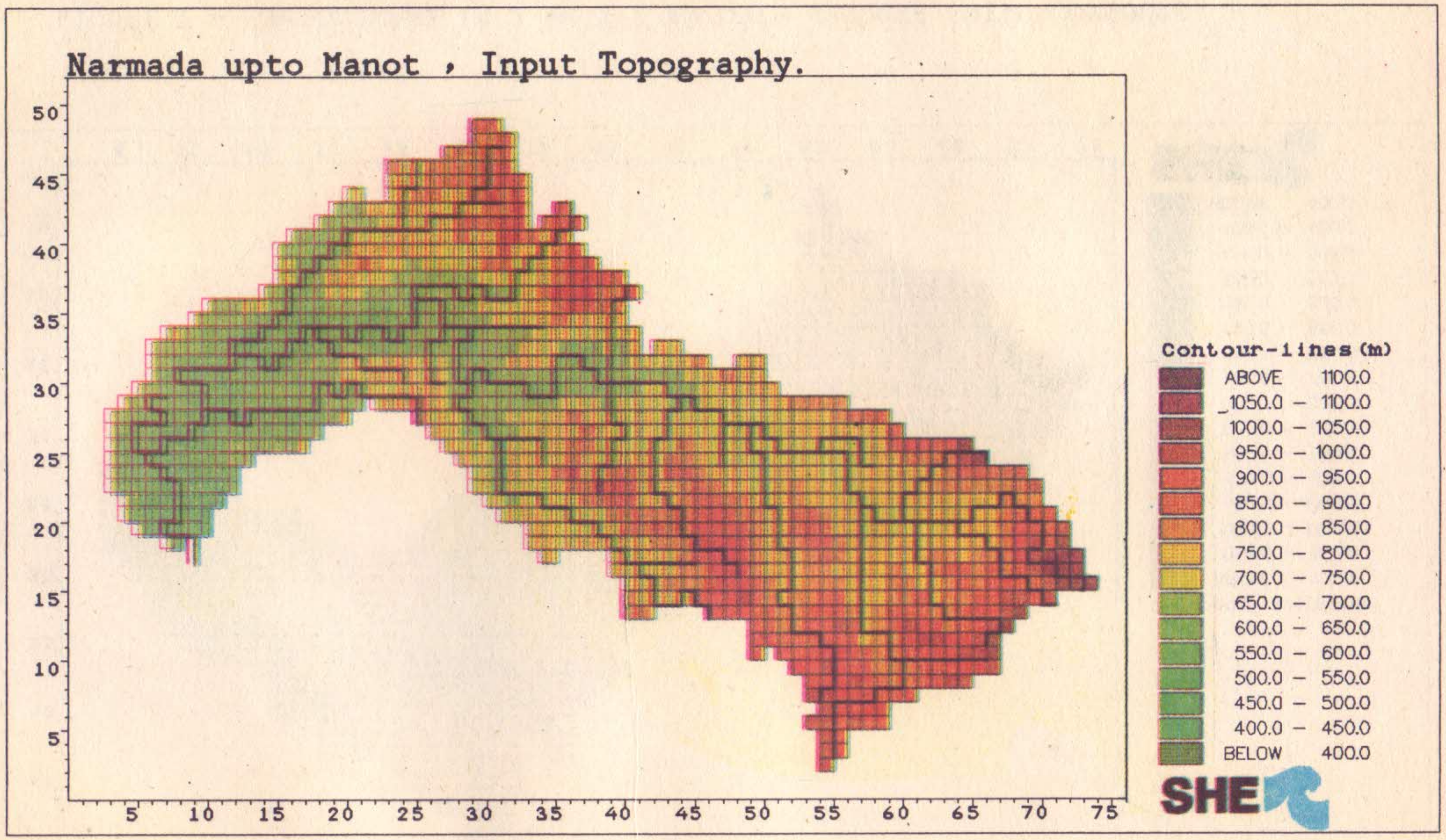


FIGURE 6 - TOPOGRAPHY IN 2 KM X 2 KM GRID NETWORK (WITHOUT CONTOURS)

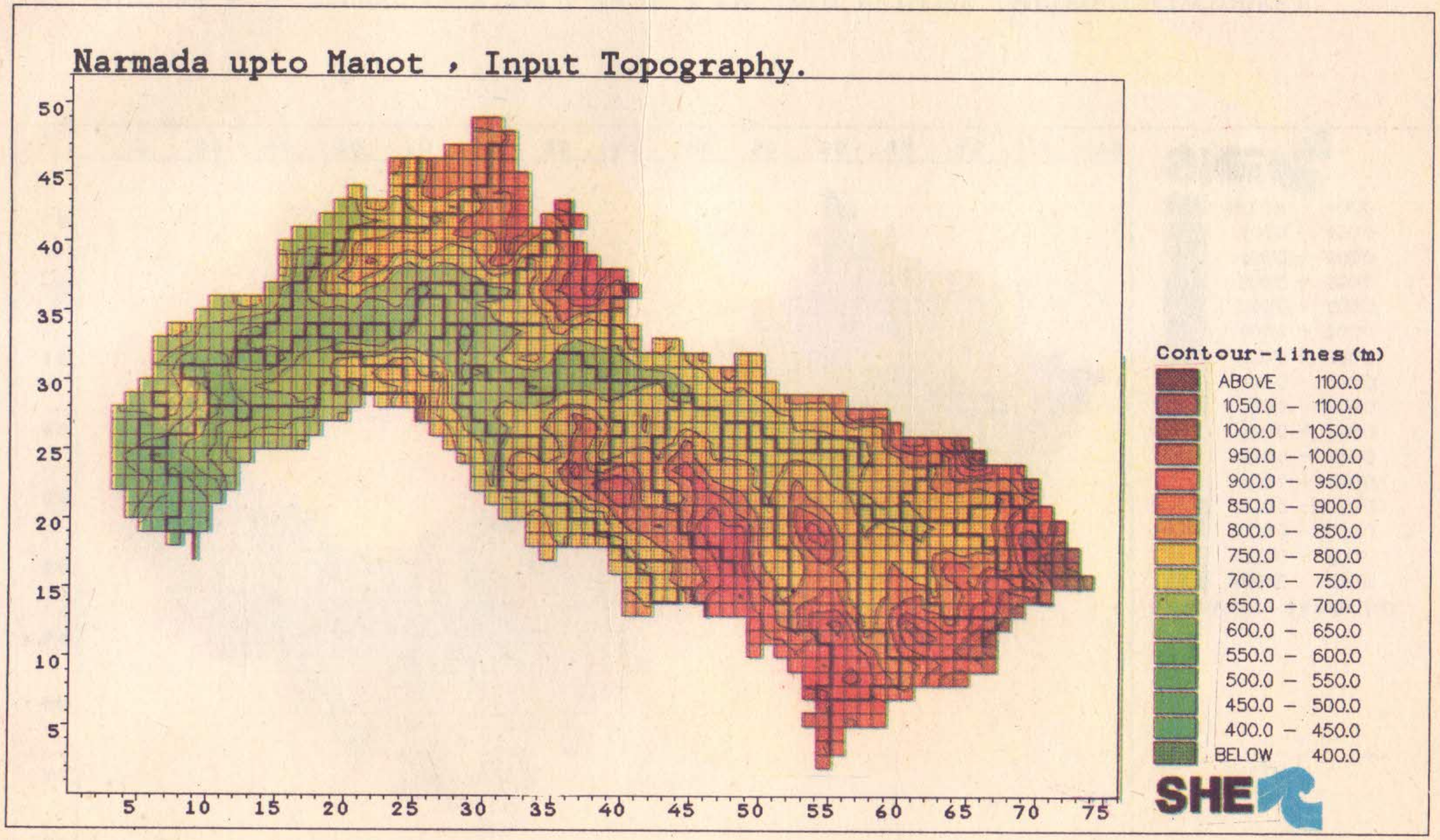


FIGURE 7 - TOPOGRAPHY IN 2 KM X 2 KM GRID NETWORK (WITH CONTOURS)

3.5 River Network

The Narmada, the largest west-flowing river of the peninsula rises near Amarkantak, in the Shahdol district of Madhya Pradesh, at an elevation of 1,057 m in the Maikala range. 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 Dudhdhara falls. The basin has a hilly terrain and is heavily dissected by the stream network (figure 8). The largest tributary in the basin has a length of approximately 90 km. The total length of the river from the head to Manot gauging site is around 269 km, all lying in the Shahdol and Mandla districts of Madhya Pradesh. The lengths of the various streams in the basin are given in table 3.

Like the peninsular rivers of India, the Narmada rises in the latter half of June and the flow reaches its maximum in the months of August and September. Thereafter, it begins to fall in October and reaches its lowest level just before the monsoon.

Systematic gauge and discharge observations were started on the Narmada only in 1947 when the Central Waterways, Irrigation and Navigation Commission (CWINC) took up investigations for formulating flood control measures and assessing how much of the available water resources of the

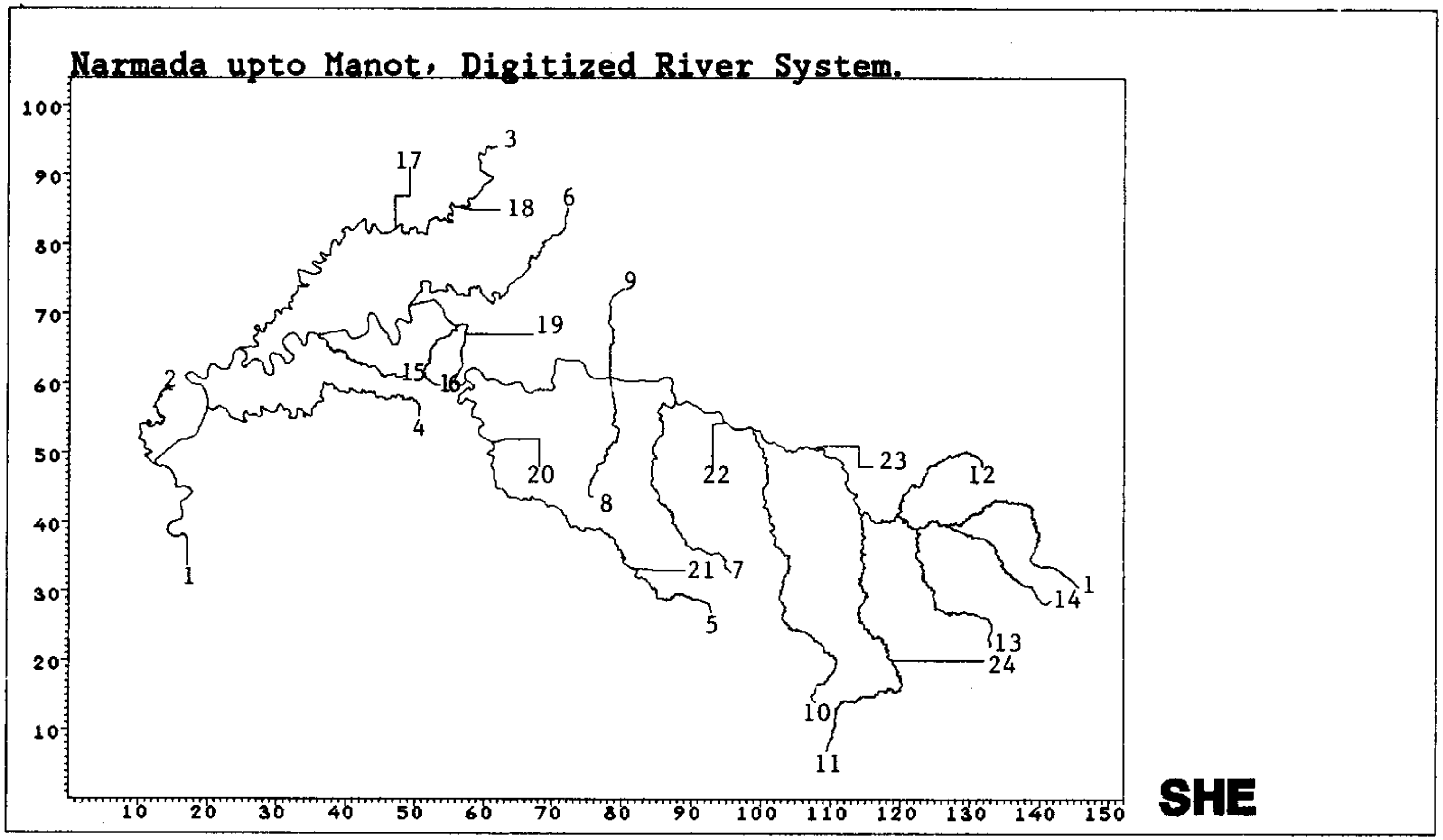


FIGURE 8 - RIVER NETWORK IN THE BASIN

Table 3 - Lengths of Streams in the Basin

Stream No.	Name	Length (km)
1	Narmada	269.03
2	Sailwara	23.08
3	Silgi	90.12
4	Dandana	54.06
5	Kharmer	73.24
6	Kanai	45.25
7	Machhrar	38.88
8	Kotrer	21.28
9	Rora	15.12
10	Chakrar	55.67
11	Seoni	65.40
12	Samrar	23.07
13	Turar	32.48
14	Karmandal	25.22
15	Renga	19.01
16	Chachar	14.49
17*		10.71
18*		6.12
19*		9.89
20*		11.01
21*		6.93
22*		7.89
23*		11.59
24*		13.21

* No specific names mentioned in the respective toposheets.

Narmada could be used for the development of irrigation, hydro-power etc. The Commission opened discharge observation stations on the Narmada and its principal tributaries during the period 1948-51. The gauging site at Manot (basin outlet) on river Narmada was established in 1948 with a purpose to know the discharge for Bilghara dam site.

3.6 Land Use

The basin has a flat low land area, mainly devoted to agricultural use, and an upland area with deciduous forest of varying density, some agricultural land and waste land. Four land use types were therefore employed - agricultural land, dense mixed forest, thin forest and waste land. The spatial distribution in the basin at the 2 km x 2 km grid scale is shown in figure 9. The proportion of basin occupied by each land use is given in table 4.

Table 4 - Land Use Pattern in the Basin

S.No.	Land Use	Area Covered (Km^2)	Proportion of Basin Covered
1	Agricultural land	2584	51.89%
2	Dense mixed forest	856	17.19%
3	Thin forest	880	17.67%
4	Waste land	660	13.25%

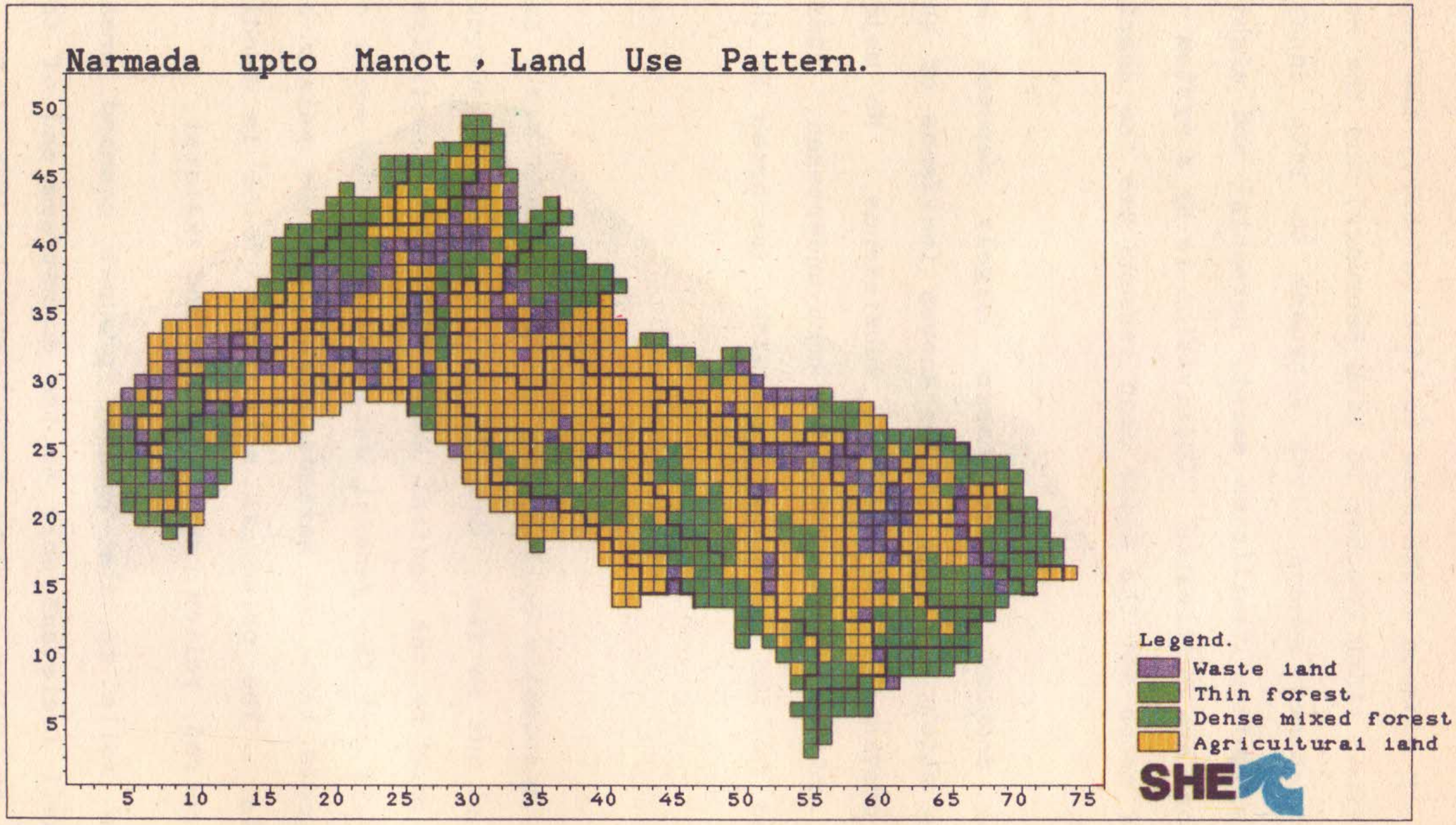


FIGURE 9 - LAND USE PATTERN IN THE BASIN

From the agricultural point of view, the seasons are the kharif or monsoon (15th June to 14th October), the rabi or cold weather (15th October to 14th February) and the hot weather or summer season (15th February to 14th June). Wherever irrigation facilities exist, perennial and eight-monthly crops are cultivated. Cultivation is by a system of rotation of crops and the major crop seasons are the kharif and the rabi.

The economy of the basin largely depends on agriculture which, in view of the uneven incidence of the rainfall, provides a low level of subsistence. No major irrigation project in the basin has been undertaken. There is a demand for the development of water resources in the basin.

3.7 Soils

No systematic soil survey of the Narmada basin has been carried out so far. Some reconnaissance soil surveys have been made by the Central Water and Power Commission. These surveys and the general data regarding the soils of India indicate that the Narmada basin consists mainly of black soils. The principal soil types found in Mandla district are red, yellow, shallow black and skeletal.

The soils in the Thanwar project command area, Mandla Tehsil (relevant only to the downstream end of the basin) are described as varying primarily with topography.

(a) Plateau lands

Soils are reddish brown to dark reddish brown, shallow to very shallow, gravelly clay to gravelly clay loam with stones and boulders on the surface.

(b) Sloping land at hill foot

Soils are yellowish brown to dark brown, shallow to moderately deep and developed in alluvium from underlying weathered basalt.

(c) Valley land between hills

Soils are deep dark greyish brown clay to clay loam.

(d) Plains

Soils are moderately deep to deep, sandy clay loam to clay loam.

In general, the soils are derived from basalt and granite parent material.

Data for two clayey soil groups in the Dindori tehsil are presented in a reconnaissance soil survey report by Kaushal and Choudhary (1976-77). In the first, roots extend to 0.96 to 1.32 m depth. In the second, the depth to the parent material is 0.93 to 1.58 m and roots extend to 0.73 to 0.93 m. Water holding capacity is 43 to 73 % and the available water holding capacity is 16 %. A permeability test at Bano gives permeabilities of 8 mm/hr at depth 0-0.75 m, 2.4 mm/hr at depth 0.75-1.50 m and 84.3 mm/hr at depth 1.50-2.25 m. The first two levels refer to clay, the lowest depth refers to weathered parent material of lighter texture.

Figure 10 presents the soil distribution in the basin, as obtained from the 1 : 2,000,000 scale map in the Agricultural Atlas of India. The following soil types are found in the basin:

(a) Medium Black Soils - Pellusterts, Chromusterts (Vertisols)

(b) Shallow Black Soils - Ustochrepts (Inceptisols)

(c) Laterite Soils - Plinthaquults, Plinthustults, Plinthudults (Ultisols)

Soil Texture - Silt loam and clay loam

Soil Reaction - Neutral (pH 6.5 to 7.5) and slightly alkaline (pH 7.6 to 8.4)

3.8 Ground Water

Deccan traps cover a very extensive area of the basin in the form of basaltic flows, together with inter-trappean beds. Ground water occurs both under water table and confined conditions. In the agricultural areas of the basin, there is an abundance of perennial wells and hand pumps, indicating the presence of substantial ground water reserves. Systematic ground water studies in the basin have been intensified for obtaining precise data on the seasonal

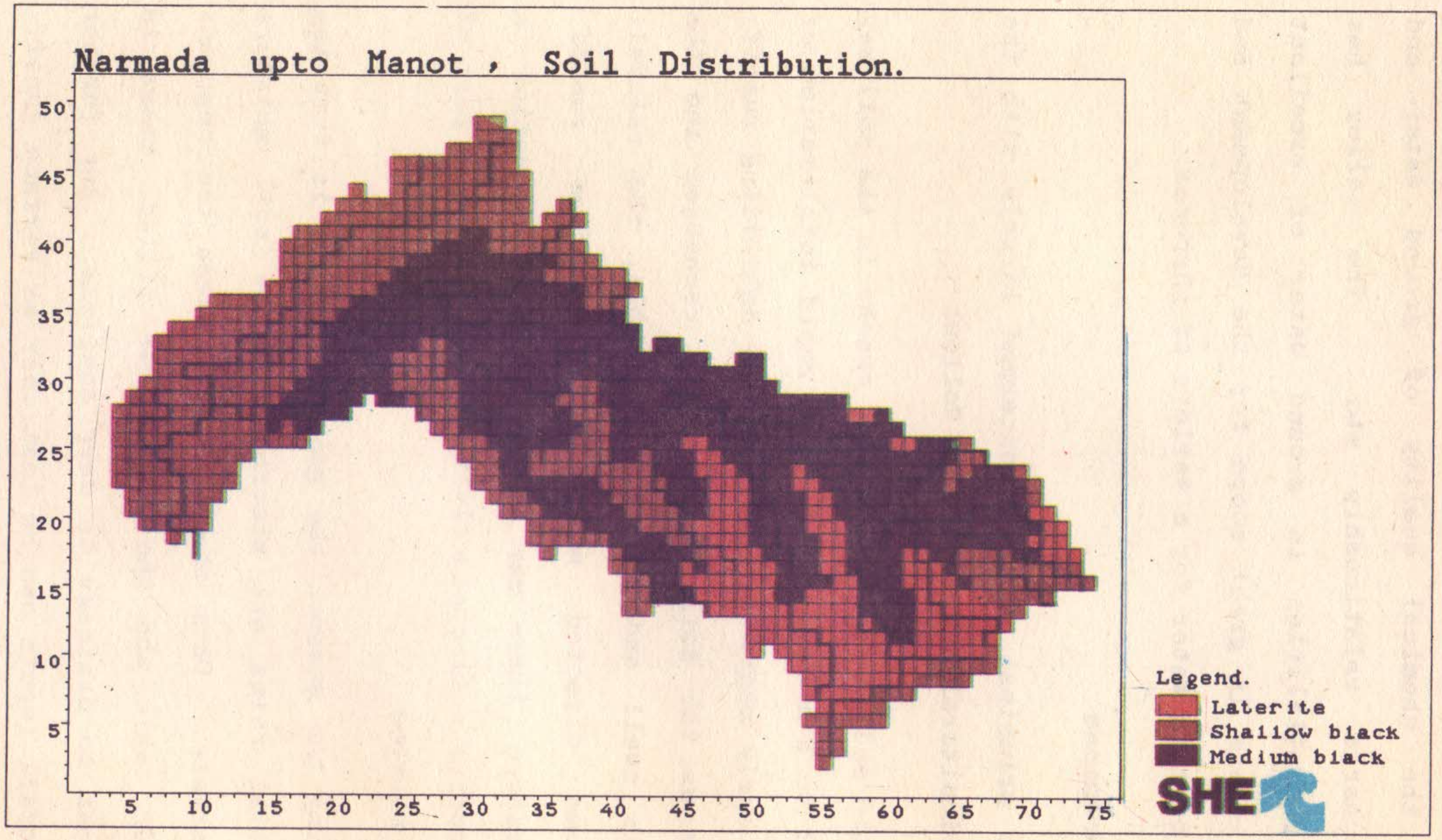


FIGURE 10 - SOIL DISTRIBUTION IN THE BASIN

fluctuations of the water table, estimate of aquifer parameters, the chemical quality of ground water and recharge-discharge relationship etc. The valley has tremendous potentialities in ground water of excellent quality and there is great scope for the development and utilization of this water for a variety of purposes.

3.9 Basin Response

Some principal points, concerned largely with the low land agricultural areas, are as follows :

(a) At the end of the dry season, cracks in the soil may be 2 to 6 m deep and support rapid infiltration of the early monsoon rains, thereby inhibiting runoff. Only as the soil reservoir is recharged and the soils swell and become impermeable, the rainfall become directed mainly into surface runoff. Therefore, there may be an apparent reduction in effective soil conductivity during the early part of the monsoon.

(b) During the monsoon the general pattern is that the initial rains are absorbed by the soil moisture reservoir. Once the storage between the regional water table and the surface is filled, there is almost no drainage to deep aquifers. Any further rainfall inputs can be lost only as surface runoff, interflow in the upper layers of the profile or evaporation.

(c) Because of the low soil conductivities, ground water recharge during the monsoon is limited, although the ground water is important in maintaining river baseflows during the dry season. The low rates of percolation and drainage also mean that about 90 percent of the total annual soil moisture depletion over the dry season is due to evapotranspiration from the root zone.

(d) The soil moisture storage is generally full at the end of the monsoon and always reaches wilting point throughout the root zone during the dry season. There is no seasonal change below the crack zone in the deep soils.

(e) The total subsurface moisture reservoir can be divided into the root zone reservoir (which can evaporate during the dry season) and the ground water reservoir which drains (slowly) below this, i.e. beyond the reach of the roots, and eventually contributes to deep storage or river baseflow. The two reservoirs are continuous and the boundary between them may be altered by changes in land use.

(f) In the upland forest areas, surface runoff may be generated at an earlier stage in the monsoon season, because of the shallower soils. The runoff may also be more concentrated in small channels, whereas in the flat low land areas, sheet flow may be more prevalent.

3.10 Data Availability

A data assembly programme was carried out to provide the hydrometeorological data and basin parameters (e.g. soil, vegetation and topographic characteristics) needed to support SHE simulations of the basin. In view of the large number of data collection agencies, both belonging to the Government of India and to the state of Madhya Pradesh, which had to be approached, a coordinated effort was set up. The data assembly programme was launched with the visits of NIH staff to data collecting agencies and to the field and gauging sites. Data were assembled for the period 1980-87.

The SHE simulates all the major aspects of the land phase of the hydrological cycle. Consequently its application require the evaluation of a large number of parameters and their spatial distributions, along with the necessary time series of data for calibration, validation and operation of the model. It was not expected that the full range of requirements would be satisfied by the available data but a list of data sources and recording instrumentation reported to be in use was drawn up. The data base for the basin is presented in table 5. Comments on the individual items are as follows :

Table 5 - Data Availability for the Narmada (upto Manot) Basin

Data Type	Data Availability
Rainfall	**Daily**
	Dindori : 1978 (June,July), 1979(February,July), 1980-87
	Vikrampur : 1985 (July-December), 1987
	Gathauri* : 1981-87 (except 1983)
	Niwas* : 1978-84, 1987
	Odhari* : 1981-86
	Sakke : 1981-86
	Shahdol* : 1981 (June-December), 1982, 1983 (June-December), 1984-86
	Parsatola*: 1981-83, 1986, 1987
	Manot : 1980-86
	Barbaspur : 1981-87
	Mandla* : 1980-88
	Hourly
	Mandla* : 1978 (January-September, November, December) 1979 (January, February, May-December) 1980 (January-March, June-September, December)

... to be continued

Table 5 (continued)...

Data Type	Data Availability
	1981 (January-April, August-December)
	1982 (January-July, September-December)
	1983 (January-December)
	1984 (January, February, April, June-October, December)
	1985 (January, June-October)
	1986 (January-December)
	1987 (June-December)
	* Station lies outside the basin
Discharge	**Daily gauge and discharge data**
	Manot (outlet) : June 1978-May 1979, September 1979 - May 1987
	Hourly gauge data
	Manot (outlet) : 1981-87 (monsoons)
Evaporation	**Daily pan evaporation data**
	Pendra Road (outside the basin) : 1978-88
Channel Cross-section	Manot : 1981-87
Rating Curves	Manot : 1978-87 (except 1979)
Ground Water Level Observations	Premonsoon and postmonsoon observations for 13 wells inside and 11 wells close to the basin in the Mandla and Shahdol districts for the period 1976-87, but not for all wells in each year

Rainfall

There are eleven ordinary raingauge stations within or near the basin. The available periods of record for each raingauge are shown in table 5. Not all the raingauge stations lie within the basin and spatial coverage with continuously recording raingauges giving hourly rainfall is especially poor. Only one hourly station (SRRG) is available lying outside the basin and operated by the India Meteorological Department. The spatial distribution of ordinary raingauge stations is uneven with upland area poorly represented. Temporal coverage is also patchy. Figure 11 presents the network of daily raingauge stations in the basin.

Discharge

Discharge data are available only at the basin outlet. The available period of record is shown in table 5. The outlet discharge gauging station defining the 4980 km^2 basin is at the road bridge at Manot. The bridge top is at bank top height and is designed to withstand submergence during floods. While the bridge is above water it is used as the platform from which to carry out current metering. The stepped stage board reaches to 18 m, the approximate height of the bridge top above the channel bed. Discharge is gauged by current meter upto three times a day during the monsoon and just once daily during winter events. Each daily

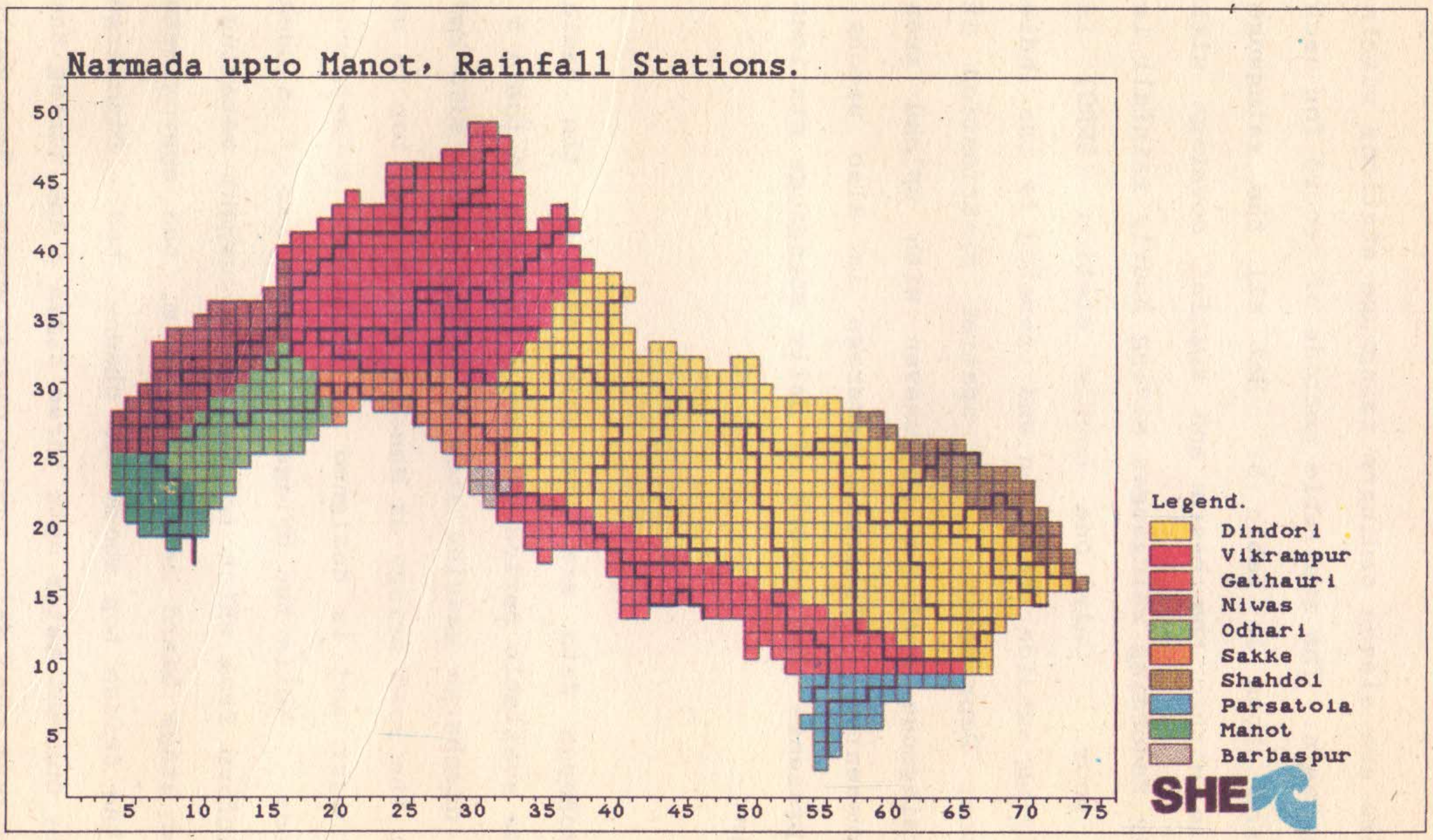


FIGURE 11 - THIESSEN POLYGONS OF RAINGAUGE STATIONS (10)

set of three discharge values and the corresponding set of three stage values are averaged arithmetically to give a single pair of stage and discharge values. These are referred to as the daily mean values. During the monsoon, stage is read at hourly intervals. In cases where the river is too high for current metering to be carried out, float gauging is sometimes used, with the velocity coefficient calibrated from measurements at lower flows.

The stage-discharge rating curves are also available for the Manot gauging site for the period 1978-87 (except 1979), as supplied by CWC and shown in figure 12. These are used to convert the measured hourly stage values to hourly discharge values for the monsoon period.

Evaporation

The basin is characterized by just one station (Pendra Road) located outside the basin. Daily pan evaporation data is available for the period 1978 to 1988. Evaporation tends to be more spatially uniform than does rainfall (at least over periods of a week or more) but even so it is likely that the spatial lumping involves some error.

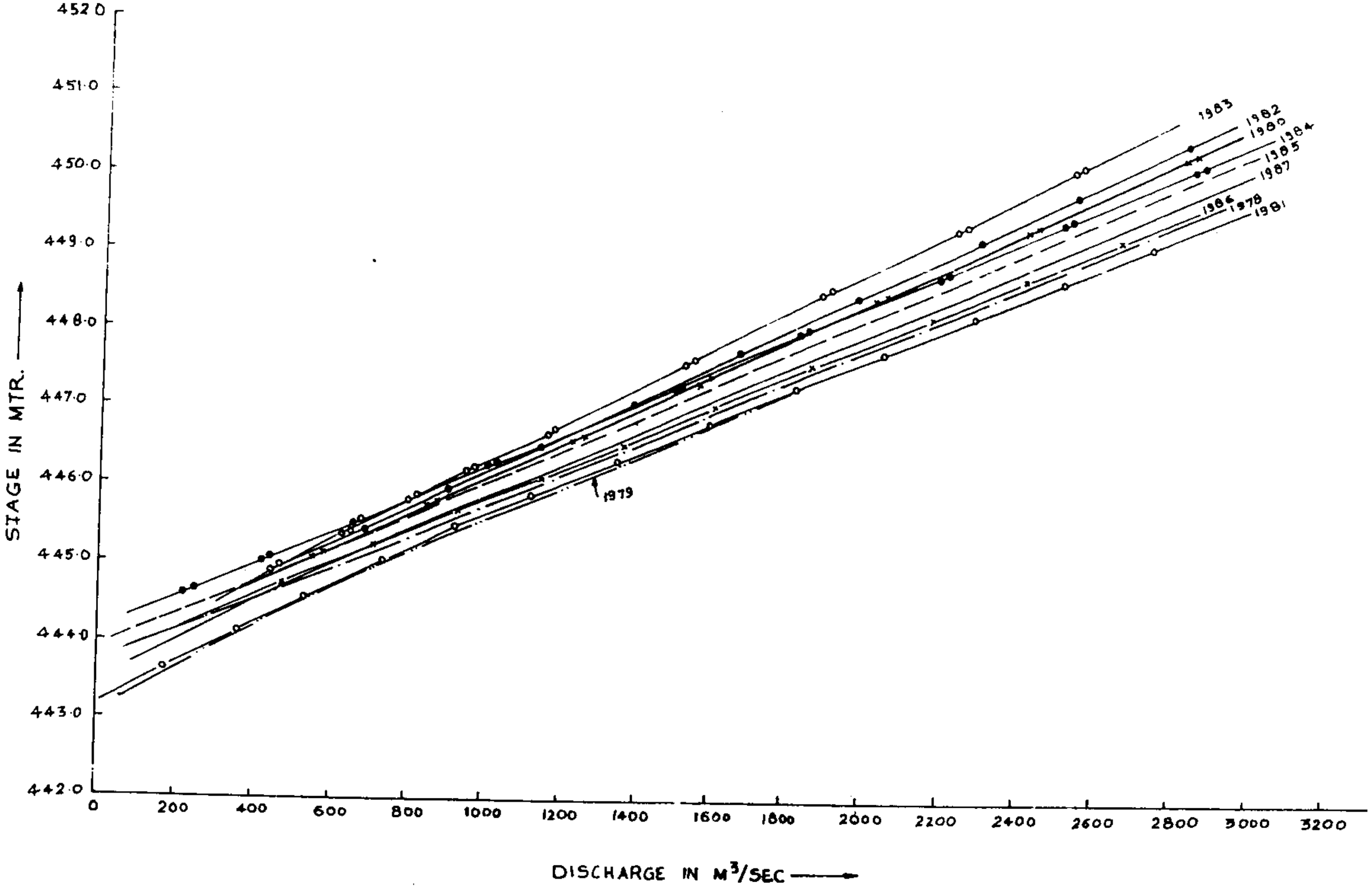


FIGURE 12 - RATING CURVES FOR THE MANOT GAUGING SITE

Topography

In all cases land and channel elevations in the basin were taken from the following toposheets issued by the Survey of India:

Scale	**Toposheet No.**
1 : 250,000	64A, 64B, 64E, 64F
1 : 50,000	64A/8,12,15,16 64B/5,6,9,10,13,14 64E/4 64F/1,2,5,6,7,9,10

Land use

Land use maps prepared by the Narmada Valley Development Authority (NVDA) on scale 1 : 250,000 are available only the west of longitude 80°E. Therefore, land use map for Narmada (upto Manot) basin was prepared from satellite imagery and the 1 : 250,000 topographic maps. The general distribution of the major land uses (agriculture, forest, waste land etc.) is available and presented in figure 9. For the agricultural land, the percentage of land devoted to each crop type is available on a district basis only and the spatial distributions have not been determined at the basin scale.

Soil distribution

Soil maps prepared by NVDA are available only the west of longitude 80°E. The soil distribution in the Narmada (upto Manot) basin was therefore obtained from 1 : 2,000,000 scale map in the 'Agricultural Atlas of India' as shown in figure 10.

Soil and vegetation properties

There is a general lack of direct information on soil and vegetation properties, root zone depths, vegetation growth, cropping pattern, soil depths, soil moisture, aquifer properties and channel cross-sectional dimensions. For the simulation work, the information has been obtained indirectly from reports and papers on neighbouring areas or by standard hydrological derivations.

Channel cross-section

Cross-sectional dimensions are available at the basin outlet (Manot) only. The approximate bank top height above the channel bed is 18 metres. Bankfull width is about 300 m and the bed width is about 145 m. The bed itself is composed of bedrock. A series of rough cross-sectional surveys made along the mainstem between the source and Sihora . in the Hiran basin, were used to derive relationships between channel dimensions and upstream channel length which were then applied to provide cross-sectional data as required throughout the Narmada (upto Manot) system.

Ground water observations

The ground water survey organisation of Madhya Pradesh Irrigation Department maintains observation wells for carrying out regular monitoring of ground water status of the state. There are 13 observation wells inside the basin and 11 close to the basin in the Mandla and Shahdol districts of Madhya Pradesh. The available period of record is shown in table 5. Figure 13 presents the network of observation wells inside the basin.

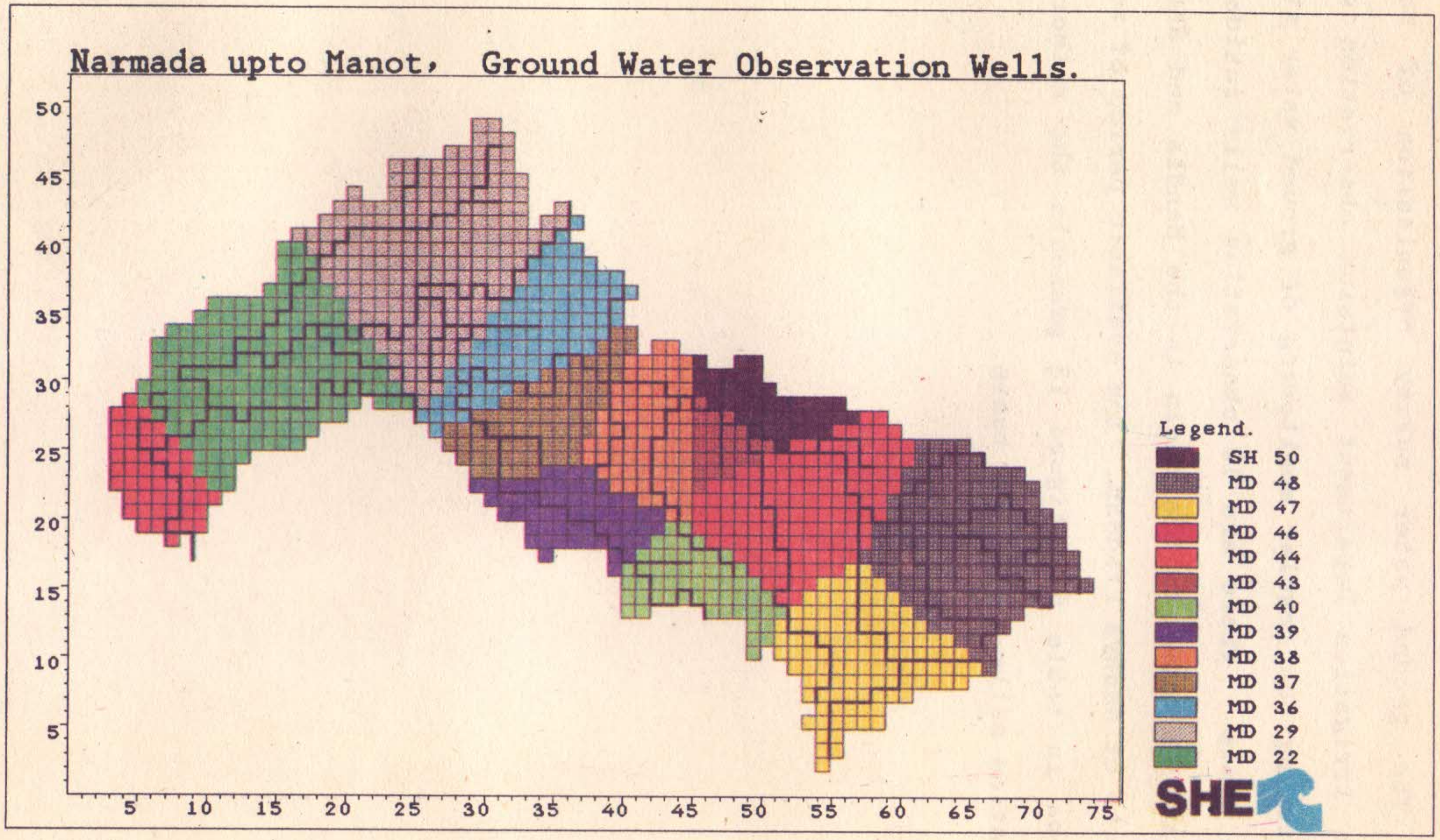


FIGURE 13 - THIESSEN POLYGONS OF GROUND WATER OBSERVATION WELLS

4.0 DATA PROCESSING AND PREPARATIONS

4.1 General

Application of the SHE involves three phases - data preparation, execution of the SHE, and retrieval and graphical display of the SHE results. In connection to the SHE, a suite of service routines are used in the data preparation phase and the presentation of the SHE results.

Application of SHE requires the provision of a large amount of parametric and input data organized in an array of data files. To each component is attached a data file. The naming of the files is usually given in a way, which identifies the specific catchment followed by three letters indicating the component:

MANOT.FRD	Frame
MANOT.SZD	Saturated Zone
MANOT.UZD	Unsaturated Zone
MANOT.OCD	Overland and Channel Flow
MANOT.ETD	Evapotranspiration

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

MANOT.PRD	Precipitation data
MANOT.EPD	Potential Evaporation data
MANOT.VED	Vegetation data (Leaf Area Index, Root Depth)
MANOT.TED	Temperature data
MANOT.EXD	Ground Water Abstraction Rates
MANOT.QOD	Observed Discharge data
MANOT.POD	Observed Ground Water Heads

A series of maps and other input describing the spatial distributed data are required in the SHE data files. The Array Formatting Routine called SHE.AF can be used for construction of the SHE data files. Based on a set of data files containing information about grid network, catchment geometry, soil and land use maps, river network etc. the SHE.AF constructs the various maps and establish the computational river system on the appropriate scale chosen. In connection with the setup of the river system, the SHE.AF is particularly useful. The river system is defined in the following files :

RIVER.DIG	Containing point values of the digitized river system. The bank levels of the rivers are attached to some points
RIVER.NUMB	Defines points in each river section

RIVER.CROSS	Cross-sections at each end of a river section

By applying the SHE.AF, the river system can be established at various grid sizes just by replacing the Grid Code data file (grid codes inside and outside the model area). SHE is run only a few time steps after having prepared the SHE data files. This serves to check the river system setup. In some cases the interpolated river bank elevations become higher than the ground-surface elevations of the adjacent grid squares. In these cases a warning message is given and corrections in the river setup data file is required. The SHE.AF can then be executed again.

A SHE application produces also a large number of temporal and spatially varying data. In order to interpret and present these results in a convenient manner, the Output Retrieval Routine SHE.OR and the Graphical Display Routine SHE.GD may be applied which present the results either as tables or graphs.

4.2 Data Processing

All the data processing, including transfer of the rainfall and discharge records to computer files, checking the files for errors and digitization of the river system etc., were carried out prior to model setup and simulation work. A large number of reports were referred for obtaining the relevant information on basin properties. Details of individual items are given below.

4.2.1 Rainfall

Only one hourly rainfall record was available outside the basin (Mandla) and this was used to distribute the daily rainfall records for all stations. Missing records of daily rainfall data were interpolated by the distance power method. Daily rainfall data of Mandla was used to fill up the missing hourly records, based upon the following criteria :

(i) If daily rainfall < 1.2 mm

- enter as a single total value at mid-day (i.e. over one hour 12.00 - 13.00)

(ii) If daily rainfall > 1.2 mm

- enter as uniform value spread over 24 hours

Distribution of domains for each rainfall station was based on Thiessen polygon approach. The daily rainfall records were distributed on an hourly basis according to the pattern measured at the nearest recording gauge (Mandla). Correlation between the rainfall patterns throughout the basin is by no means assured, so this method of distributing rainfall temporally forms a considerable source of uncertainty in the inputs. This uncertainty is further exacerbated by the uneven spatial distribution of raingauges (upland area is poorly represented) and by the infilling necessary to close gaps in the measured time series.

Out of the 10 raingauge stations (excluding Mandla which has got zero weight) for the basin, only 7 stations having the higher weights were selected for the simulations, in order to reduce the computing requirements (figure 14). Thiessen weights and area represented by each raingauge station are shown in table 6. Figures 15 and 16 present the variation of mean rainfall over the basin for the period 1982 to 1987.

Table 6 - Thiessen Weights of Raingauge Stations

S.No.	Raingauge Station	Thiessen Weight	Area Represented (Km^2)
1	Dindori	0.418	2081.64
2	Vikrampur	0.216	1075.68
3	Gathauri	0.131	652.38
4	Niwas	0.066	328.68
5	Odhari	0.078	388.44
6	Sakke	0.052	258.96
7	Shahdol	0.039	194.22
	Total	1.000	4980.00

4.2.2 Discharge

For the outlet discharge calibration data, hourly discharge values were obtained from the measured stage values for each monsoon period. The rating curves were those derived by the Central Water Commission for each monsoon season. Errors in using the curve arise from its derivation, as a power law, from arithmetically averaged data and from its presentation as a single valued function

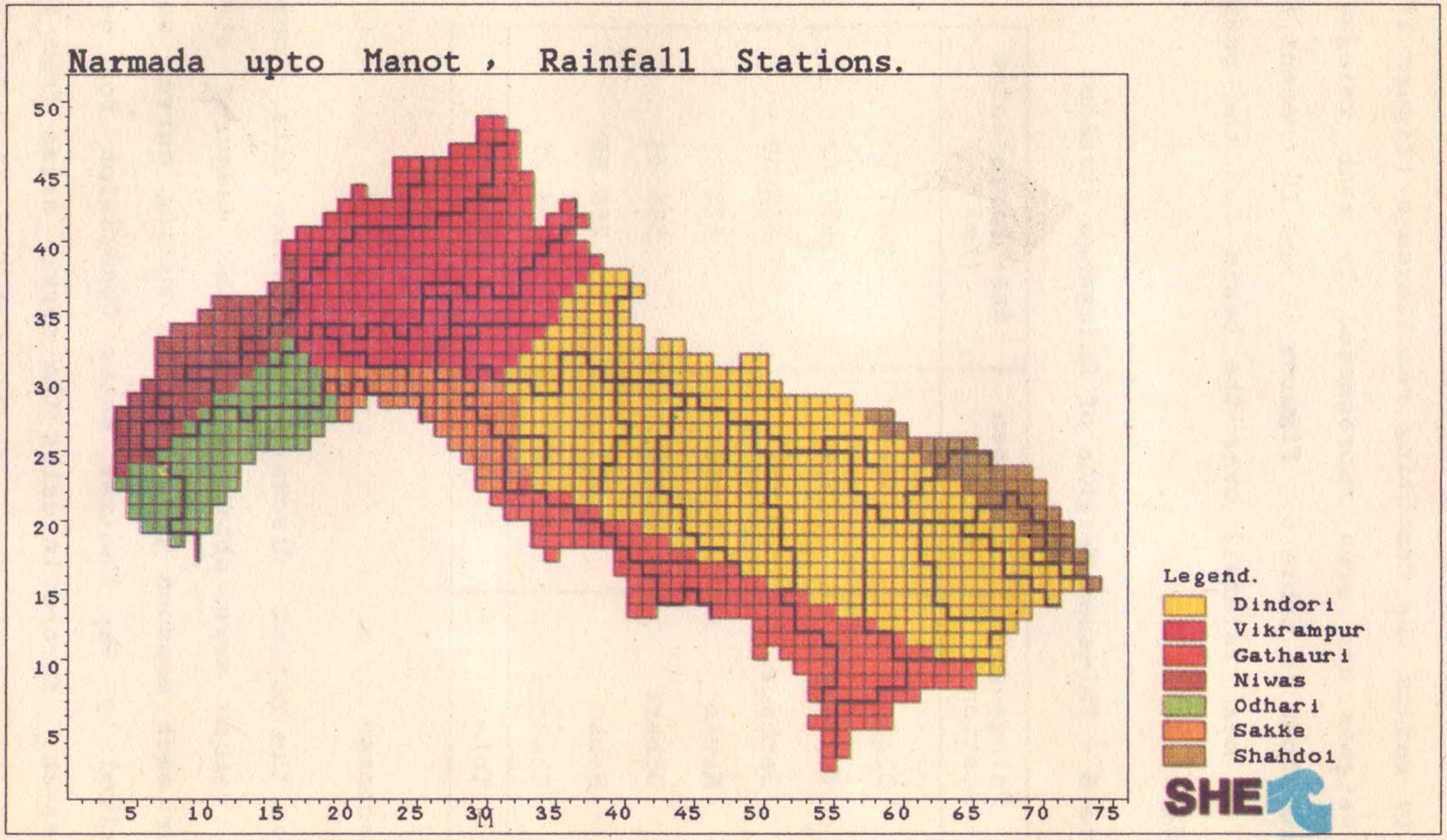


FIGURE 14 - THIESSEN POLYGONS OF RAINGAUGE STATIONS (7)

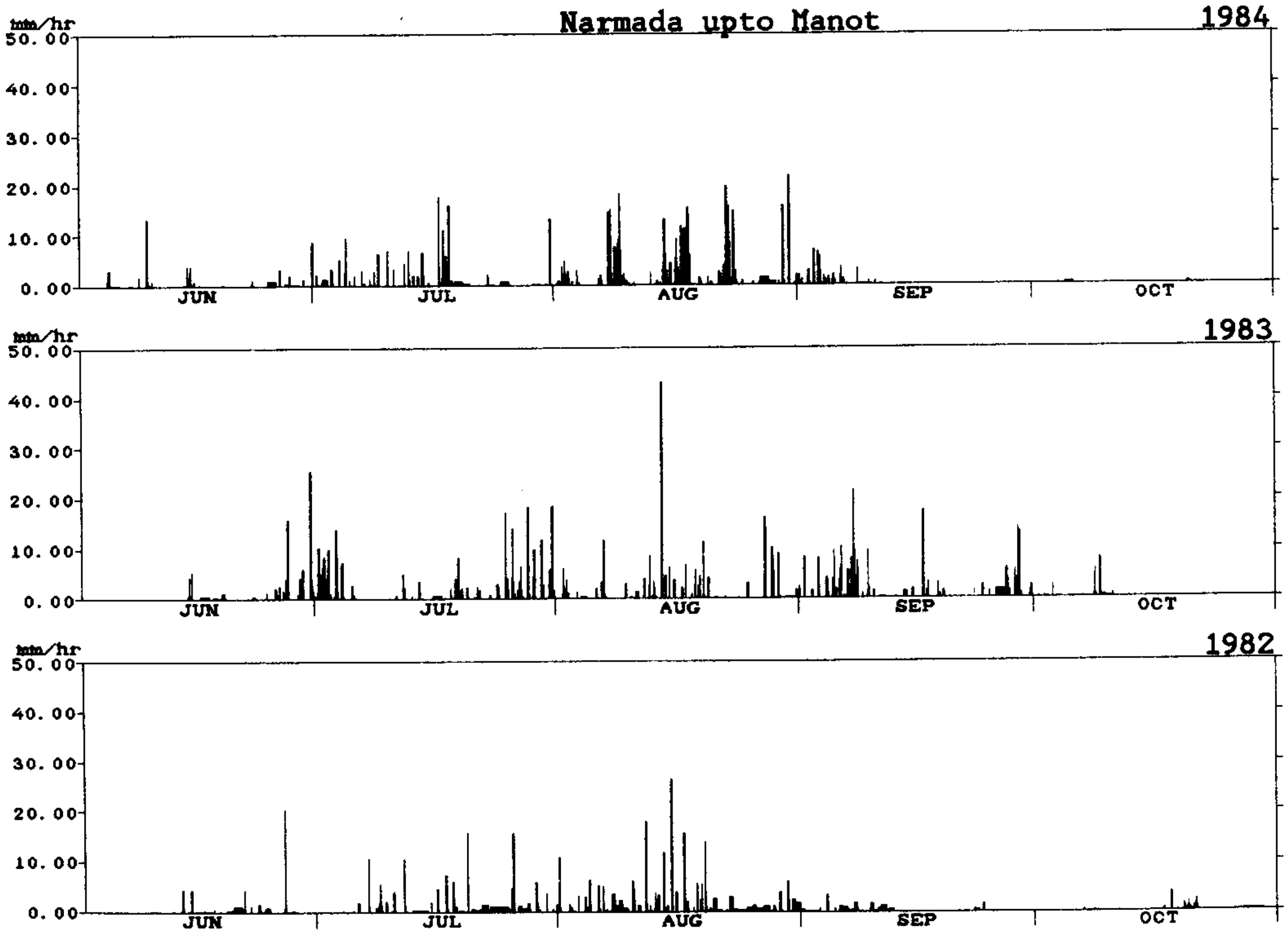


FIGURE 15 - VARIATION OF MEAN RAINFALL OVER THE BASIN FOR THE PERIOD 1982 - 84

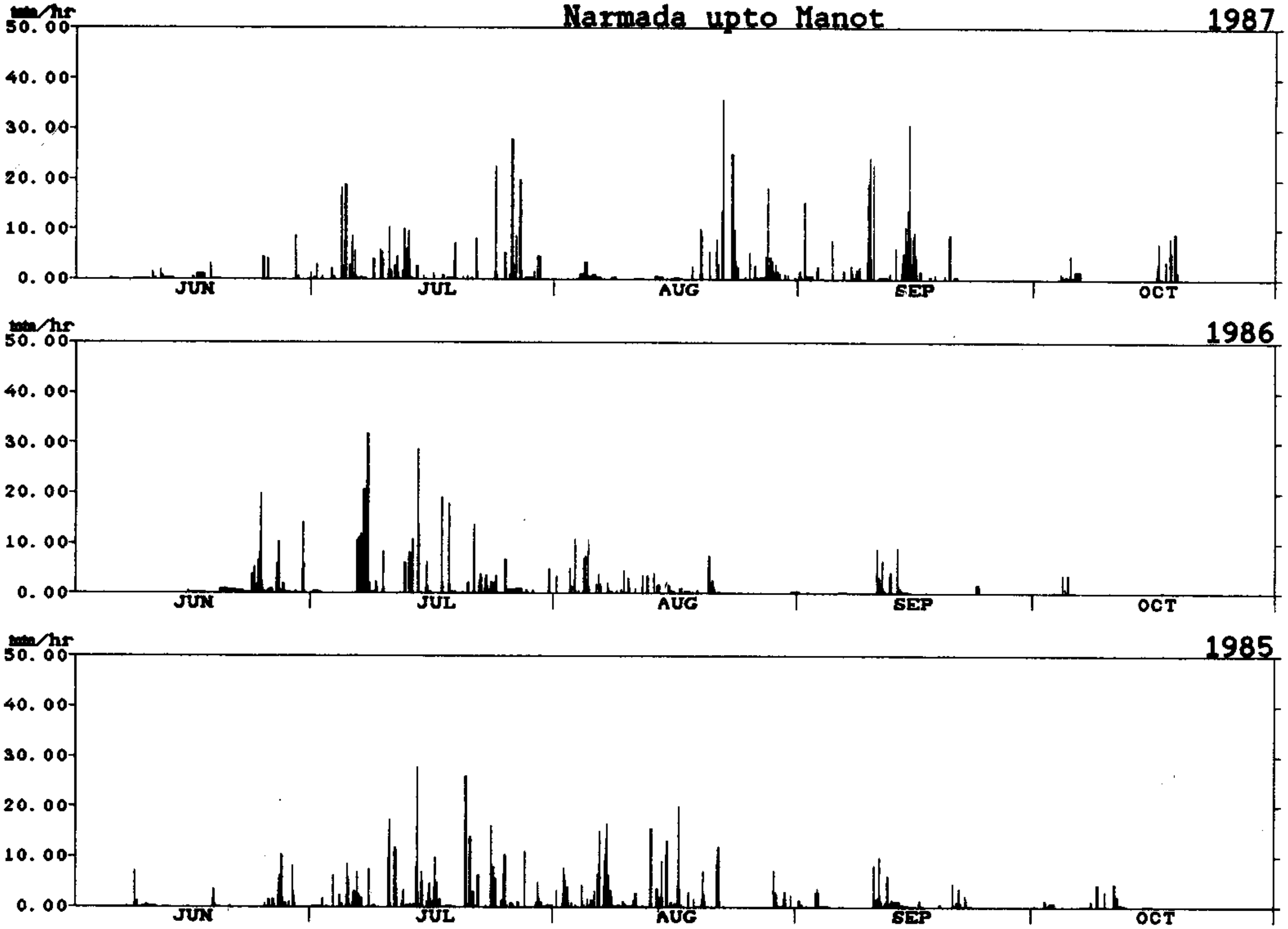


FIGURE 16 - VARIATION OF MEAN RAINFALL OVER THE BASIN FOR THE PERIOD 1985 - 87

which does not allow for event and seasonal hysteresis effects. Since the maximum recorded stages were for flows larger than those with the maximum measured discharge, the rating curves had to be extrapolated. The accuracy of extrapolation was tested using independent calculations based on the Manning/Strickler equation and was found to be adequate. Typical measured monsoon peak discharges for the simulation period are upto 5762 m^3/s at the Manot gauging site.

4.2.3 Evaporation

Potential evaporation was assumed to be given by the pan evaporation data of Pendra Road multiplied by a factor (0.7) and to apply uniformly in the basin. The provision of hourly evaporation rates from the daily records involves considerable temporal lumping.

A summary of the observed monthly rainfall, discharge and potential evaporation values is presented in table 7.

4.2.4 River system

Catchment boundary and the river system were digitized from the topographical maps and by making use of 'READNIHDIG' (a SHE-related service program), data were written in SHE-plot input format on the following files:

GRID.DIG	-	catchment boundary
RIVER.PLOT	-	river system

Table 7 - Observed Monthly Rainfall, Discharge and Potential Evaporation

Year	Month	Areal Mean Rainfall (mm)	Discharge at Manot (outlet) (mm)	Potential Evaporation (mm)
1982	January	38.43	3.55	41.28
	February	16.53	3.60	55.68
	March	7.33	1.13	102.24
	April	0.06	0.42	139.44
	May	2.84	0.64	149.04
	June	67.88	0.31	107.28
	July	216.72	15.70	85.20
	August	504.77	328.32	52.56
	September	110.80	88.37	67.44
	October	18.77	3.45	63.84
	November	11.58	7.23	46.56
	December	0.02	3.23	47.04
1983	January	0.13	1.45	55.68
	February	14.55	1.90	58.32
	March	0.00	0.97	125.76
	April	0.18	0.31	146.64
	May	3.15	0.16	152.88
	June	124.50	4.78	124.32
	July	405.04	125.40	62.88
	August	299.79	212.36	64.08
	September	356.61	252.78	58.08
	October	35.53	3.24	66.48
	November	0.00	11.25	58.32
	December	2.62	6.80	49.44
1984	January	69.82	23.05	43.68
	February	27.17	9.39	55.44
	March	0.00	3.20	117.84
	April	7.90	1.27	135.36
	May	0.00	0.54	189.84
	June	72.81	1.84	90.48
	July	233.74	34.40	59.52
	August	657.43	504.57	56.40
	September	78.43	69.33	66.24
	October	3.37	5.36	66.96
	November	0.00	5.21	60.00
	December	0.00	3.70	60.00

...to be continued

Table 7 (continued)...

Year	Month	Areal Mean Rainfall (mm)	Discharge at Manot (outlet) (mm)	Potential Evaporation (mm)
1985	January	60.69	7.46	35.04
	February	22.59	8.15	66.72
	March	0.00	1.41	119.52
	April	1.58	0.78	156.48
	May	0.09	0.21	168.96
	June	72.99	3.26	124.32
	July	480.52	241.10	54.96
	August	384.96	405.33	58.08
	September	82.99	70.34	69.84
	October	32.19	16.80	70.56
	November	0.00	7.71	61.44
	December	0.00	4.87	54.48
1986	January	3.67	3.17	56.88
	February	103.88	6.77	48.48
	March	3.02	3.55	106.08
	April	8.64	0.77	138.48
	May	3.13	0.35	151.68
	June	158.52	56.66	113.04
	July	511.54	460.80	63.84
	August	145.05	230.41	66.72
	September	70.36	109.60	77.76
	October	11.16	62.84	64.08
	November	0.29	6.65	49.44
	December	67.96	6.86	37.92
1987	January	43.28	6.54	37.92
	February	80.76	5.21	55.20
	March	9.52	4.38	99.36
	April	2.90	1.22	129.12
	May	18.46	0.53	116.64
	June	38.28	89.04	111.60
	July	401.16	160.71	64.56
	August	394.64	216.56	61.92
	September	337.34	362.19	58.56
	October	90.58	Not available	66.48

Figures 17 and 18 show the digitized boundary and digitized river system respectively.

4.2.5 Topography

Topographic elevations were read from 1:50,000 scale contour maps superimposed on a grid system of 1 km x 1 km (2 cm x 2 cm). The elevations were read at the corners of the grid squares. The grids were connected to the longitudinal and latitudinal coordinates to have identical origin in the coordinate system.

4.2.6 Land use and soil distribution

To describe soil type areas and vegetation type areas in the SHE system, grid code maps are used. The polygons enclosing the areas were digitized with the 'SHEDIG' program (service program), using polygon type. Figures 19 and 20 present the digitized land use pattern and digitized soil distribution respectively. Grid code maps were then made by 'SHEOL' (SHE overlay maker) from digitized polygons with associated code values.

The land use was further split into components for hilly or upland areas (>810 m), semi-hilly or hillslope areas (640-810 m) and low land areas (<640 m), giving a total of twelve categories. The distributions for the basin are shown in table 8 and figure 21.

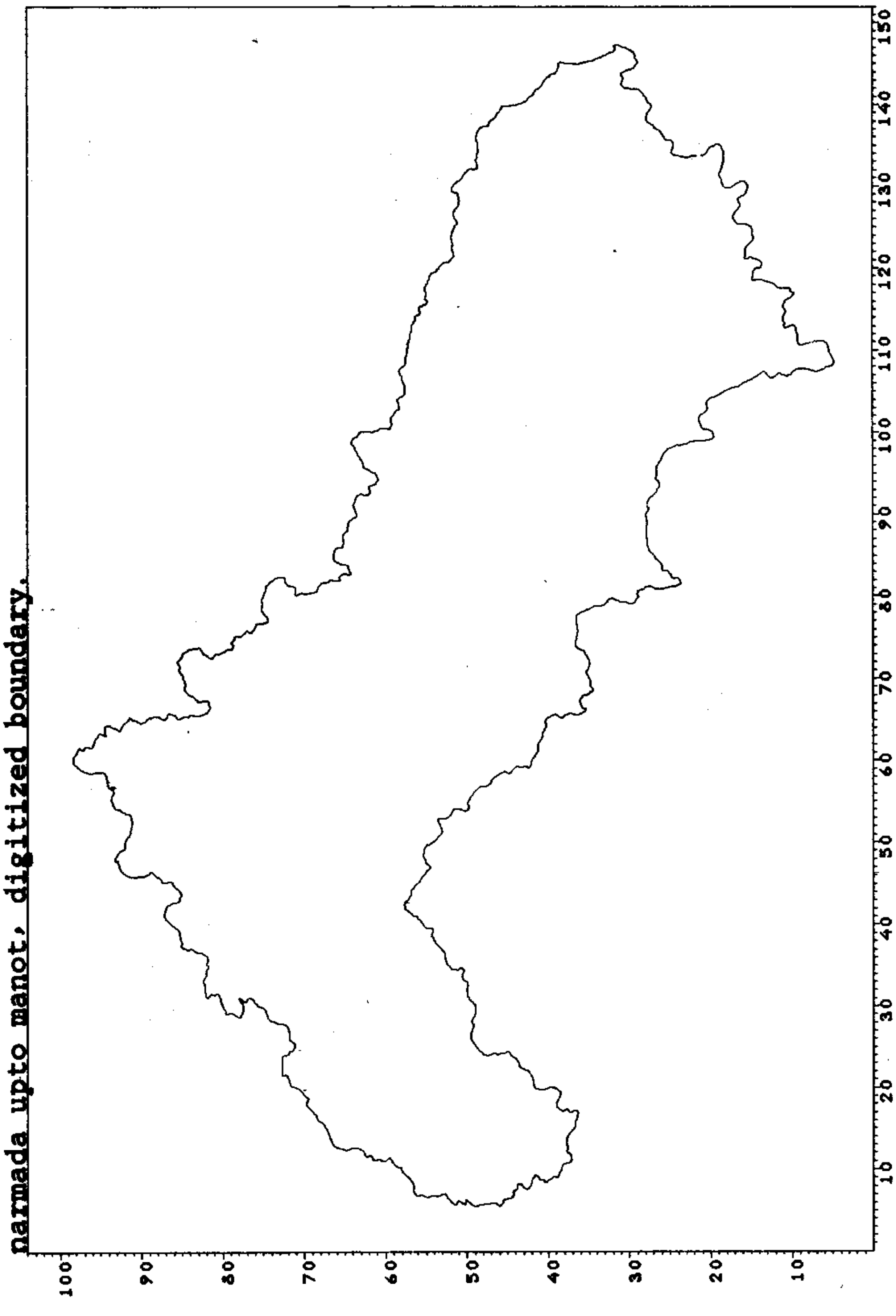


FIGURE 17 - DIGITIZED BOUNDARY OF THE BASIN

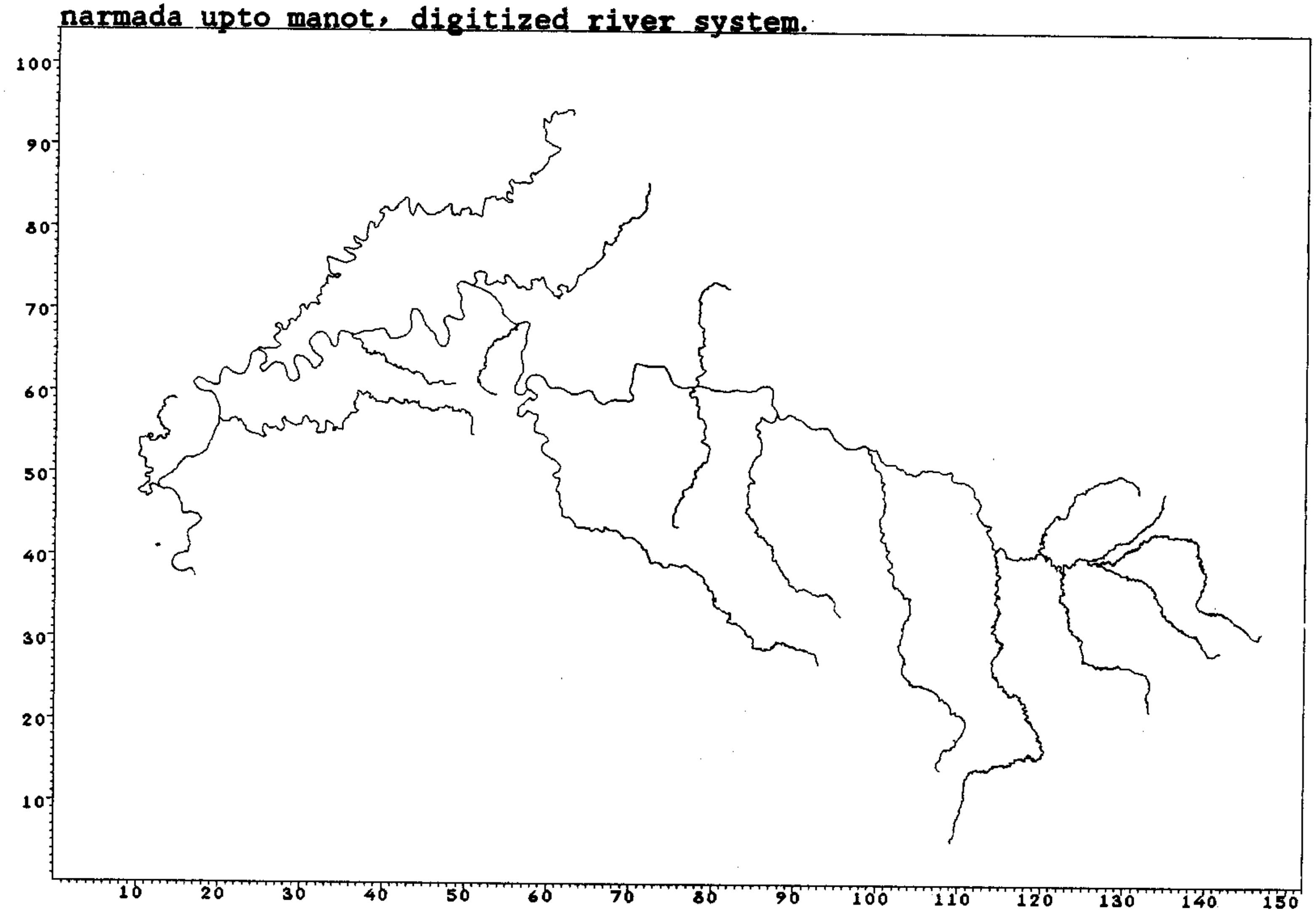


FIGURE 18 - DIGITIZED RIVER SYSTEM OF THE BASIN

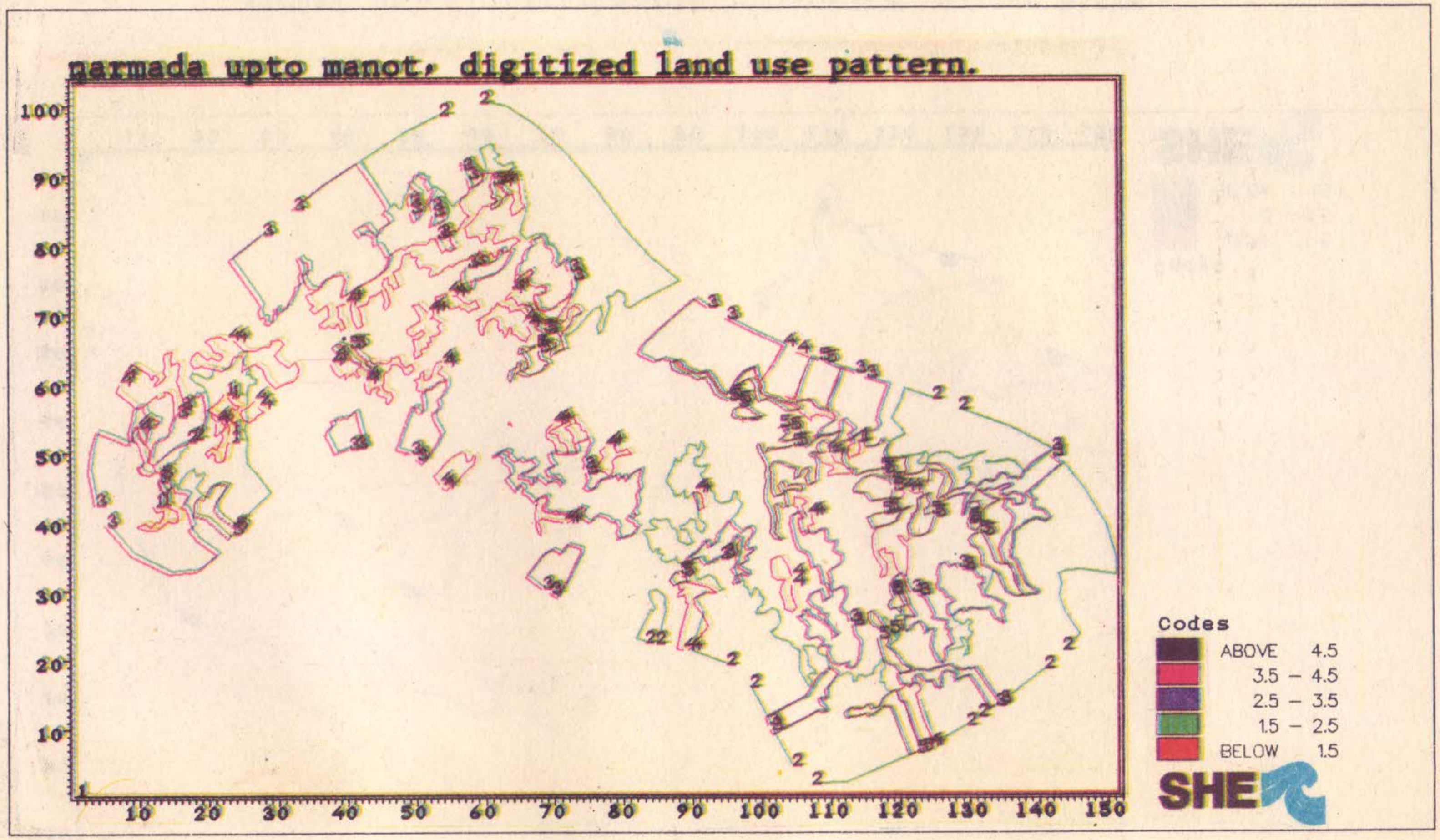


FIGURE 19 - DIGITIZED LAND USE PATTERN OF THE BASIN

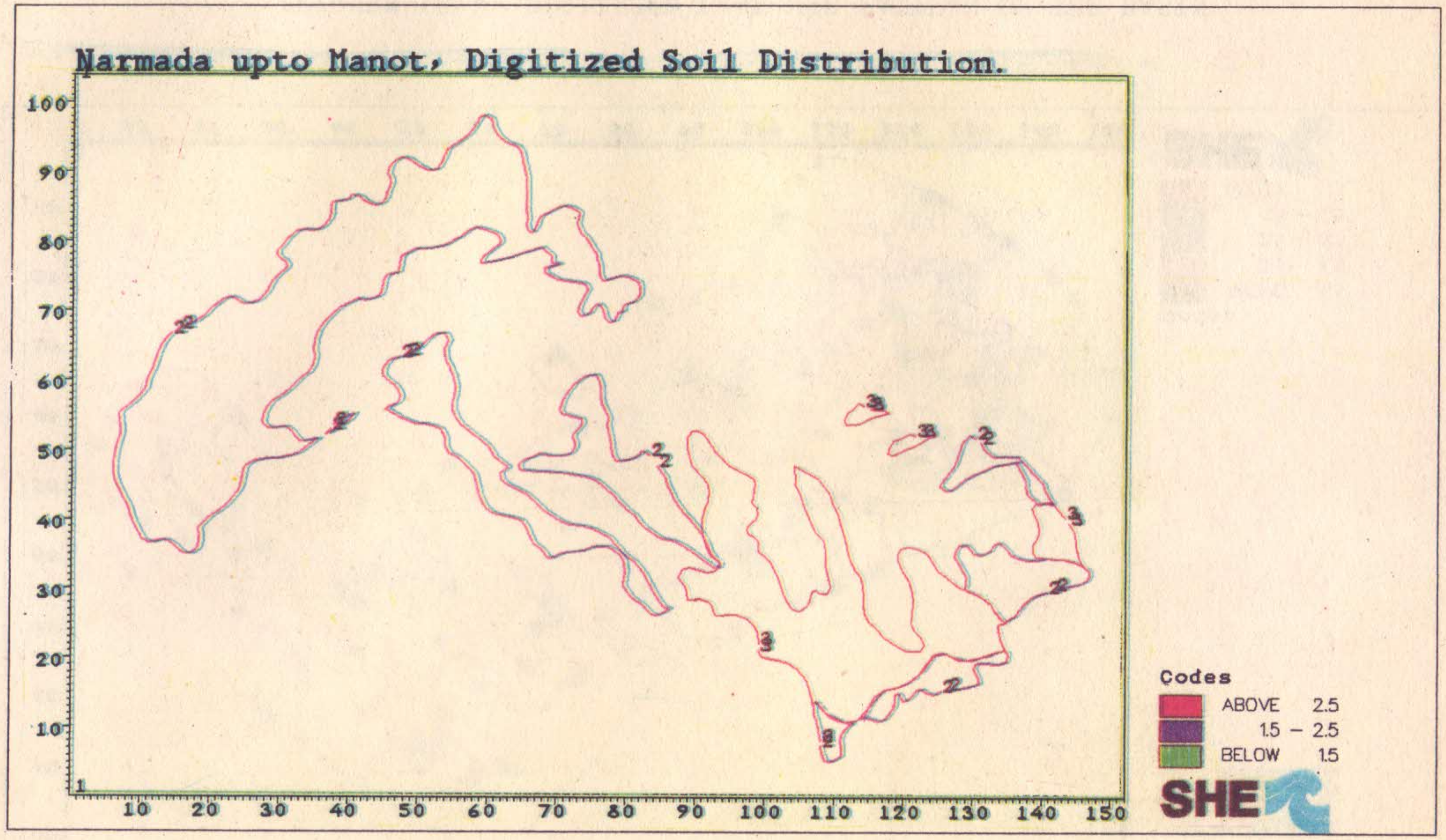


FIGURE 20 - DIGITIZED SOIL DISTRIBUTION OF THE BASIN

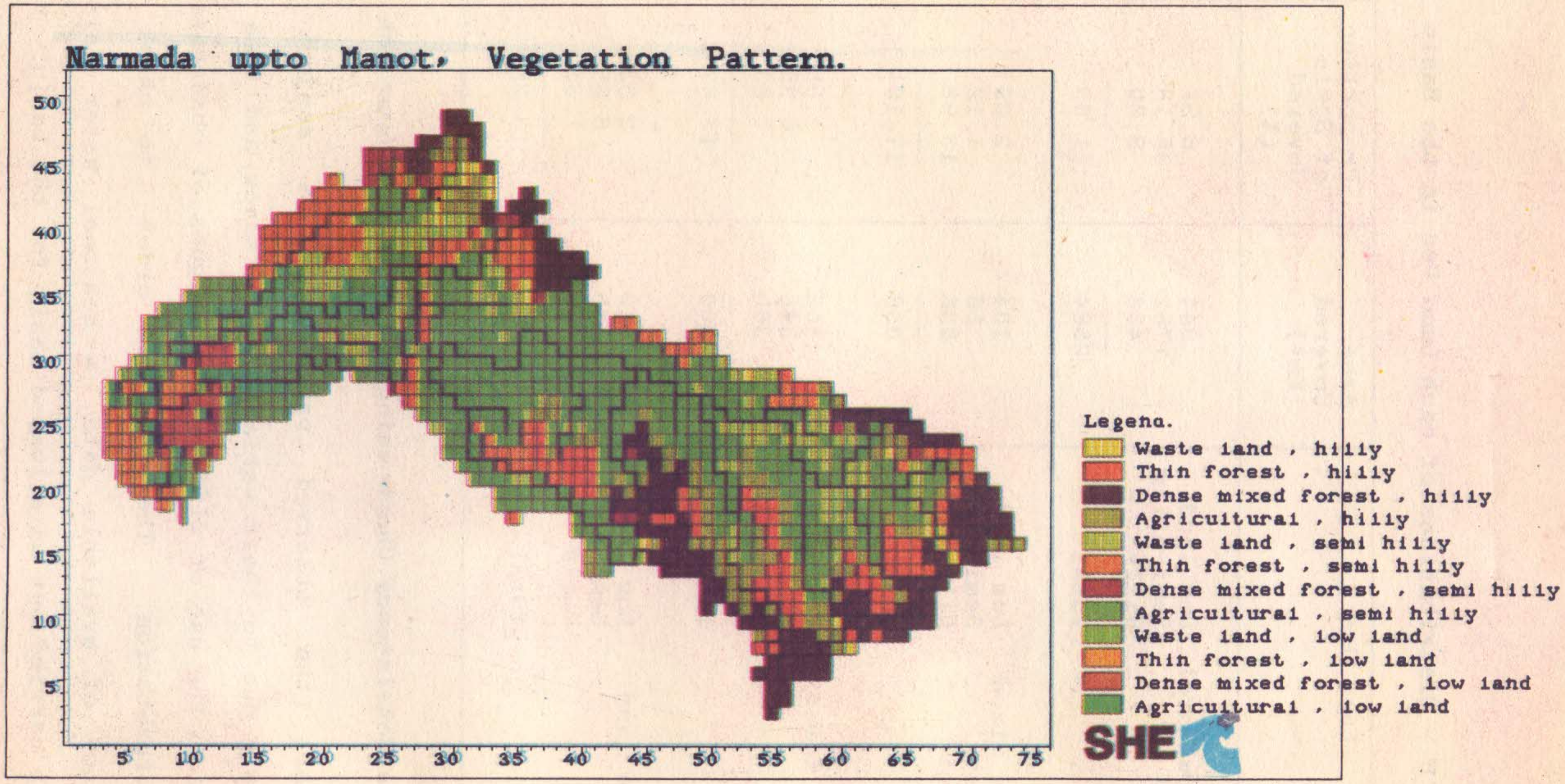


FIGURE 21 - VEGETATION PATTERN IN THE BASIN

Table 8 - Distributions of each Land Use in the Basin

Land Use		Area Covered (Km^2)	Proportion of Basin Covered (%)
Agricultural land:	Low land	344	6.91
	Semi-hilly	1752	35.18
	Hilly	488	9.80
	Total	2584	51.89
Dense mixed forest:	Low land	104	2.09
	Semi-hilly	56	1.12
	Hilly	696	13.98
	Total	856	17.19
Thin forest:	Low land	152	3.05
	Semi-hilly	348	6.99
	Hilly	380	7.63
	Total	880	17.67
Waste land:	Low land	116	2.33
	Semi-hilly	448	8.99
	Hilly	96	1.93
	Total	660	13.25

4.3 Data Consistency Check using Water Balance Approach

All the observed parameters are subject to uncertainty due to their variability in space and time and also due to the use of different techniques of observations and interpretation. Therefore, in order to check the consistency of available data, a seasonal water balance study was carried out on a lumped basis for the basin. This established the ratio between rainfall and runoff and at the same time contributed to an improved understanding of the processes of basin response. The water balance study was carried out in the following manner -

(i) Monsoon season

(a) Plot runoff versus rainfall (figure 22).

(b) Assuming actual evaporation as 75% of potential evaporation, Recharge to ground water, R_1 = rainfall - runoff - actual evaporation.

(c) Assuming recharge to ground water, R_2 = 15 % of rainfall.

(ii) Non-monsoon season

(a) Estimation of base flow volume from daily discharge records.

(b) Plot base flow versus R_1 (figure 23).

(c) Plot base flow versus R_2 (figure 24).

(d) Plot (runoff-base flow) versus rainfall (figure 25).

The components of water balance computations are shown in table 9. It was observed from the plots that, in general, the relations exhibit a systematic trend within the reasonable limits. However the data points for the year 1986-87 in all these plots were found to lie far away from the general trend of data, thereby indicating its inconsistency. Therefore, it was decided that the data of

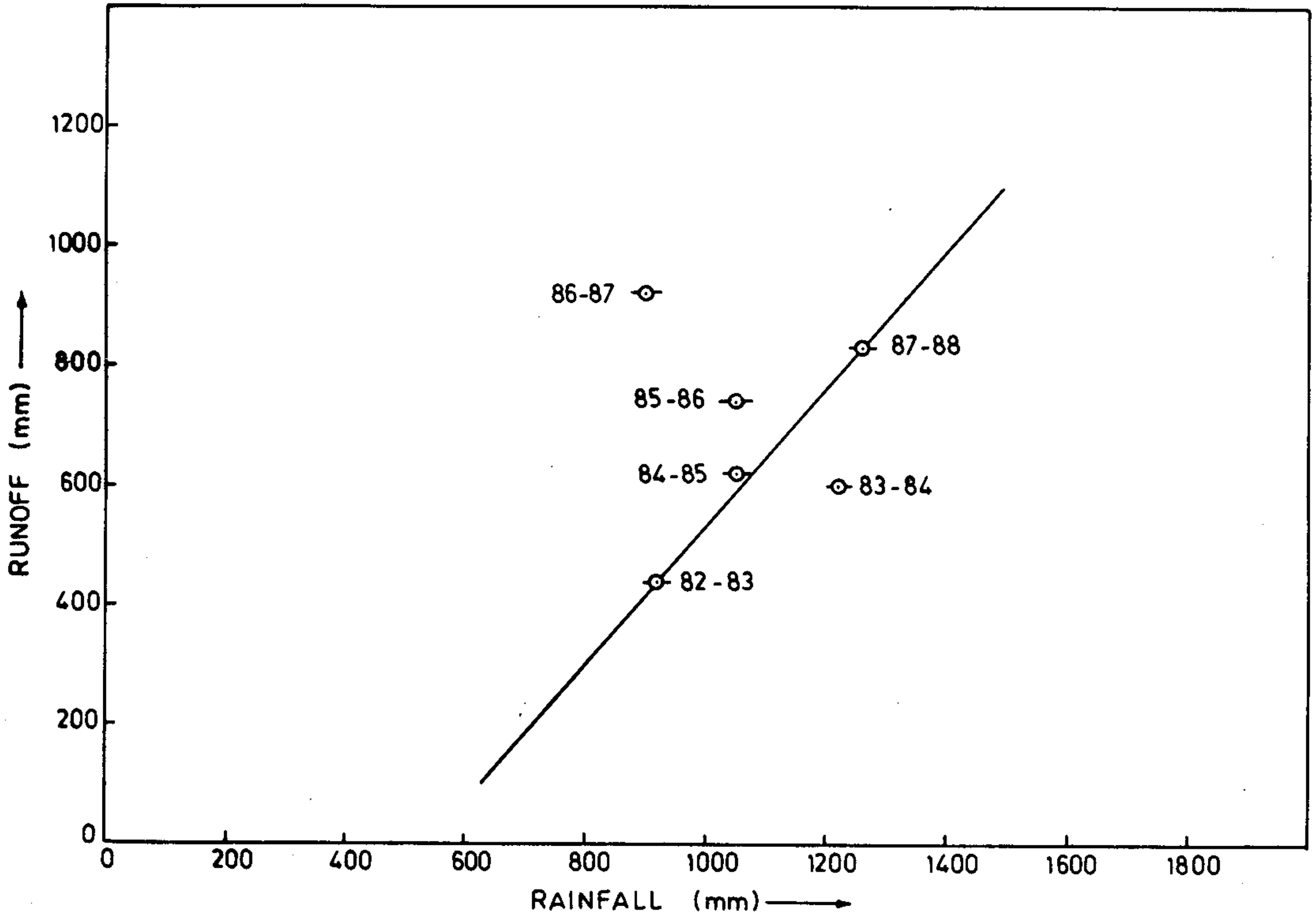


FIGURE 22-VARIATION OF RUNOFF WITH RAINFALL IN MONSOON SEASON

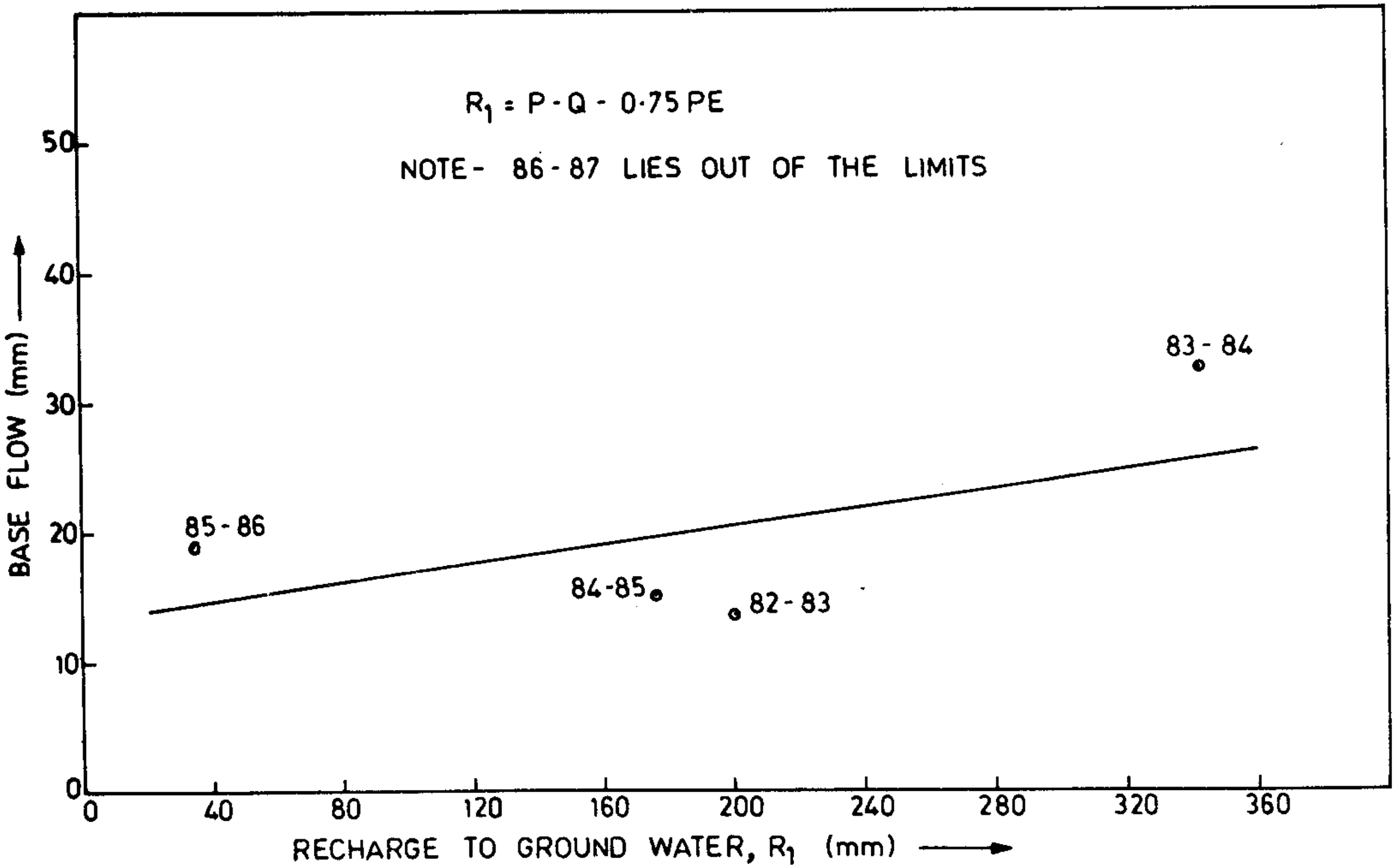


FIGURE 23-VARIATION OF BASE FLOW WITH GROUND WATER RECHARGE (WATER BALANCE)

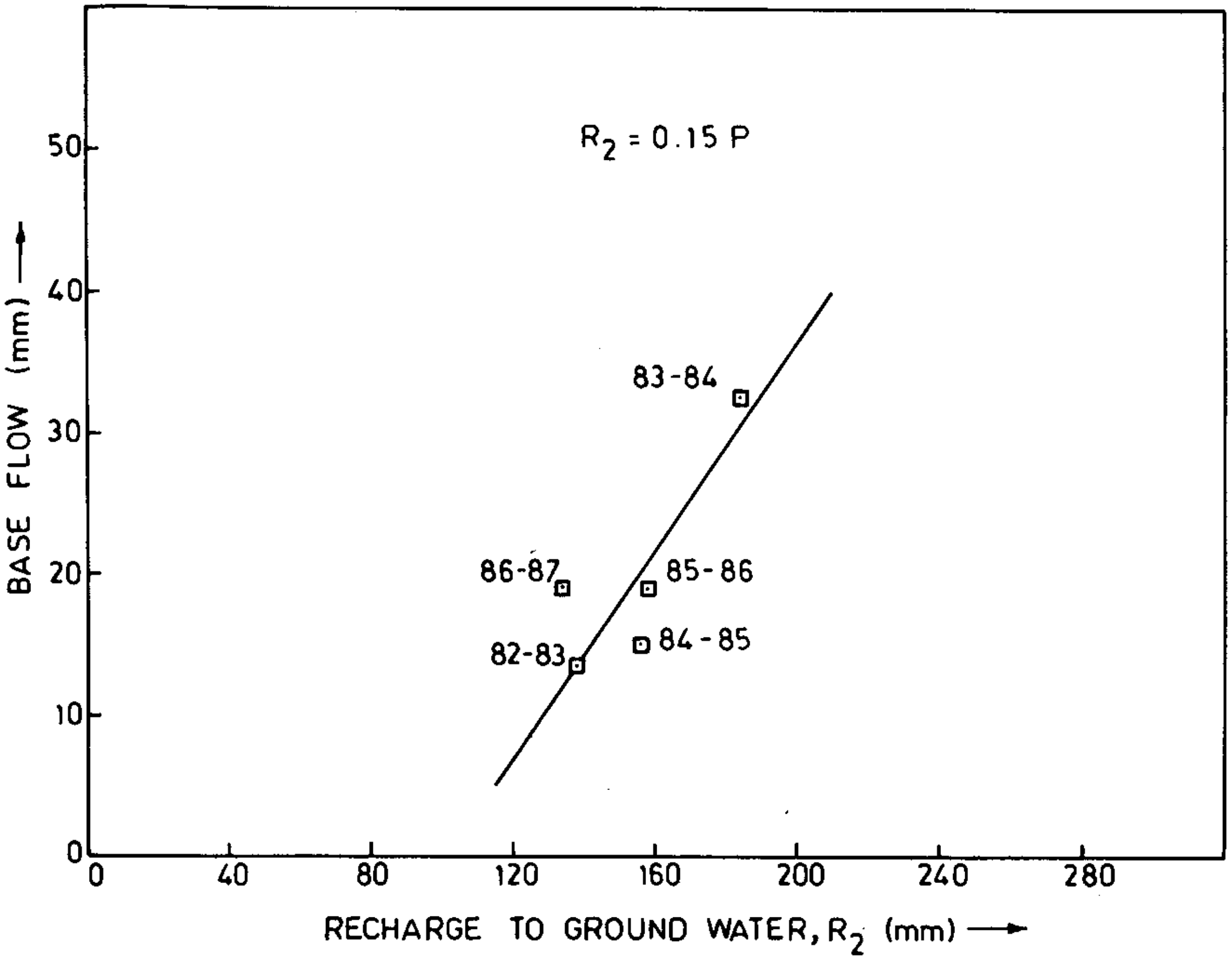


FIGURE 24- VARIATION OF BASE FLOW WITH GROUND WATER RECHARGE (ADHOC NORMS)

FIGURE 46 - OBSERVED AND SIMULATED HYDROGRAPHS (1984) AT THE MANOT GAUGING SITE (CALIBRATION AND SENSITIVITY 2)

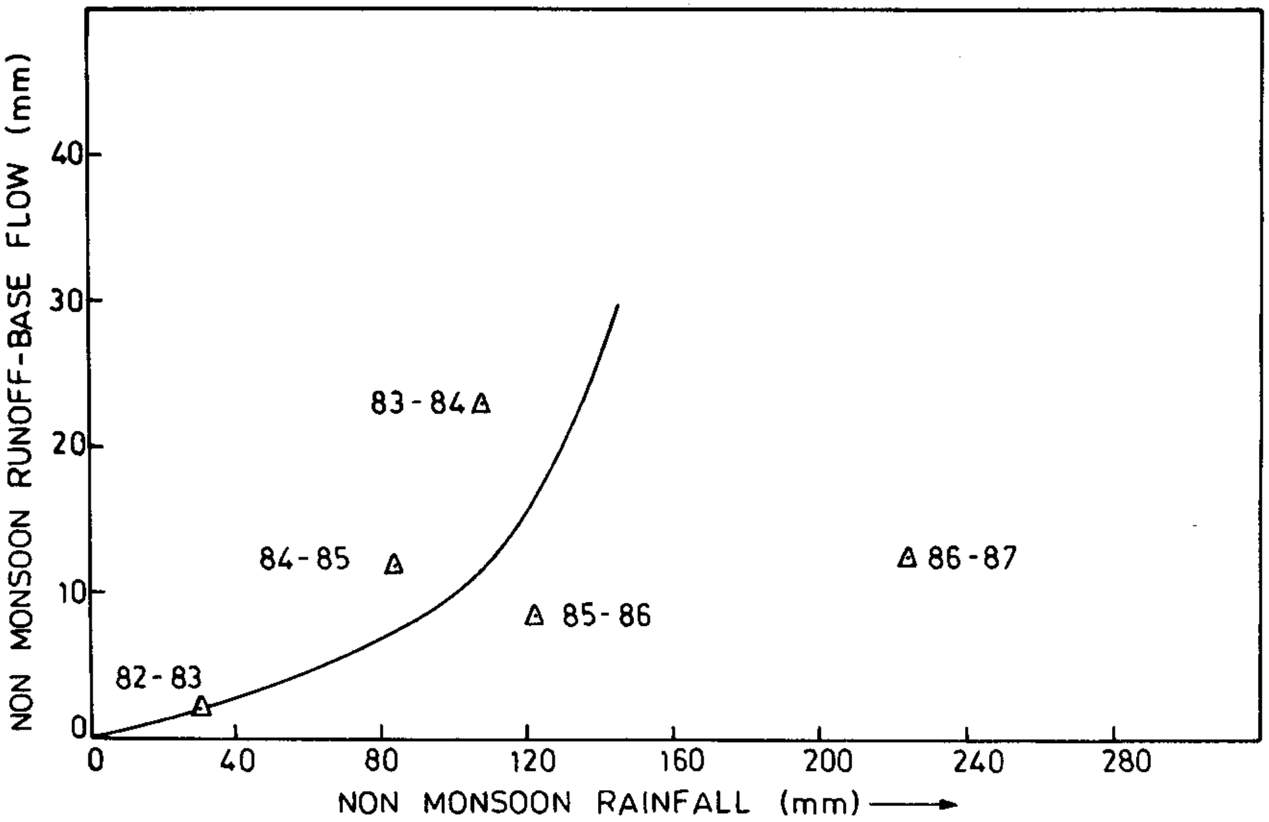


FIGURE 25- RELATION BETWEEN NON MONSOON RAINFALL AND (RUNOFF-BASE FLOW)

Table 9 - Water Balance of the Basin

Note : All quantities are in mm.

S. No.	Year	Rainfall		Runoff		Potential Evaporation		Base Flow	Runoff Coefficient	(Q_2-Q_B)	Actual Evaporation in Monsoon	Recharge to Ground Water in Monsoon	
		Monsoon	Non-monsoon	Monsoon	Non-monsoon	Monsoon	Non-monsoon					$R_1=P_1-Q_1$ $-0.75PE_1$	$R_2=0.15P_1$
		P_1	P_2	Q_1	Q_2	PE_1	PE_2	Q_B	(Q_1/P_1)		$(0.75PE_1)$		
1	1982-83	918.94	29.61	436.15	15.25	376.32	632.88	13.50	0.47	1.75	282.24	200.55	137.84
2	1983-84	1221.47	107.51	598.56	55.50	375.84	649.92	32.49	0.49	23.01	281.88	341.03	183.22
3	1984-85	1045.78	84.95	615.50	26.92	339.60	666.72	15.02	0.59	11.90	254.70	175.58	156.87
4	1985-86	1053.65	122.34	736.83	27.19	377.76	617.52	18.76	0.70	8.43	283.32	33.50	158.05
5	1986-87	896.63	223.17	920.31	31.39	385.44	525.60	18.87	1.03	12.52	289.08	-312.76	134.49
6	1987-88	1262.00	N.A.	828.50	N.A.	363.12	N.A.	N.A.	0.66	-	272.34	161.16	189.30

N.A. denotes that data is not available.

1986-87 may not be used in the simulations. The data for other years (1982-83 to 1985-86 and 1987-88) were assumed to be consistent as a result of the above water balance study and were used in simulation studies.

4.4 Model Setup

The first stage in the model setup was the construction of the computational grid network and channel system used to represent spatial distribution. For the basin a basic array for parameter evaluation and distribution was prepared with grid squares of 1 km x 1 km. A topographic elevation, soil type code, vegetation type or land use code and a meteorological station code were then assigned to each square on the basis of available map information. However, the use of grid squares of 1 km x 1 km in the simulations would have resulted in impractically long computer run times. Using the SHE Array Formatting Routine, the number of squares used to represent the basin were therefore reduced by converting the basic network into network with squares of 2 km x 2 km and 4 km x 4 km. The former scale formed the basis for calibration work while the latter was used in the sensitivity analysis. Figures 26, 27 and 28 present the networks with grid squares of 1 km x 1 km, 2 km x 2 km and 4 km x 4 km respectively.

Within the SHE the network is mapped by a series of channel links superimposed on the grid square boundaries. Coarser grid scales produce different drainage densities in

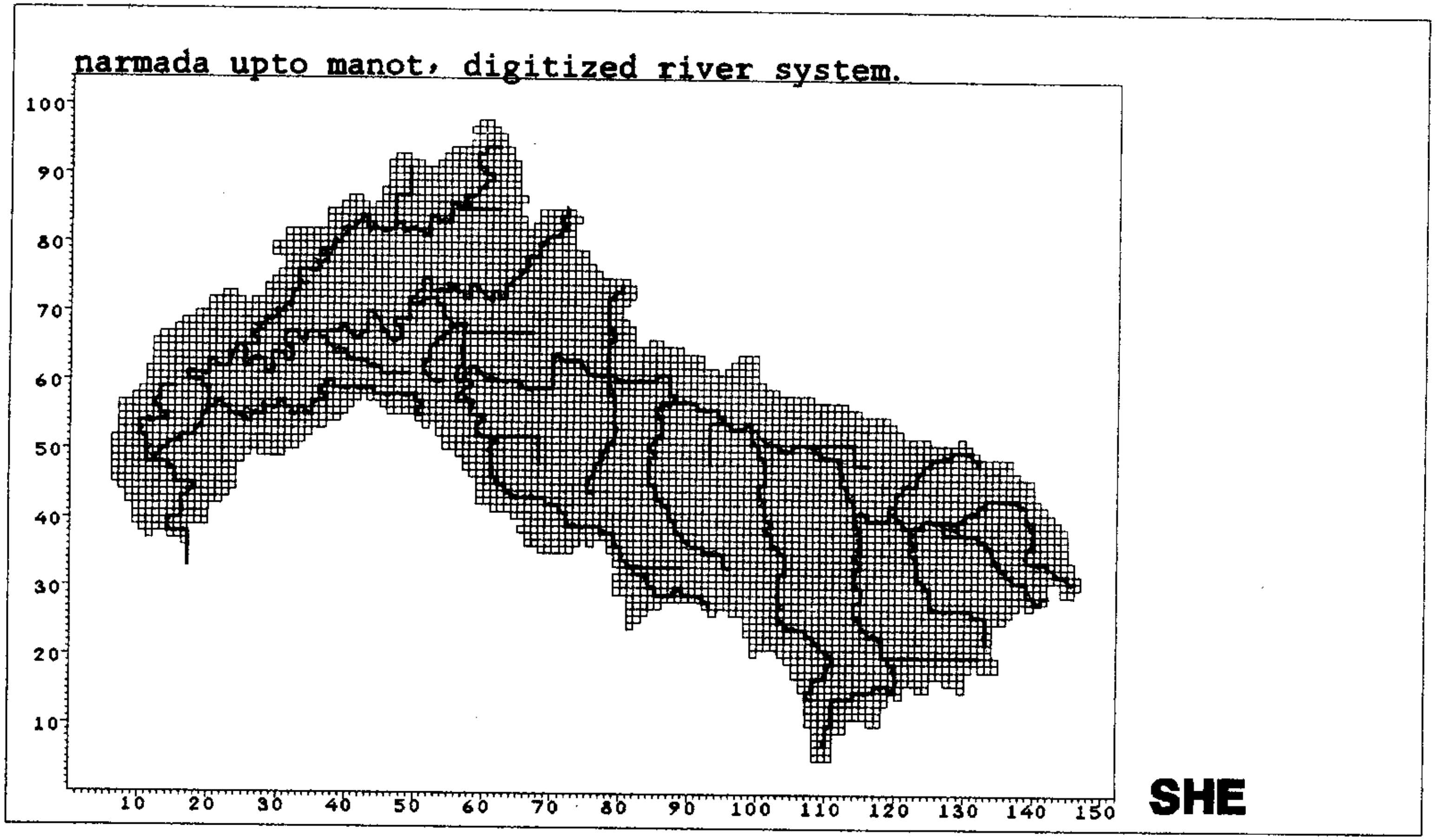


FIGURE 26 - RIVER SETUP IN 1 KM X 1 KM GRID NETWORK

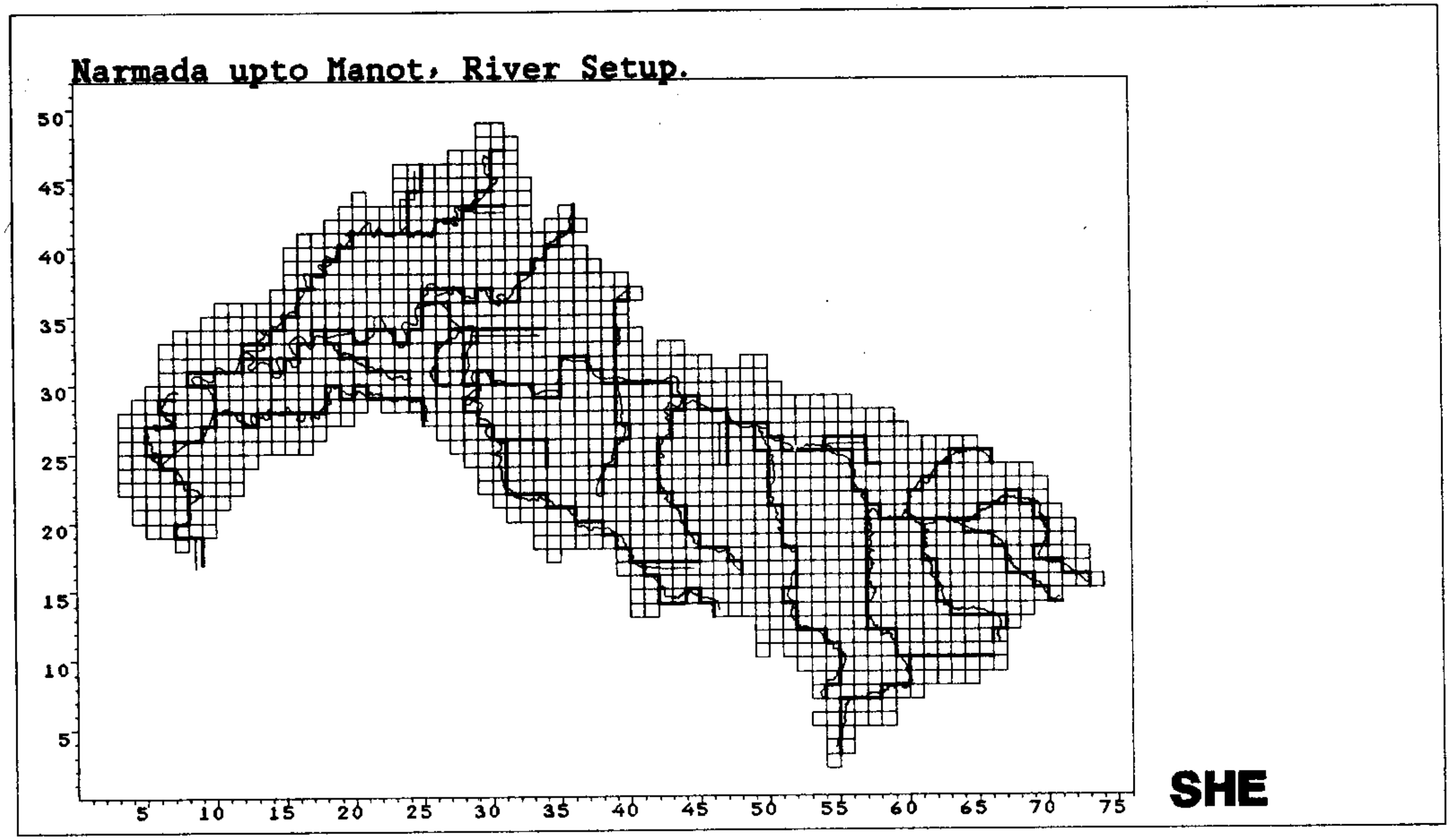


FIGURE 27 - RIVER SETUP IN 2 KM X 2 KM GRID NETWORK

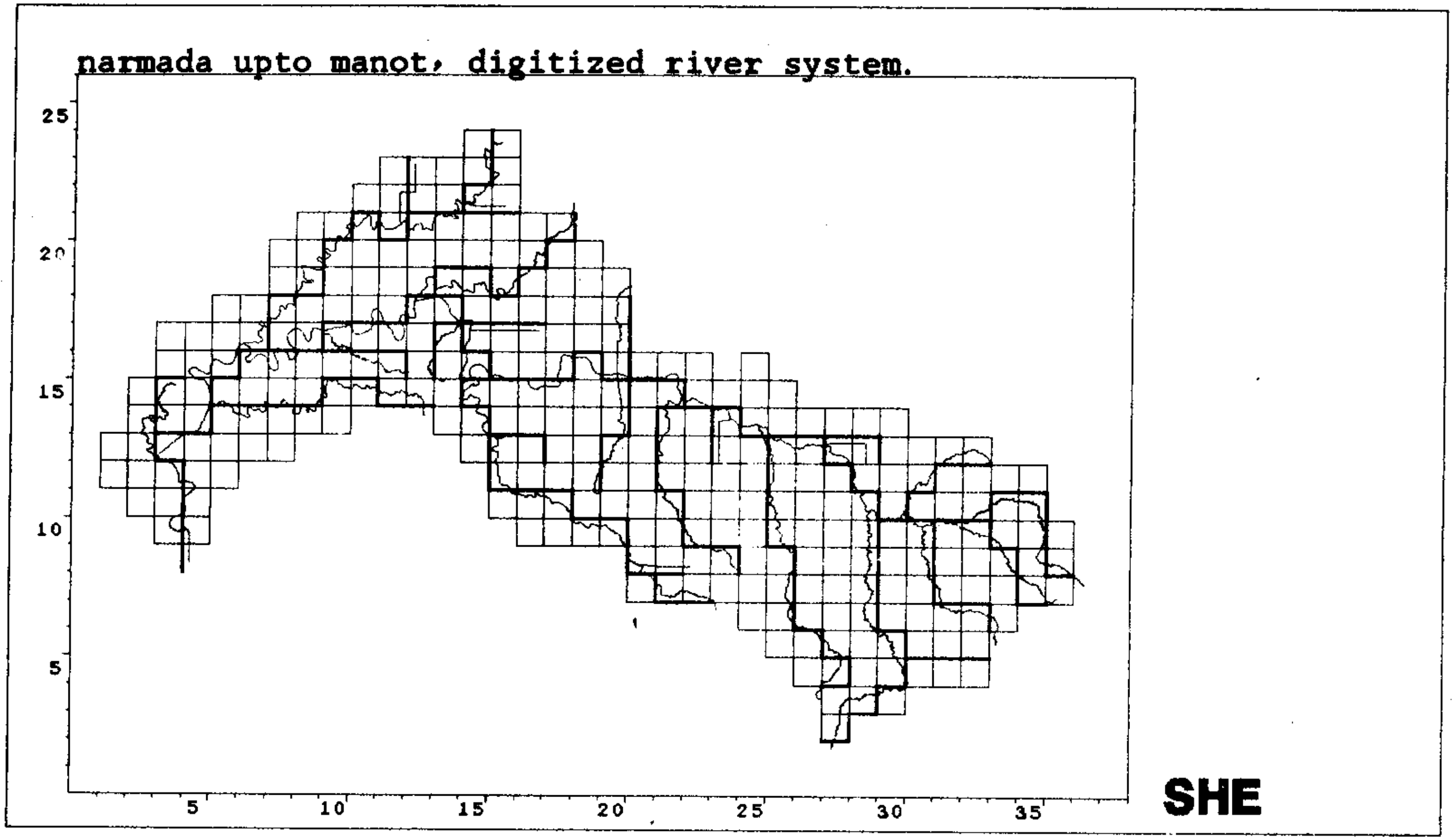


FIGURE 28 - RIVER SETUP IN 4 KM X 4 KM GRID NETWORK

terms of the ratio of the number of channel links to the number of grid squares. Table 10 compares the number of grid squares and river links used to represent the basin at different scales.

Table 10 - Grid and Channel Network Dimensions for Different Grid Scales

Grid Square Size (KmxKm)	Represented Basin Area (Km^2)	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	4956.50	19826	2124	0.107
1x1	4955.00	4955	991	0.200
2x2	4980.00	1245	455	0.365
4x4	4912.00	307	202	0.658

With the arrays established, initial test runs were carried out to check for errors in the grid arrangements, river links and topographic representations and to ensure that surface flows (overland and channel flows) within the basin could be modelled realistically. At this stage, hypothetical rainfall, evapotranspiration and soil infiltration data were used. These simple tests provided a good 'shake-out' for the basin models and enabled a number of 'teething problems' such as river elevations set higher than bank elevations, to be eliminated. Then the way was clear for simulations with full representations of the basin, based on measured input data, evaluation of soil and vegetation parameters and the available understanding of basin hydrology.

4.5 Parameter Evaluation

There are no direct measurements of soil and vegetation parameters available for the basin and therefore evaluations depend on parameter transfer from the literature on neighbouring areas. Information on the upper Betwa basin formed a useful guide in parameter evaluations.

4.5.1 Soil parameters

Soils in the flat low land areas were assumed to resemble those in the Betwa basin. A certain amount of information is available on these soils. Soils in the uplands are less deep than those in the low land areas but, in general, relevant information is scanty. The relevant parameter values actually used in the simulations, are given in table 11. Only one retention curve was used based on the data given in table 12 and assumed to be the same for low land and upland soils.

Three categories of soil depth were defined, for flat low land areas (deep soils), for hillslopes or semi-hilly areas (intermediate depths) and for upland or hilly areas (shallow soils), the distributions obtained from the topographic maps. The soil depths were determined from analysis of well levels. The values adopted as best estimates for the calibrations are shown in table 13.

Table 11 - Physical Characteristics of Soil

S.No.	Soil Parameter	Value
1	Water content at saturation (equal to the porosity of the soil)	0.478
2	Effective water content at saturation, adjusted for trapped air volumes	0.450
3	Water content at field capacity	0.384
4	Corresponding tension at field capacity	-1.000 m
5	Water content at wilting point	0.180
6	Residual water content (inaccessible water content in soil due to adsorption)	0.180
7	Saturated conductivity	0.100 m/day
8	Exponent for conductivity/ moisture content relation	12.000

Table 12 - Retention Curve Table used for all Soil Types

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

Table 13 - Estimates of Soil Depth

Ground Elevation Range (m)		Soil Depth (m)
Low land	< 640	7.0
Semi-hilly	640-810	2.5
Hilly	> 810	1.5

4.5.2 Vegetation parameters

The main vegetation parameters concern root zone depth (needed in simulating the effect of evapotranspiration on the unsaturated zone) and the leaf area index (needed to calculate the net precipitation). In the agricultural area, crops are grown during the monsoon and the winter season while the forest is in leaf during the period June to December. The transpiration from the vegetation depends on the density of the crop green material, described by the leaf area index, the actual soil moisture content in the root zone and the root density. The interception storage capacity also depends on the vegetation type and its stage of development through the leaf area index.

Table 14 - Root Zone Depth and Leaf Area Index

Month	Agricultural Land		Dense Mixed Forest		Thin Forest		Waste Land	
	Root Zone Depth (m)	LAI	Root Zone Depth (m)	LAI	Root Zone Depth (m)	LAI	Root Zone Depth (m)	LAI
January	0.6	4.0	2.0	5.0	1.0	3.0	0.5	1.0
February	0.6	4.0	2.0	3.5	1.0	2.5	0.5	1.0
March	0.6	4.0	2.0	2.0	1.0	2.0	0.5	1.0
April	0.6	2.0	2.0	2.0	1.0	2.0	0.5	1.0
May	0.6	2.0	2.0	4.0	1.0	3.5	0.5	1.0
June	0.6	2.0	2.0	7.0	1.0	5.0	0.5	1.0
July	0.6	3.0	2.0	7.0	1.0	5.0	0.5	1.0
August	0.6	5.0	2.0	7.0	1.0	5.0	0.5	1.0
September	0.6	5.0	2.0	7.0	1.0	5.0	0.5	1.0
October	0.6	2.0	2.0	7.0	1.0	5.0	0.5	1.0
November	0.6	0.5	2.0	5.5	1.0	4.0	0.5	1.0
December	0.6	2.5	2.0	4.0	1.0	3.0	0.5	1.0

The leaf area index (LAI), defined as the area of one side of leaves per unit area of soil surface, varies usually between 0 and 7. Table 14 shows the time variation of root zone depth and leaf area index for the four land use types used in the simulations.

4.5.3 Overland and channel flow parameters

The Strickler roughness coefficient for overland flow was assumed to be spatially uniform in the basin. In reality variations might be expected according to land use and whether the overland flow occurs as sheet flow or in rivulets. However, no information on such variations was available. For overland flow, the Strickler roughness coefficient is likely to lie between about 0.04 (typical of sheet flow in grass) and 2-20 (typical of flow in grass-lined channels). For the simulations, it was varied between 2 $m^{1/3}/s$ and 4 $m^{1/3}/s$ and used as a calibration factor.

For the channel flow, sample calculations using measured flow and cross-sectional data gave Strickler coefficients in the range of 15 to 30 $m^{1/3}/s$. These values, equivalent to Manning's n of 0.033 to 0.066, are characteristic of river channels.

4.5.4 Channel cross-sections

In defining the channel cross-sections, use was made of some rough surveys made in the Hiran basin, giving the bankfull dimensions at various distances along the main stem. Channel dimensions vary with the upstream drainage area and empirical dependencies can therefore be established to enable the dimensions to be calculated at all parts of the river system. In this case, drainage area was considered to be inconvenient to measure for more than a few points. A more convenient parameter to measure is upstream channel length, since this also varies closely with upstream drainage area (figure 29 a), it can be used as the basis for calculating channel dimensions. The Hiran data were therefore used to produce the empirical relationships shown in figure 29, giving bankfull cross-sectional area A, bankfull depth d, bankfull (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. Since river lengths represented on the SHE grid system tend to be slightly larger than the map lengths, the relationship between the two lengths was also derived based on a 2 km SHE grid (figure 29 b). Tested against the outlet channel dimensions for the Narmada (upto Manot) and Ganjal basins, the Hiran relationships apply reasonably well (figure 29). In most cases their data points lie within the scatter of the Hiran data. These relationships were therefore used to define the channel dimensions at all parts of the Narmada (upto Manot) river system as defined for the SHE (table 15).

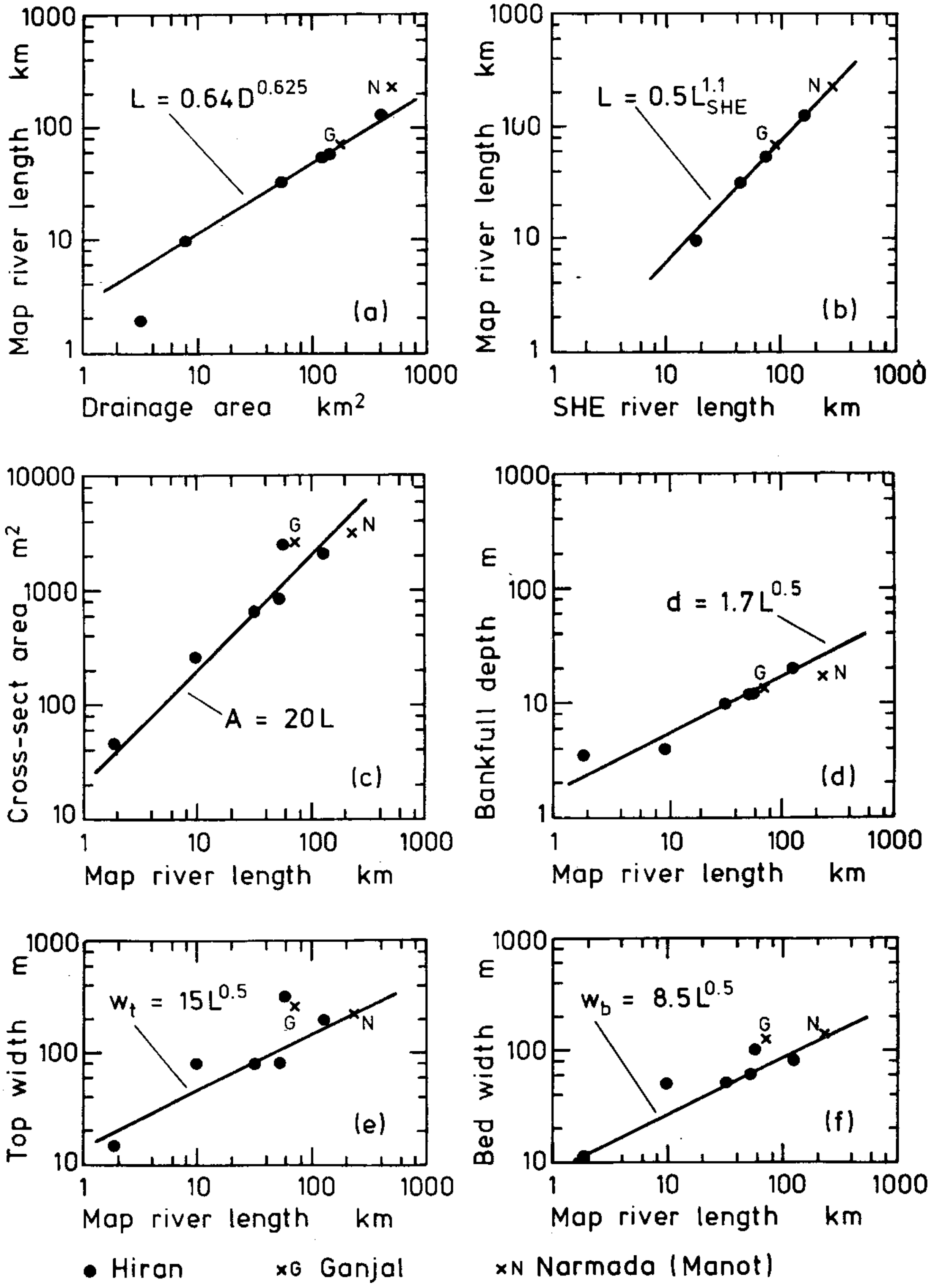


FIGURE 29 - CHANNEL DIMENSION RELATIONSHIPS BASED ON DATA OF THE HIRAN BASIN

Table 15 - Channels Cross-sections (RIVER.CROSS)

Number of Actual River Section	Number of Levels	Downstream Section						Upstream Section						Strickler Coefficient in River Section
		d_N	W_N	d_N	W_N	d_N	W_N	d_N	W_N	d_N	W_N	d_N	W_N	
1	3	0	139.4	13.94	192.7	27.88	246.0	0	6.0	0.60	8.3	1.20	10.6	30
2	3	0	13.0	12.80	18.0	25.61	23.0	0	6.0	0.60	8.3	1.20	10.6	30
3	3	0	57.7	11.31	79.7	22.62	101.7	0	6.0	0.60	8.3	1.20	10.6	30
4	3	0	32.1	12.20	44.3	24.40	56.6	0	6.0	0.60	8.3	1.20	10.6	30
5	3	0	70.0	7.57	96.7	15.14	123.5	0	6.0	0.60	8.3	1.20	10.6	30
6	3	0	38.0	8.62	52.5	17.24	67.0	0	6.0	0.60	8.3	1.20	10.6	30
7	3	0	51.5	5.46	71.2	10.92	90.9	0	6.0	0.60	8.3	1.20	10.6	30
8	3	0	25.3	6.09	34.9	12.19	44.6	0	6.0	0.60	8.3	1.20	10.6	30
9	3	0	17.9	6.09	24.8	12.19	31.7	0	6.0	0.60	8.3	1.20	10.6	30
10	3	0	83.9	4.80	116.0	9.60	148.0	0	6.0	0.60	8.3	1.20	10.6	30
11	3	0	134.2	3.53	185.5	7.05	236.8	0	6.0	0.60	8.3	1.20	10.6	30
12	3	0	52.9	3.16	73.1	6.31	93.3	0	6.0	0.60	8.3	1.20	10.6	30
13	3	0	80.1	2.93	110.7	5.87	141.3	0	6.0	0.60	8.3	1.20	10.6	30
14	3	0	69.1	2.64	95.6	5.28	122.0	0	6.0	0.60	8.3	1.20	10.6	30
15	3	0	13.9	9.90	19.2	19.81	24.5	0	6.0	0.60	8.3	1.20	10.6	30
16	3	0	12.8	8.18	17.7	16.36	22.6	0	6.0	0.60	8.3	1.20	10.6	30
17	3	0	16.1	4.83	22.2	9.65	28.3	0	6.0	0.60	8.3	1.20	10.6	30
18	3	0	17.0	2.60	23.6	5.20	30.1	0	6.0	0.60	8.3	1.20	10.6	30
19	3	0	8.9	8.04	12.3	16.07	15.7	0	6.0	0.60	8.3	1.20	10.6	30
20	3	0	13.3	5.97	18.4	11.95	23.5	0	6.0	0.60	8.3	1.20	10.6	30
21	3	0	20.7	2.42	28.7	4.83	36.6	0	6.0	0.60	8.3	1.20	10.6	30
22	3	0	11.4	5.02	15.7	10.04	20.1	0	6.0	0.60	8.3	1.20	10.6	30
23	3	0	19.6	4.28	27.1	8.57	34.5	0	6.0	0.60	8.3	1.20	10.6	30
24	3	0	50.0	1.91	69.1	3.82	88.2	0	6.0	0.60	8.3	1.20	10.6	30

d_N : distance between bed level and level N in the cross-section (m)

W_N : width (m) at level N

4.5.5 Initial conditions

Initial conditions for a simulation are specified in terms of the depth of the phreatic surface. In this case, for simulations of individual monsoon periods, the depths are defined for 1 March. The values adopted in simulations are estimates rather than measurements but take into account available information on well levels.

4.5.6 Unsaturated zone calculations

Unsaturated zone calculations were carried out directly for 27 specified grid squares out of the total 1245 grid squares representing the basin. Within the SHE there is a facility for limiting the calculations to selected squares, each representative of a domain of squares, then transferring the calculated results at each time step to the other squares in the domains. This can produce a considerable saving in computation time since the unsaturated zone component is otherwise a major user of cpu time. With the large number of grid squares and long simulation periods being used for the basin, this facility was therefore used throughout the simulations. However, the results are more approximate than if the calculations are carried out for all squares and it is necessary to balance saving in computation time against representation of the basin.

5.0 CALIBRATION AND VALIDATION

5.1 General

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

Given the large number of parameters it is not realistic to obtain an accurate calibration by gradually varying all the parameters singly or in combination. A more sensible approach is to attempt a coarser calibration using only the few parameters to which the simulation is most sensitive. The only way in which the SHE can simulate a suitable response is by computing the rainfall excess and its travel to the channel network as overland flow. Simulating the transmission of saturated subsurface flow is important during low flow situations. The parameters which determine the quantity of rainfall which is diverted into overland flow and the rate of movement of that overland flow are thus more important. These are : the saturated values of soil conductivity and moisture content and the soil moisture tension curve for the unsaturated zone; the saturated zone conductivity; and the flow resistance coefficients for the overland and channel flows.

5.2 Calibration Approach

Calibration was carried out for a 2 km x 2 km representation of the basin, mainly by adjusting a few key parameters and examining their effects on the simulated hydrographs. Several trial-and-error runs were carried out. The Strickler roughness coefficients for overland and channel flow were used principally to calibrate hydrograph peaks, the saturated conductivity for the unsaturated zone determined the amount of infiltration and thence the runoff hydrograph volume, the saturated zone conductivity affected base flow discharges, while the soil crack and surface detention submodels were used to moderate the amount of infiltration and runoff in the early stages of the monsoon. The effect of varying the initial phreatic surface depth was also investigated. However, the hydrological parameters characterizing the basin were kept more or less the same. The choice of simulation period was determined by the availability of hourly rainfall and hourly gauge data. In carrying out simulations, it was necessary to restrict the maximum solution time step to 2 hours.

The aim of the calibration was to reproduce the measured stream hydrographs for the catchment. The SHE package program does not have a quantitative optimisation method to minimize errors in the simulation beyond an arbitrary level and as such simulated and observed hydrographs were compared by eye.

Finally, a model is not validated until, using the calibrated parameter set, it has successfully simulated independent events which have not been used for the calibration. Consequently the technique employed here was to calibrate the parameter set for the storm events during the period March 1982 to February 1985 and then apply those values in the simulation of the other events during the periods March 1985 to February 1986 and March 1987 to December 1987, changing only the initial level of the phreatic surface. The data of 1986-87 was not used due to inconsistency detected in water balance computations, as already discussed in section 4.3.

The following data handling packages were used in order to analyse the simulation results ·

(a) A postprocessor package which can automatically retrieve, compile and present the simulation inputs, outputs and parameter distributions in a convenient form as tables or graphs. The package comprises the SHE Output Retrieval Routine and the SHE Graphical Display Routine.

(b) SHE.AC reads a time series of observed values or simulation results and writes a new time series of accumulated values.

A sound understanding of basin behaviour is essential for successful field application of the SHE. Using reports on the neighbouring region, the characteristics described in section 3.9, were used in interpreting the simulation results.

5.3 Calibration

Calibration for the period 1982-84 was carried out on the basis of comparisons between simulated and observed monthly outlet hydrograph volumes, outlet peak discharges, outlet base flow discharges and phreatic surface elevations. The details of calibration trials for individual parameters are given below.

5.3.1 Soil parameters

Experience elsewhere with the SHE suggests that simulation results are generally sensitive to the values of the soil parameters. However, these parameters were not varied during the calibration because the uncertainties in rainfall input and other parameter values rendered fine tuning of the soil parameters as an unjustifiable exercise.

5.3.2 Surface detention

A simple surface detention submodel was used to simulate surface ponding effect. Surface storage of overland flow delays the release of runoff to a river system and thus affects the generation of the hydrograph.

5.3.3 Overland flow

An implicit technique was used in the numerical solution procedure for the overland flow calculations which overcomes the problem of maintaining mass continuity and permits the use of larger calculation time step, thereby reducing cpu time requirements.

The 2 km x 2 km grid representation of the basin was used for the simulations. Initial runs were carried out with the Strickler resistance coefficient for the overland flow set at the value of 4.0. However, simulated hydrograph peaks overestimated the measured peaks while the recession was steep by comparison with the observed pattern. Coefficients of 3.0, 2.5 and 2.0 were tested and eventually a value of 2.5 was found to produce reasonable agreement between observation and simulation for all three simulation years. The use of the lower values (implying higher resistance) relative to the values measured elsewhere (around 10.0) with rainfall simulators (Engman, 1986) is justified in terms of scale. Rainfall simulator plots, not more than about 30 m^2 in area, are relatively uniform and exhibit sheet flow. At the 2 km x 2 km scale of the SHE simulation grids, topography, vegetation and soils are considerably less uniform and both sheet and rivulet overland flows are likely. It is not therefore to be expected that the same surface resistance coefficient will apply in both cases.

5.3.4 Crack infiltration

It was observed that runoff was being overestimated during the early stages of the monsoon periods. This might be because the model did not allow for the influence of soil cracking on infiltration. Cracks to a depth of about 1 m are observed in the black cotton soil of the region. However, pre-monsoon ploughing of the fields generally obscures at least the surface appearance of cracks in the fields. Cracks act to increase infiltration above that expected for uncracked soil at the beginning of the monsoon. Then as the monsoon progresses and the supply of moisture causes the soils to swell, the cracks disappear and effective conductivity is decreased. A simple crack submodel was therefore used in order to decrease the simulation overestimates. During the period from March until the date when the accumulated net rainfall exceeds a specified volume (300 mm), a fixed percentage (15%) of the net rainfall is directed to bypass the root zone and enter the unsaturated zone at the specified base of the cracks. This increases the overall infiltration thereby reducing runoff. The bypass water also produces a higher soil moisture below the root zone in comparison with the case for non-cracking soils and saturation is simulated as extending both upwards and downwards from this level.

5.3.5 Initial phreatic surface depth

Each simulation period began on 1st March and the initial phreatic surface levels were therefore defined from consideration of pre-monsoon well levels. Attempts to improve both surface and subsurface (baseflow) response by varying the initial phreatic surface depth were inconclusive. In any case, the imposed initial conditions, although based on general information for the region, retain a degree of arbitraryness. For the basin, continuous simulation from one monsoon season to the next, was carried out by linking the 1982, 1983 and 1984 monsoons. This provided a more accurate representation of the antecedent conditions for the monsoon period. The initial soil moisture conditions for the second are then determined according to the simulated loss of soil moisture to evaporation and, to a lesser extent, to drainage during the dry season separating the two monsoons.

Figure 30 shows variations in simulated phreatic surface depth for different land uses for the calibration period. The patterns conform with observations for the region, except in simulating a relatively long period in which the phreatic surface lies at the ground surface. It

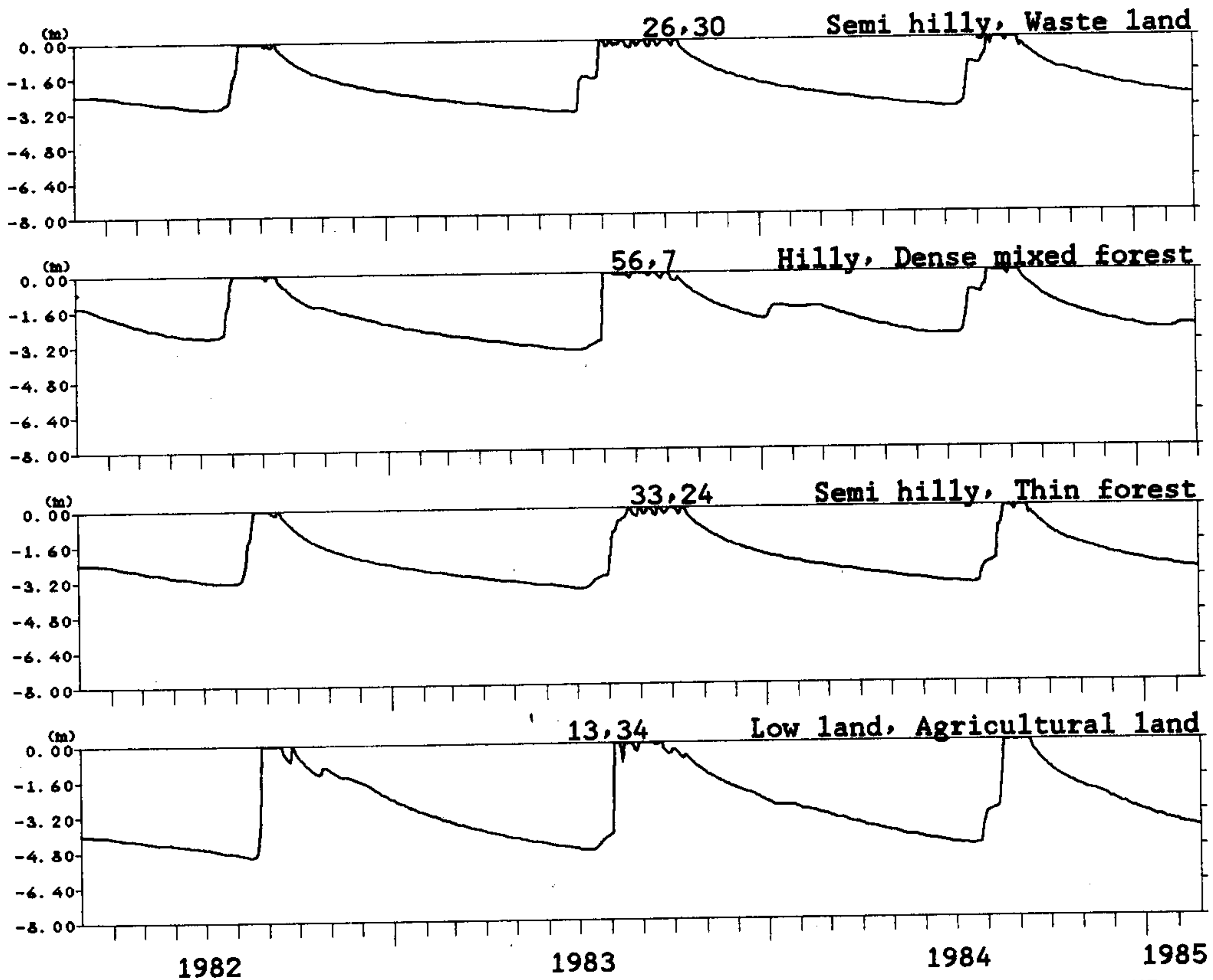


FIGURE 30 - VARIATIONS IN SIMULATED PHREATIC SURFACE DEPTH FOR DIFFERENT LAND USES (CALIBRATION)

seems unlikely that such a period of complete waterlogging in the forest areas occurs in practice since it implies widespread loss of trees. However, the simulated antecedent conditions for successive monsoons return to roughly the same level as the imposed initial conditions. Figures 31 to 36 present the pre-monsoon and post-monsoon phreatic surface depths in the basin for the calibration period. Calibration against well data has not been possible but the patterns conform with general observations for the region.

5.3.6 Unsaturated zone

Under the conditions of heavy rain falling on dry soil, typical of the early monsoon conditions, numerical instabilities and mass balance errors may occur in the simulations if the calculation time step and vertical distance step in the soil column are not kept below critical values. A mass balance check was made for each node point in the vertical for the unsaturated zone calculations. In the mass balance check the error is tested against a specified tolerance and if it exceeds this value, the dependent variables are corrected and the exercise repeated. The solution of the highly nonlinear equation of unsaturated flow is sensitive to the size of the time step and a careful manual check of the mass balance error, for example, inspection of water table fluctuations is recommended in any simulation run.

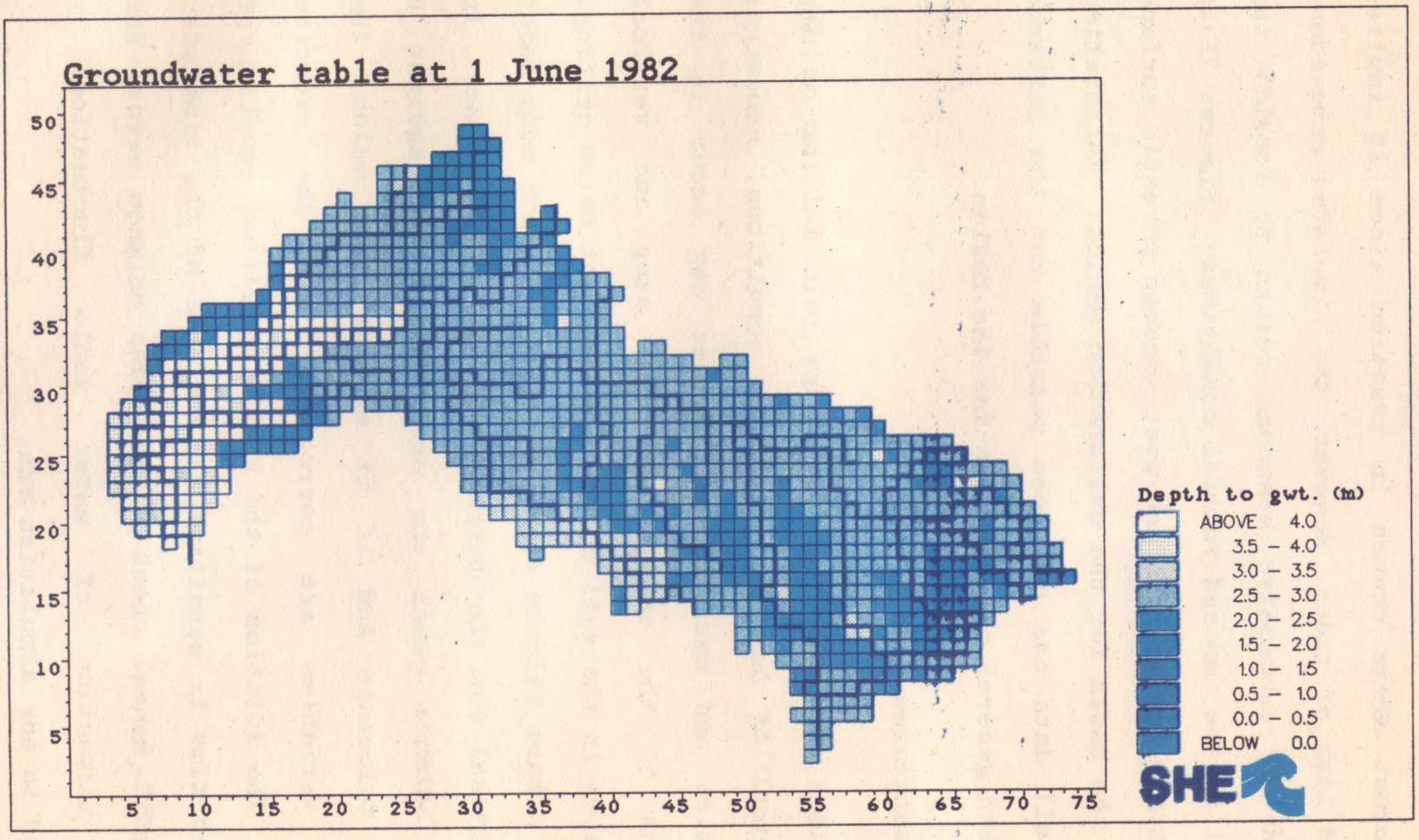


FIGURE 31 - PRE-MONSOON (1982) PHREATIC SURFACE DEPTHS IN THE BASIN

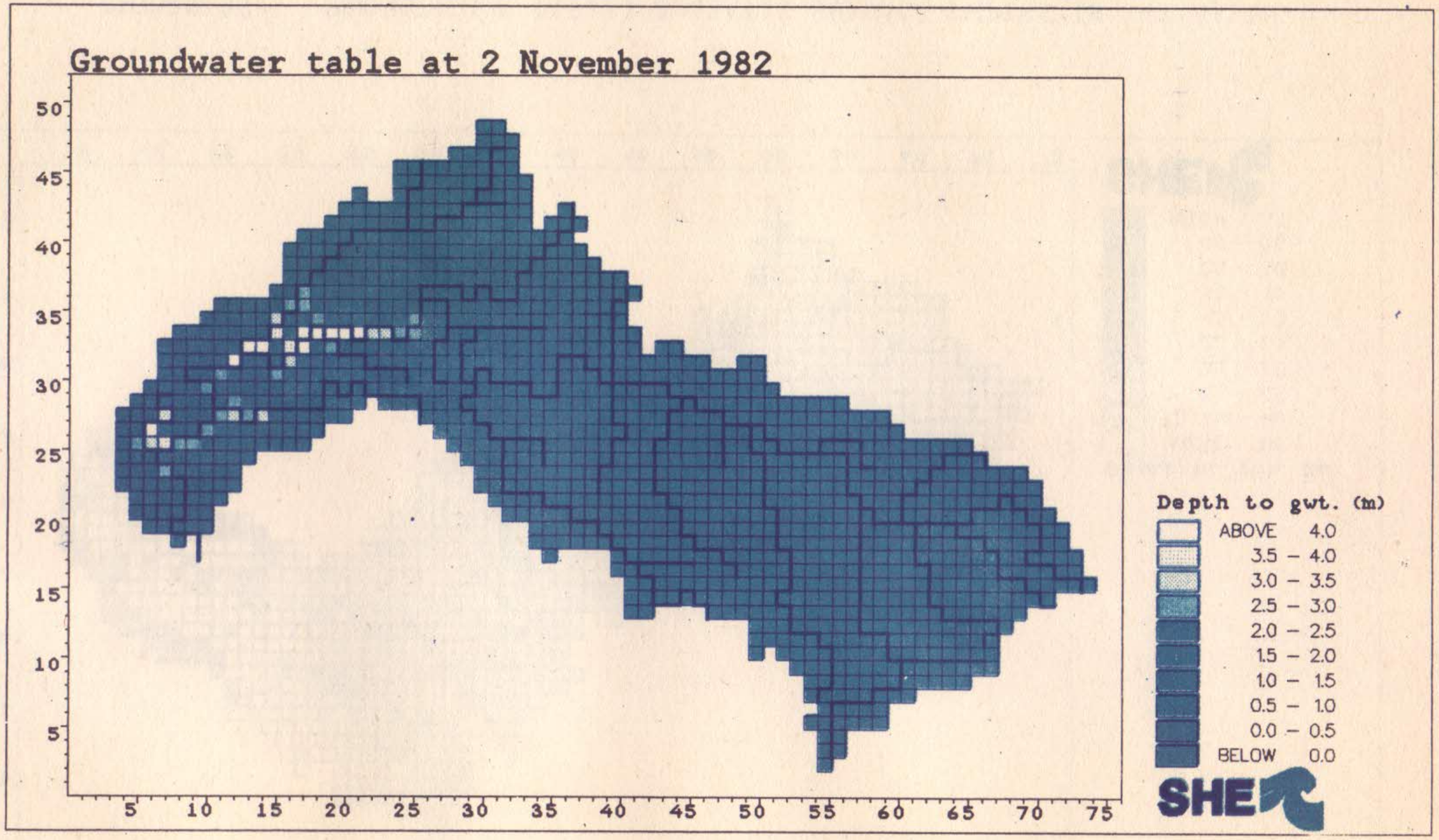


FIGURE 32 - POST-MONSOON (1982) PHREATIC SURFACE DEPTHS IN THE BASIN

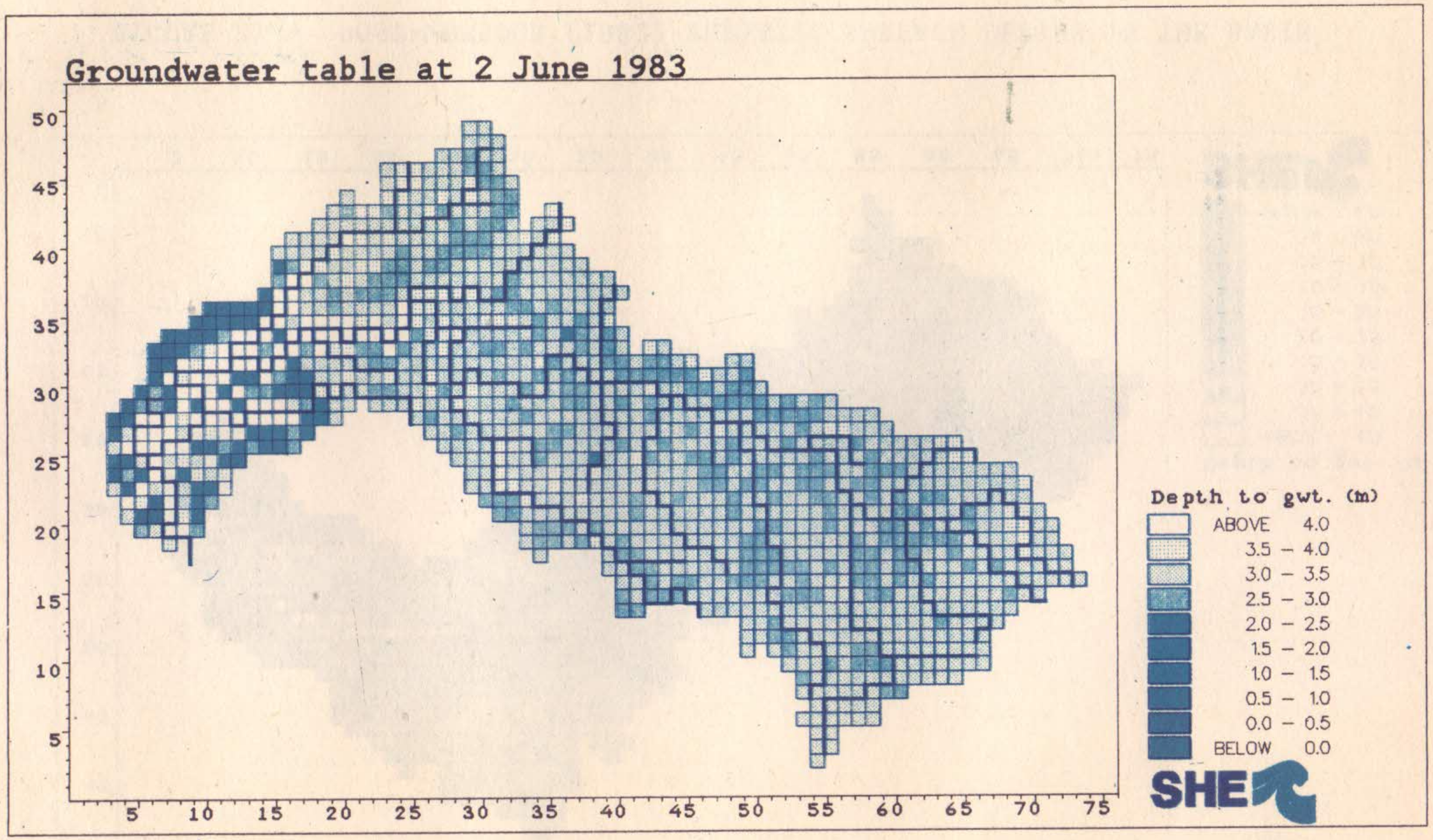


FIGURE 33 - PRE-MONSOON (1983) PHREATIC SURFACE DEPTHS IN THE BASIN

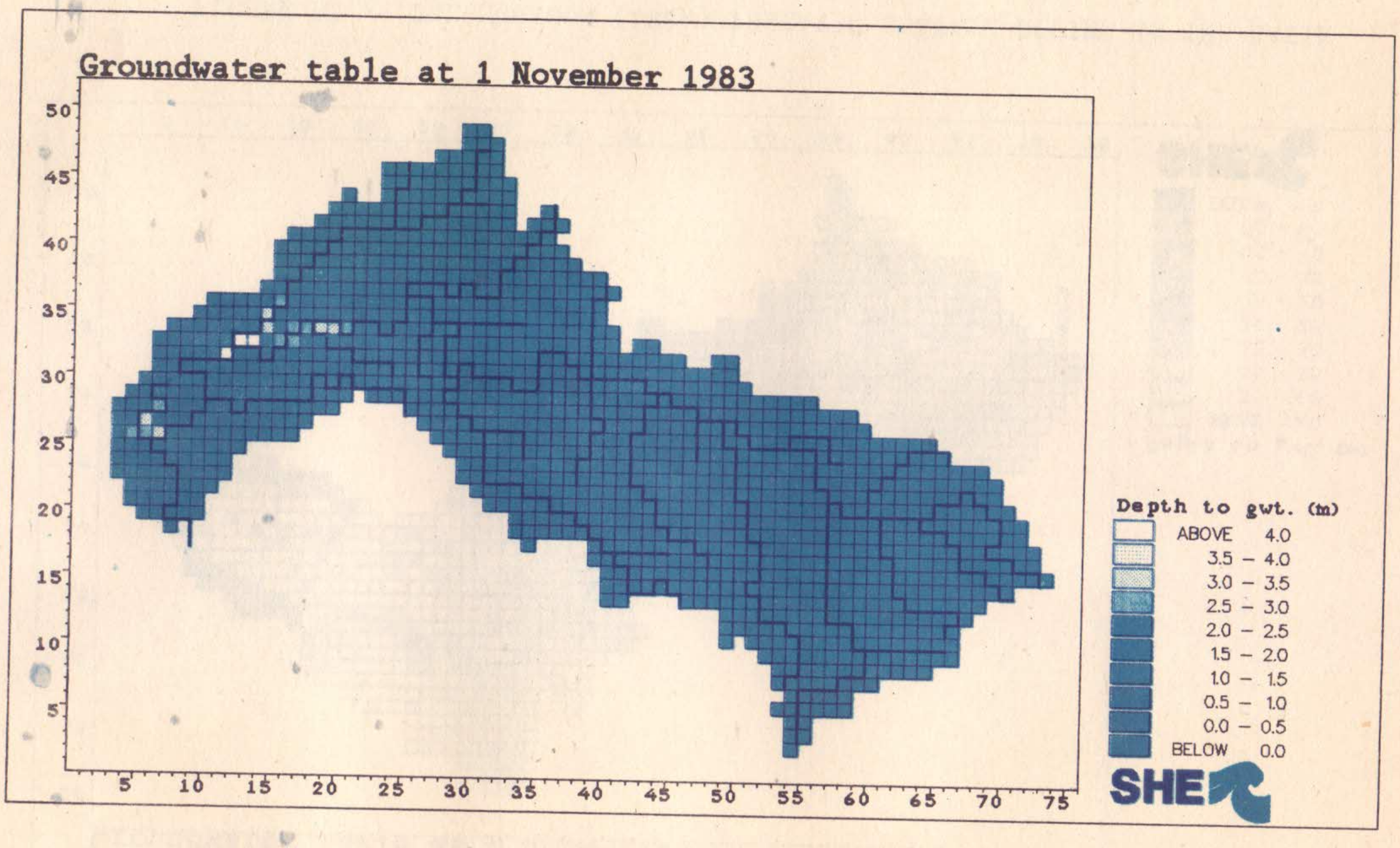


FIGURE 34 - POST-MONSOON (1983) PHREATIC SURFACE DEPTHS IN THE BASIN

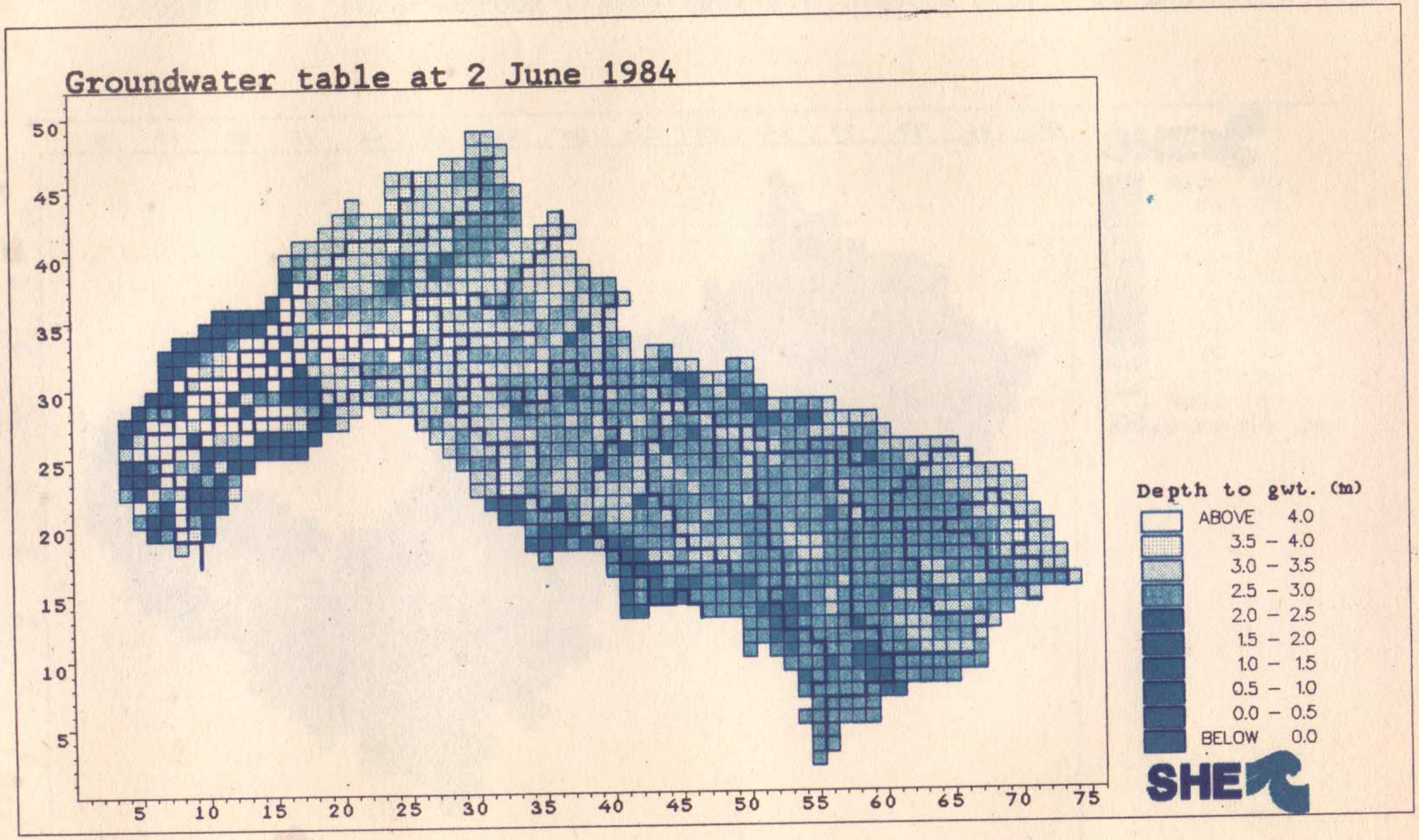


FIGURE 35 - PRE-MONSOON (1984) PHREATIC SURFACE DEPTHS IN THE BASIN

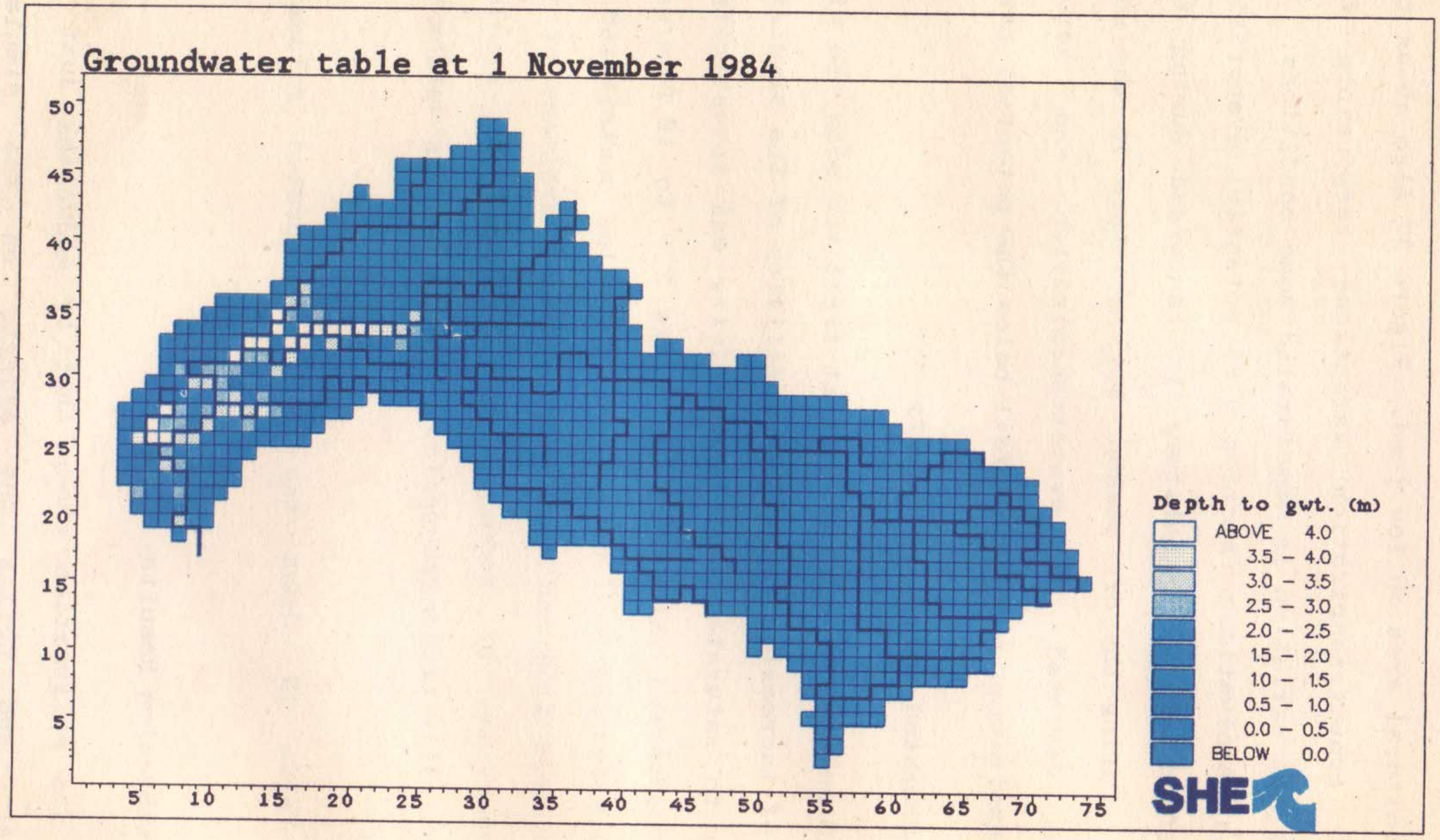


FIGURE 36 - POST-MONSOON (1984) PHREATIC SURFACE DEPTHS IN THE BASIN

Figure 37 shows the unsaturated zone conditions for the agricultural area on low land. Figure 37 also shows the simulated evapotranspiration variations responsible for producing the variation in unsaturated zone conditions. In line with observations (section 3.9) potential evaporation is satisfied and soil moisture is recharged during the monsoon. During the dry season, soil moisture in the root zone is depleted by evapotranspiration and actual evapotranspiration rates then fall below the potential rate.

5.3.7 Saturated zone conductivity

Simulated base flows were at first too slow, so with the aim of increasing them, the sensitivity of the simulated response to saturated zone conductivity was investigated. Tests encompassed values in the range 2.5 to 10.0 m/day, eventually setting on 7.5 m/day. This value contributed to a higher base flow and supported a faster drainage of the soil reservoir, so reducing the tendency to simulate unrealistically prolonged periods of waterlogging during the monsoon.

Table 16 shows the final calibrated parameter values.

5.4 Calibration Results

The calibration shows that by adjusting just few parameters and noting the effects on the simulated hydrographs for the catchment and relating the responses to

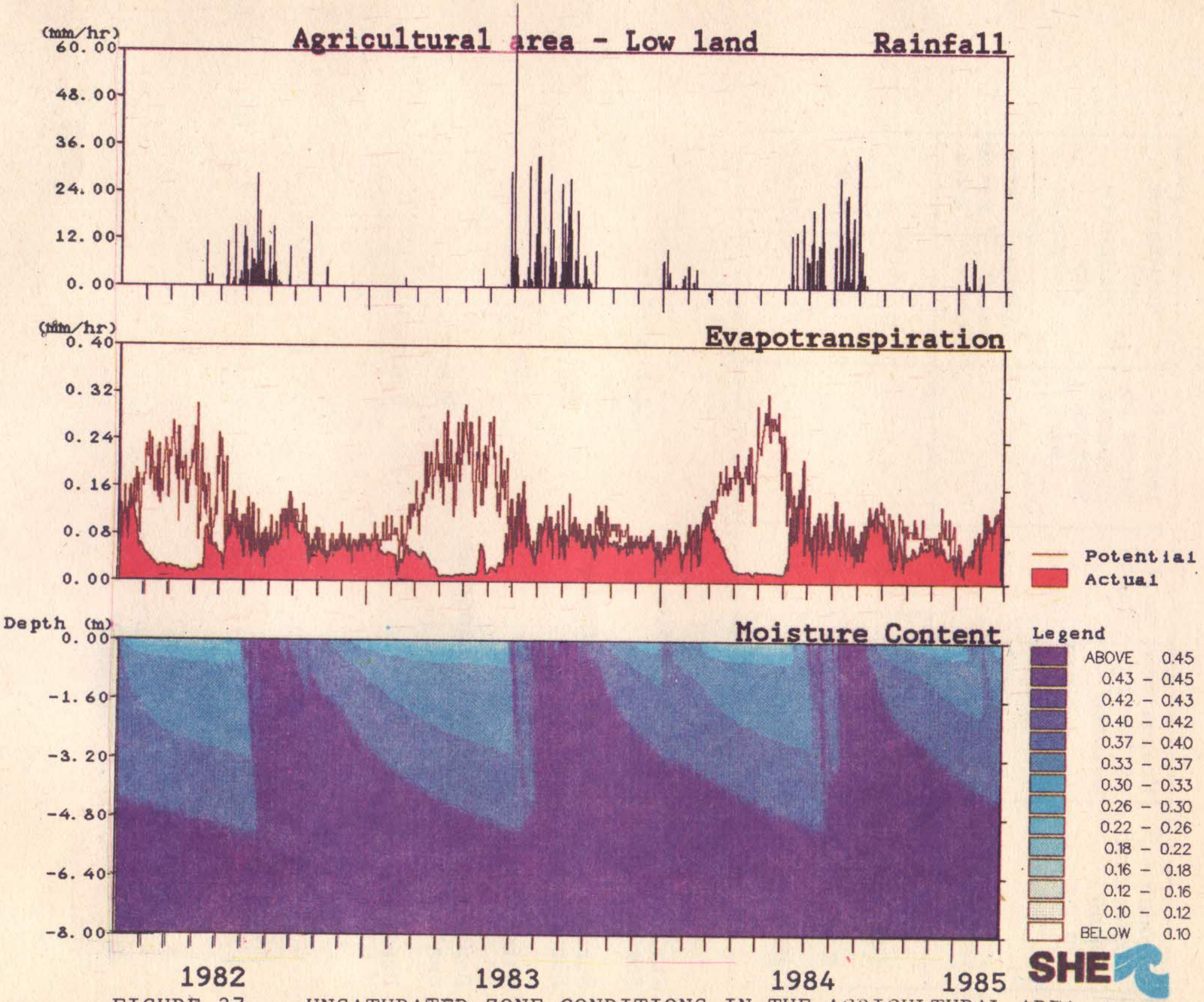


FIGURE 37 - UNSATURATED ZONE CONDITIONS IN THE AGRICULTURAL AREA ON LOW LAND (CALIBRATION)

Table 16 - Calibrated Parameter Values

Ground Elevation Range	Proportion of Basin Covered (%)	Soil Depth (m)	Initial Depth to Phreatic Surface (m)	Saturated Soil Conductivity (m/day)	
				Unsaturated Zone	Saturated Zone
Low land	14.38	7.0	4.0	0.1	7.5
Semi-hilly	52.28	2.5	2.4	0.1	7.5
Hilly	33.34	1.5	1.4	0.1	7.5

Strickler roughness coefficient for overland flow = 2.5 $m^{1/3}/s$

Strickler roughness coefficient for channel flow = 30 $m^{1/3}/s$

Detention storage = 0.02 m

Depth below surface to drainage system = 0.4 m

Drainage coefficient = 0.01

the characteristics of the catchment, it is possible by physical reasoning to improve the simulation. Figure 38 shows patterns of simulated hydrographs for the "best-fit" run. The figure depicts the comparisons of the simulated and measured discharge time series at the basin outlet for 1982, 1983 and 1984. Comparisons of the monthly mass balance and the yearly peak discharges between the simulated and observed hydrographs are shown in table 17. The calibration in general can be considered as satisfactory, when given the present uncertainty in the rainfall input and parameter values.

The following observations were made -

(i) For the calibrations, the hydrograph volumes are simulated well, but agreement is poorer for the peak discharges (table 17). The overestimation of peak discharge in 1984 might be due to the error involved in extrapolation of rating curves.

(ii) For the year 1982 the simulations are significantly in error, although the errors cancel each other as far as the overall simulation is concerned. It is not clear why these errors exist, especially as the simulation for the year 1984 is good. Checks on the measured rainfall and discharge data do not show any faults which might cause the errors. It is difficult to improve one of the simulations without further increasing the error in the other.

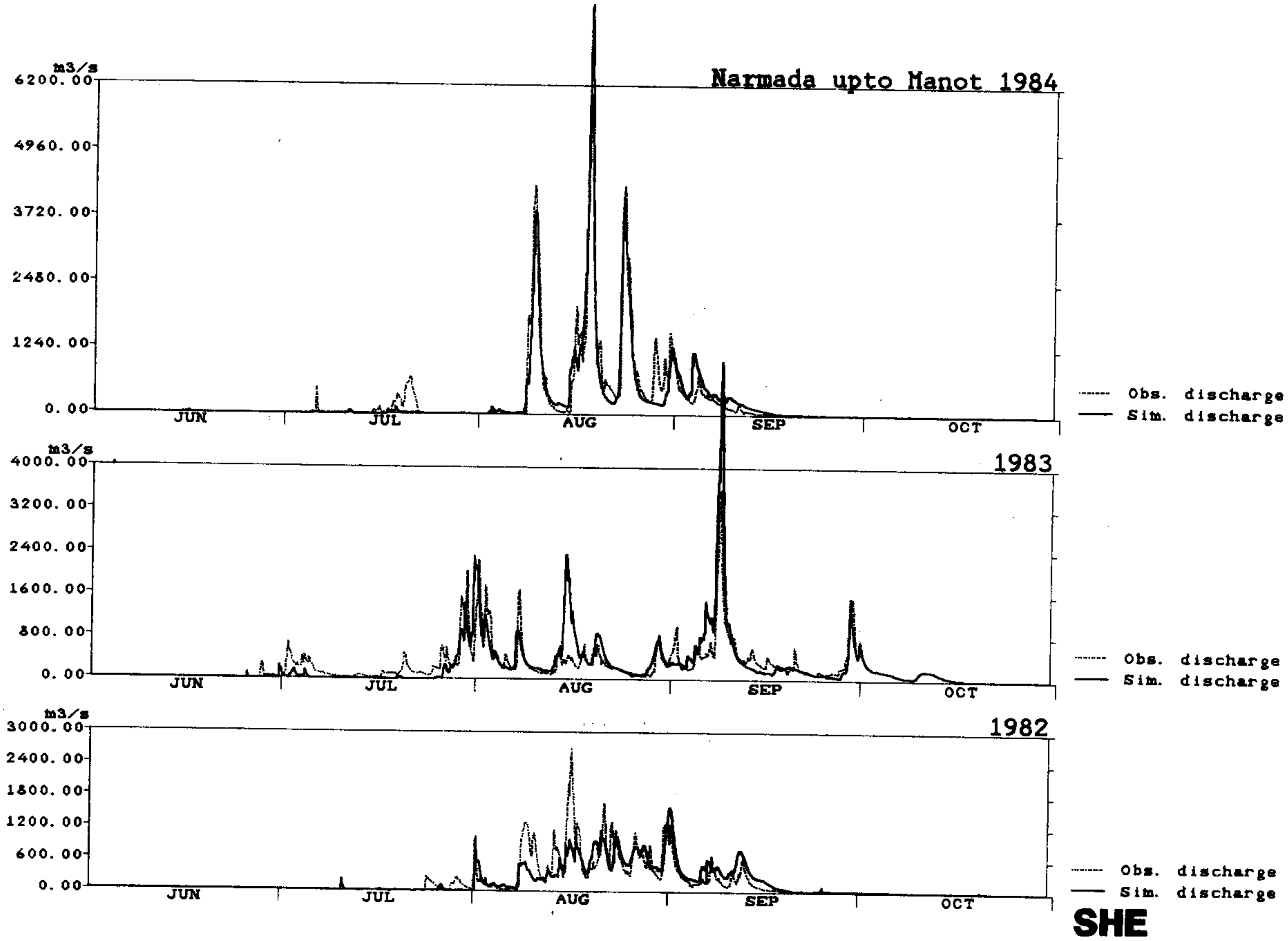


FIGURE 38 - OBSERVED AND SIMULATED HYDROGRAPHS (1982,1983 AND 1984) AT THE MANOT GAUGING SITE (CALIBRATION)

Table 17 - Comparisons of Monthly Volumes and Yearly Peak Discharges for Observed and Simulated Hydrographs at the Manot Gauging Site for Calibration Period

Year	Month	Areal Mean Rainfall (mm)	Hydrograph Volumes(mm)/ Peaks (m^3/s)	
			Observed	Simulated
1982	June	67.88	0.31	1.53
	July	216.72	15.70	4.48
	August	504.77	328.32	266.43
	September	110.80	88.37	137.99
	October	18.77	3.45	7.43
	Total	918.94	436.15	417.86
	Peak discharge		2687.78	1591.22
1983	June	124.50	4.78	2.05
	July	405.04	125.40	65.70
	August	299.79	212.36	263.18
	September	356.61	252.78	285.96
	October	35.53	3.24	45.08
	Total	1221.47	598.56	661.97
	Peak discharge		3577.89	6011.77
1984	June	72.81	1.84	1.09
	July	233.74	34.40	6.63
	August	657.43	504.57	474.52
	September	78.43	69.33	108.60
	October	3.37	5.36	6.33
	Total	1045.78	615.50	597.17
	Peak discharge		6052.15	7751.07

(iii) Base flows are less well simulated, but the error involved is small compared with the total runoff volumes (figure 39).

The results were encouraging in that they reflected the observed trends in soil moisture distribution for the wet and dry seasons, and similarly the simulated discharges were of the correct overall pattern and order of magnitude. Also the simulations were obtained using parameter values which all fell within physically realistic ranges, even though the degree to which those values were representative of actual basin conditions was unknown. On the negative side, the simulations indicated extensive periods of waterlogging which are unlikely to have occurred in reality. It is probable that all the errors could be reduced by painstakingly altering the various parameters singly or in combination and also by carrying out detailed field measurements. However, the results would be subject to the law of diminishing returns. Therefore the calibrations presented can be considered as satisfactory.

5.5 Validation

Using the calibration results, simulations were carried out for the years 1985 and 1987. The catchment parameters were kept at the same values and the only adjustment was to the initial phreatic surface levels.

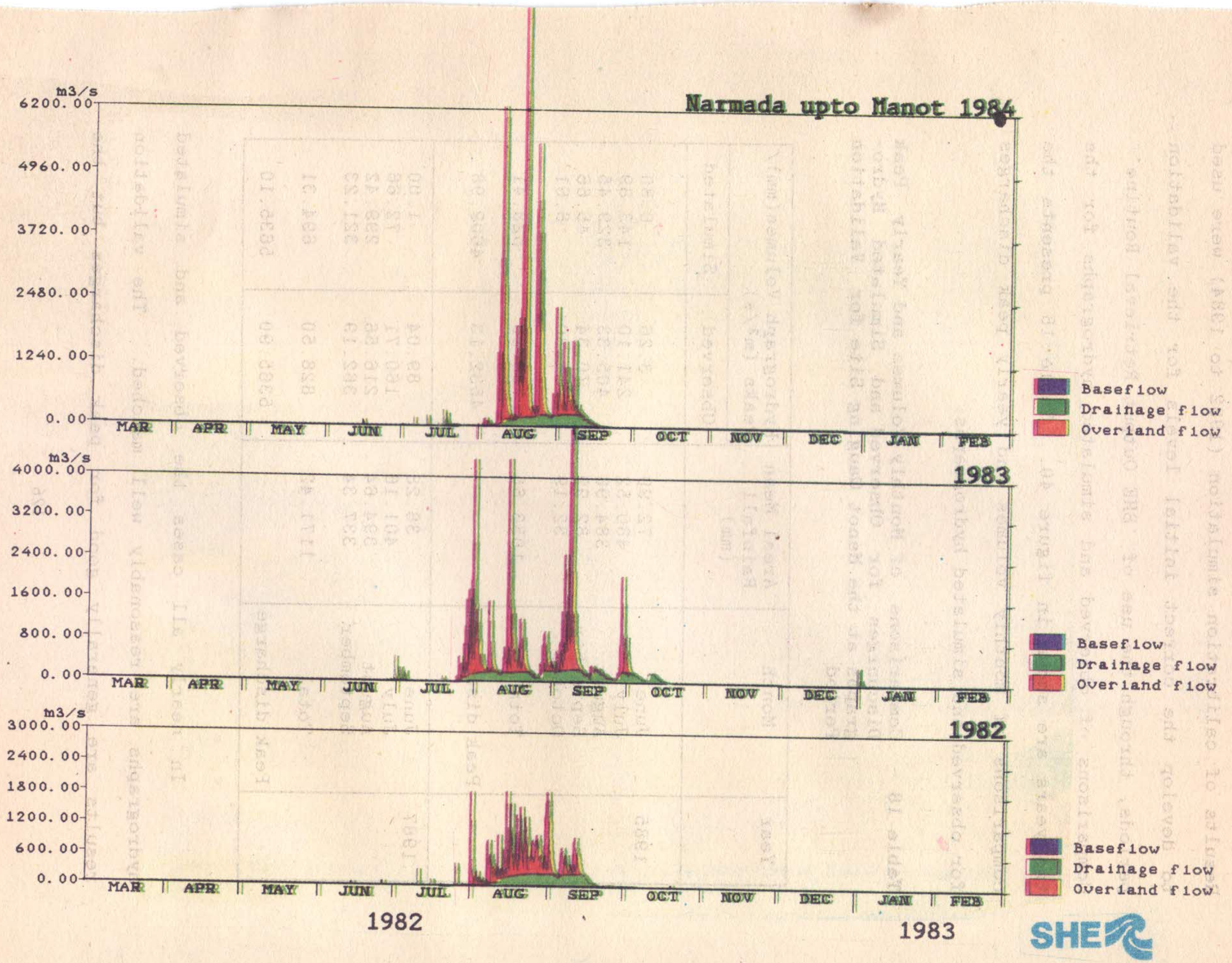


FIGURE 39 - BASE FLOW, DRAINAGE FLOW AND OVERLAND FLOW (CALIBRATION)

Results of calibration simulation (1982 to 1984) were used to develop the correct initial levels for the validation periods, through the use of 'SHE Output Retrieval Routine' **Comparisons of** observed and simulated hydrographs for the two years are shown in figure 40. Table 18 presents the comparisons of monthly volumes and yearly peak discharges for observed and simulated hydrographs.

Table 18 - Comparisons of Monthly Volumes and Yearly Peak Discharges for Observed and Simulated Hydrographs at the Manot Gauging Site for Validation Period

Year	Month	Areal Mean Rainfall (mm)	Hydrograph Volumes(mm)/ Peaks (m^3/s)	
			Observed	Simulated
1985	June	72.99	3.26	0.80
	July	480.52	241.10	143.89
	August	384.96	405.33	329.45
	September	82.99	70.34	45.66
	October	32.19	16.80	8.61
	Total	1053.65	736.83	528.41
	Peak discharge		4532.13	4609.98
1987	June	38.28	89.04	1.00
	July	401.16	160.71	72.66
	August	394.64	216.56	299.42
	September	337.34	362.19	321.23
	Total	1171.42	828.50	694.31
	Peak discharge		5365.90	5635.10

In nearly all cases the observed and simulated hydrographs are reasonably well matched. The validation results are generally good for peak discharges but the

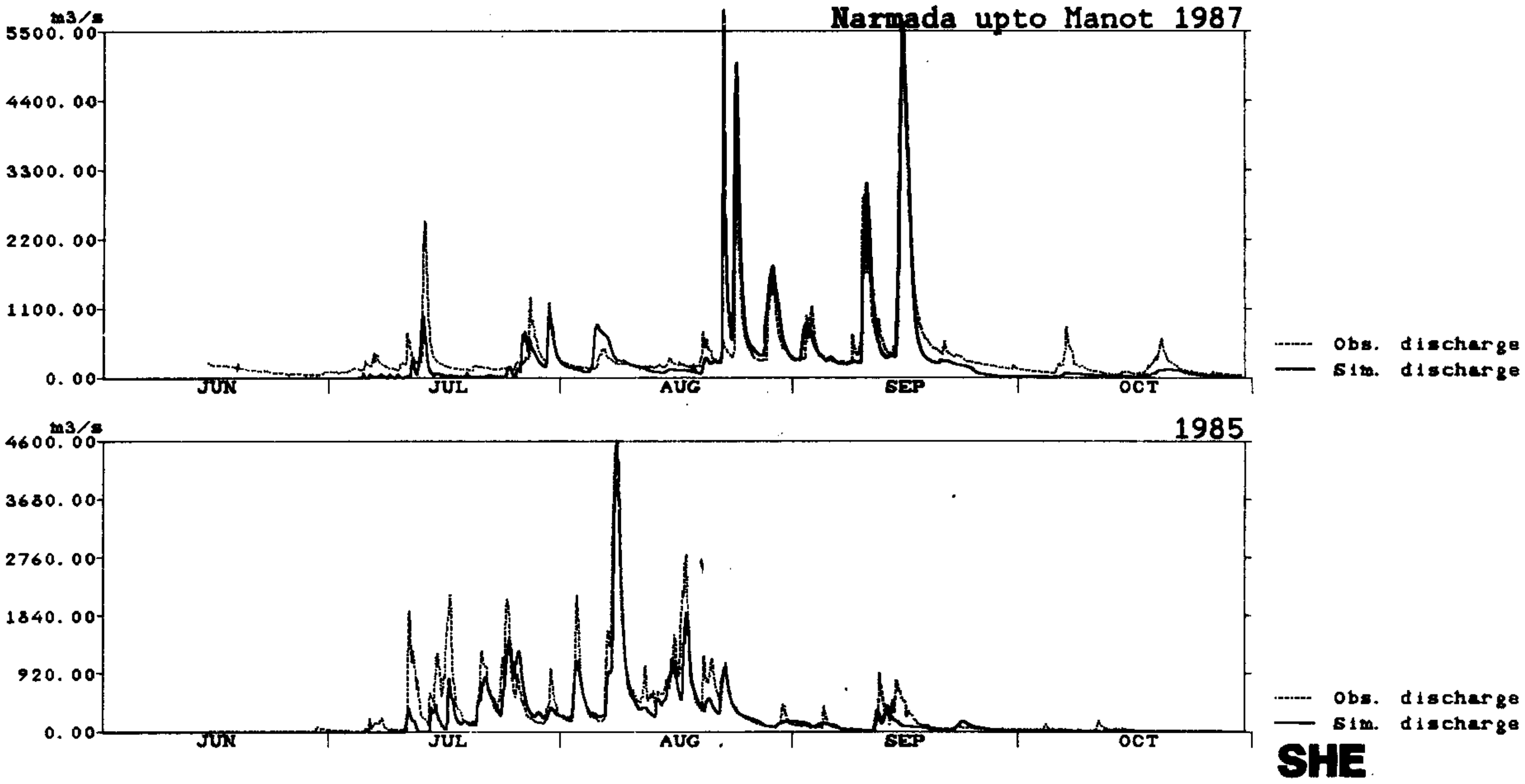


FIGURE 40 - OBSERVED AND SIMULATED HYDROGRAPHS (1985 AND 1987) AT THE MANOT GAUGING SITE (VALIDATION)

hydrograph volumes are underestimated specifically for 1985. The results both validate the model and show that an effective calibration can be based on changes to a minimum of parameters.

5.6 Remarks

Despite the problems posed by uncertainty in the rainfall data and the parameter base, the simulation results are encouraging. Improvement in the particular problem areas will require consideration of the following :

(a) There is considerable uncertainty in the spatial and temporal distributions of the rainfall input data and in the values and distributions of the hydrological parameters. In hydrological modelling, parameter values are often calibrated to allow the model to reproduce as closely as possible the measured response to measured rainfall input. If the measured input is in error, the parameter values may be adjusted in compensation but may not then be truly representative of the basin properties. Application of those parameter values in a simulation involving different input conditions may then produce erroneous results. Consequently the rainfall input data must be improved before the parameters can be calibrated at any other than a coarse level.

(b) The parameter values (particularly for the soils) should be evaluated more accurately, if necessary by field measurements in the basin. Sensitivity tests can show which parameters are the most important and therefore require the most attention. Similarly, improved information on basin water balance and hydrological response will indicate in what direction the simulations should be modified to produce closer agreement between the measured and simulated balances.

(c) The initial phreatic surface depth can have a significant effect on the simulations for an ensuing monsoon season. The conditions must ,therefore, be carefully based on all available information or else obtained for a given monsoon period by running the model from the previous monsoon period.

(d) Grid size, river channel representation, the ratio of the number of channel links to grid squares, calculation time step and the intervals at which rainfall input is specified, all influence the simulation results. Sensitivity tests are needed to show what the effects are and to provide guidance on selection of these quantities for future applications.

(e) Where appropriate, additional hydrological processes should be represented within the SHE.

6.0 SENSITIVITY ANALYSIS

6.1 General

Sensitivity analysis is useful for identifying the model parameters which have significant effect on the simulation results and therefore need to be evaluated most accurately. The analysis is also useful for indicating the effect on the output of a given level of uncertainty in the input and for providing information on how well the model can simulate the impacts of changes in basin characteristics.

6.2 Alternative Scenarios

The calibration and operation of physically - based distributed catchment models such as SHE requires an approach different from that associated with black box or even lumped physically-based models. In particular, physically-based distributed models, while not requiring lengthy hydrological records for their calibration, do require the evaluation of a large number of parameters describing the physical characteristics of the catchment on a spatially distributed basis. In principle the parameters and their distributions can be measured in the field but the expense of such an effort applied to all the parameters would prohibit practical implementation of the models. Alternatives to intensive field surveys are available but, since they inevitably involve approximations, they have given rise to questions concerning the accuracy with which the parameters and their spatial distributions need to be evaluated. Further questions have arisen concerning the difficulty of calibrating parameter sets involving large number of parameters and the degree to which point field measurements can be used to represent average conditions at the large spatial scales of the grid squares used in the numerical simulations. Thus before physically-based distributed models can be used with confidence it needs to be shown that evaluation of the parameter sets does not pose an undue problem.

So far very little research has been carried out to address the above points systematically. Therefore a sensitivity analysis is required to be carried out with the aim of defining the accuracy with which the various parameters must be evaluated and calibrated. The specific questions which can be considered, include the following:

(i) How sensitive are simulations to model 'structural' parameters, such as grid spacing and time steps, as opposed to model catchment parameters, such as soil conductivity and flow resistance coefficients ? To what extent can a change in one be balanced by a change in the other ?

(ii) To which catchment parameters are the simulations most sensitive and how accurately must those parameters be defined ?

(iii) Given the number of catchment parameters involved in the SHE, to what extent is it possible to achieve equally satisfactory calibrations based on different combinations of realistic parameter values ?

(iv) How important is it to allow for the spatial distributions of rainfall input data and catchment parameters ?

6.3 Analysis and Results

The sensitivity analysis is presented within the context of an application of the SHE to the Narmada (upto Manot) basin. Calibration and validation of the model for the basin have already been described in chapter 5. It should be noted that the results are unlikely to be directly applicable to different types of catchments, although the basic technique remains appropriate.

In order to minimize the computing requirements, the sensitivity analysis was restricted to only 1984 hydrographs used in the calibration. In each of the test, just one parameter was altered from the calibrated parameter set. The simulated response (in terms of hydrograph monthly volumes and annual peak discharge) was then compared with the calibration simulation derived for the year 1984 and accounted for the differences by physical reasoning. The ability to follow this approach is a particular advantage of using physically-based distributed models, providing extra information regarding parameter sensitivity and promoting confidence in the results. The range over which the value of each parameter was varied, is based on the limits within which each parameter can reasonably be evaluated on the basis of current knowledge. In the following the simulated hydrographs based on the calibrated parameter set are referred to as the "reference" simulations.

The following sensitivity tests were performed:

(a) Sensitivity to model 'structural' parameter
  - Representation of the basin by grid squares of 4 km x 4 km.

(b) Sensitivity to flow resistance
  - Strickler roughness coefficient for overland flow reduced from 2.5 to 1.0.
  - Strickler roughness coefficient for channel flow reduced from 30 to 15.

Table 19 presents the comparisons of volumes and peaks of simulated discharges for "reference" and test hydrographs and figures 41, 46 and 47 compare the predicted hydrographs with the measured and the "reference" hydrographs.

(a) Sensitivity to model 'structural' parameter

Grid spacing is the most important 'structural' parameter. It is desirable to make it as large as possible

Table 19 - Comparisons of Volumes and Peaks of Observed and Simulated Discharges for Sensitivity Tests

Year	Month	Observed Discharge (mm)	Simulated Discharge: Calibration (mm)	Simulated Discharge: Sensitivity 1 (mm)	Simulated Discharge: Sensitivity 2 (mm)	Simulated Discharge: Sensitivity 3 (mm)
1984	June	1.84	1.09	0.98	1.04	1.12
	July	34.40	6.63	3.42	5.95	6.81
	August	504.57	474.52	474.10	467.46	469.97
	September	69.33	108.60	109.04	121.82	118.95
	October	5.36	6.33	3.68	6.61	6.50
	Sum	615.50	597.17	591.22	602.88	603.35
	Peak (cumecs)	6052.15	7751.07	7554.06	5958.84	6975.02

Sensitivity test 1 : Representation of the basin by grid squares of 4 Km x 4 Km

Sensitivity test 2 : Strickler roughness coefficient for overland flow reduced from 2.5 to 1.0

Sensitivity test 3 : Strickler roughness coefficient for channel flow reduced from 30 to 15 since computing requirements are then minimized. At the same time, though the larger the values assigned, the greater is the possibility of inaccurate representation of the catchment and its hydrological response. Compromise values are therefore needed.

In the reference simulations the grid spacing was 2 km. To study the sensitivity to grid spacing, a parameter set was prepared with grid squares of 4 km x 4 km. This reduced the number of squares representing the basin from 1245 to 307 and increased the proportion of basin per square from 0.08 % to 0.32 %. The comparison of observed, "reference", and test hydrographs (figure 41) indicate that there is almost no difference between reference and test simulations. It can therefore be concluded that the contributing area for overland flow is little affected by a change in grid spacing. Figures 42, 43 and 44 present the spatial variation (pre-monsoon and post-monsoon) and temporal variations (for different land uses) of phreatic surface levels. The simulated phreatic surface levels fluctuate according to observed trends although a quantifiable comparison was not possible. Actual evapotranspiration and the distribution of soil moisture conditions in the vertical are shown in figure 45. Generally the pattern compares favourably with the response expected on the basis of known basin behaviour. Therefore, comparisons of the tests made with spacings of 2 km and 4 km suggest that, for the Narmada (upto Manot) basin, the

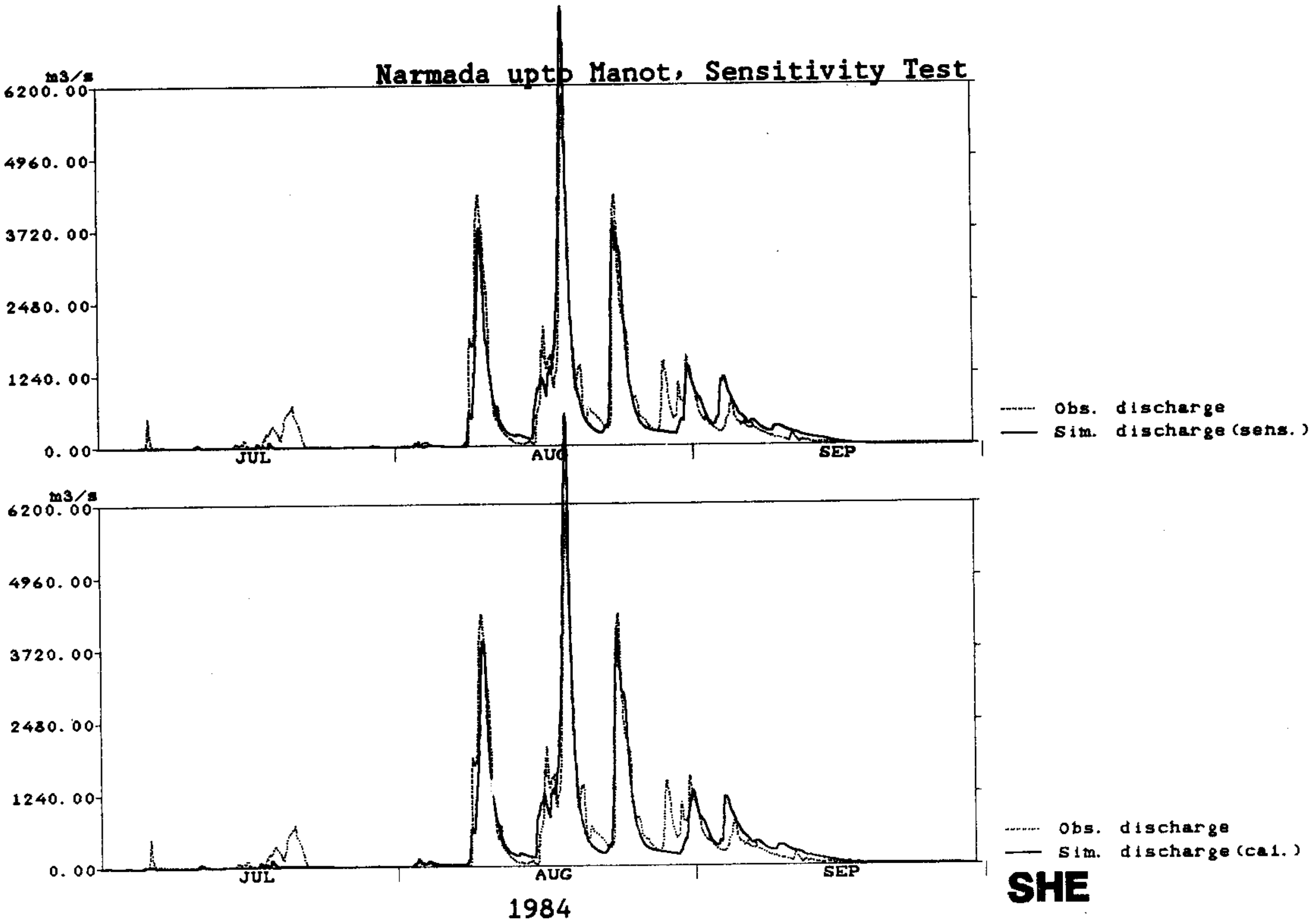


FIGURE 41 - OBSERVED AND SIMULATED HYDROGRAPHS (1984) AT THE MANOT GAUGING SITE (CALIBRATION AND SENSITIVITY 1)

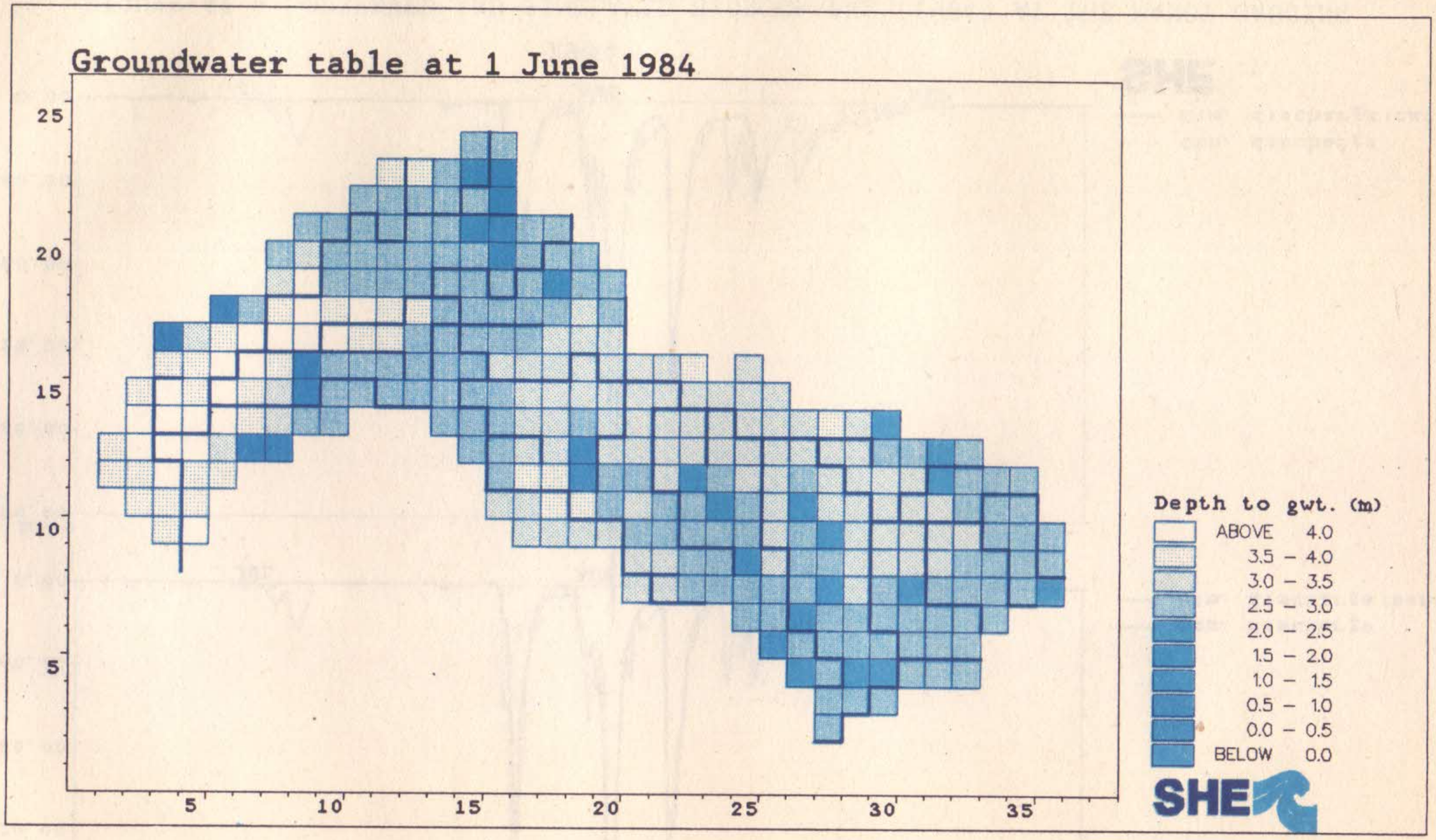


FIGURE 42 - PRE-MONSOON (1984) PHREATIC SURFACE DEPTHS IN THE BASIN (SENSITIVITY 1)

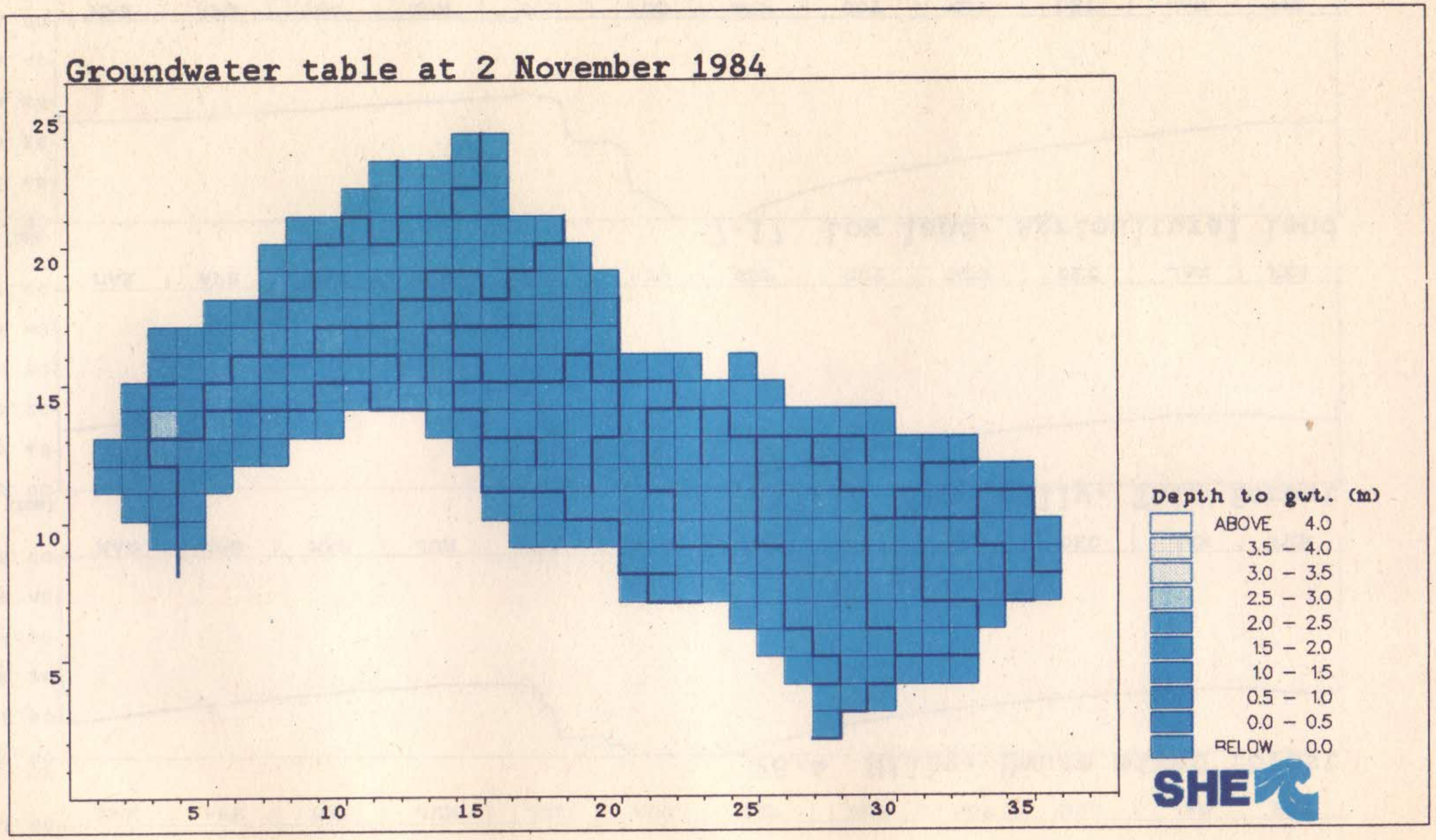


FIGURE 43 - POST-MONSOON (1984) PHREATIC SURFACE DEPTHS IN THE BASIN (SENSITIVITY 1)

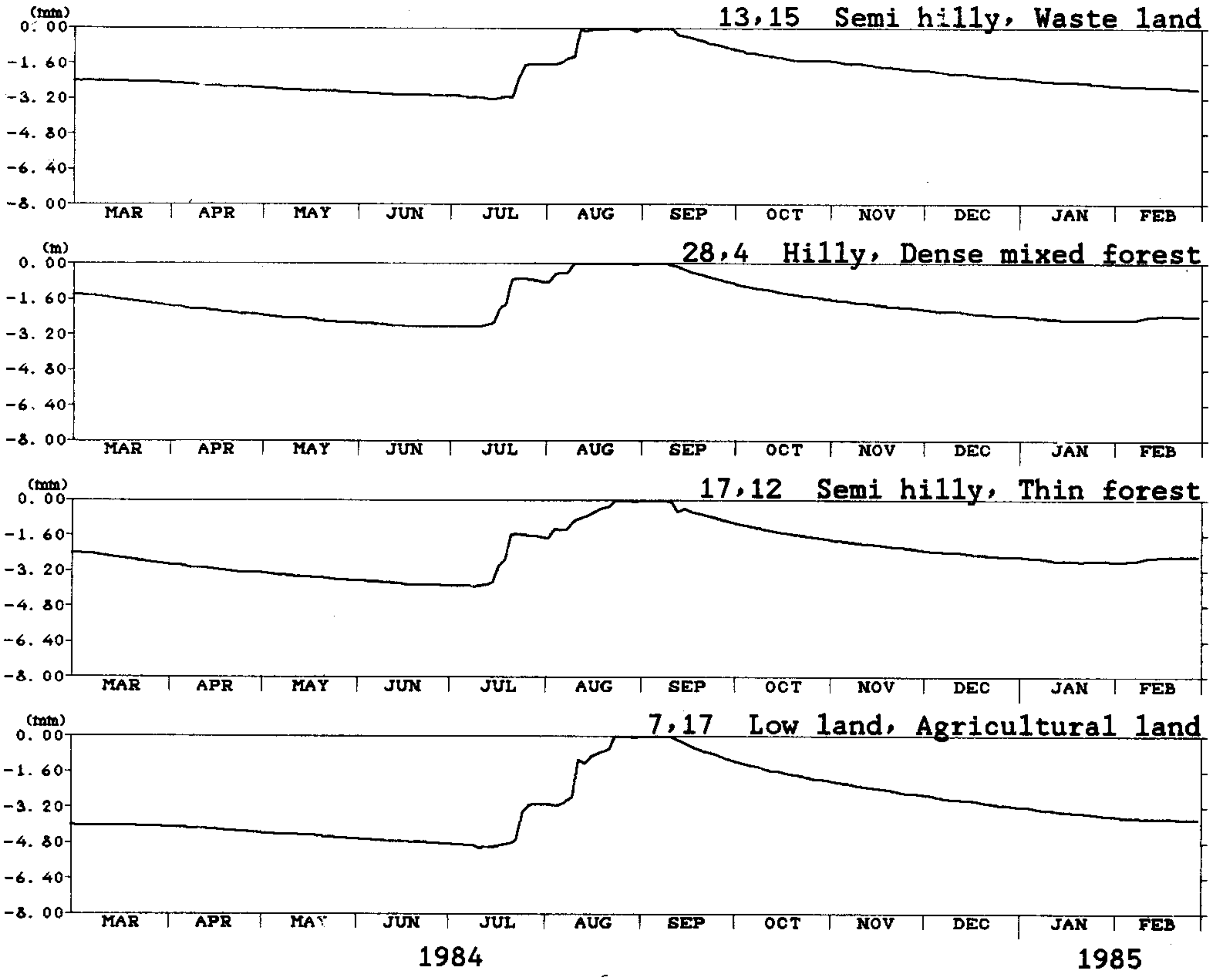


FIGURE 44 - VARIATIONS IN SIMULATED PHREATIC SURFACE DEPTH FOR DIFFERENT LAND USES (SENSITIVITY 1)

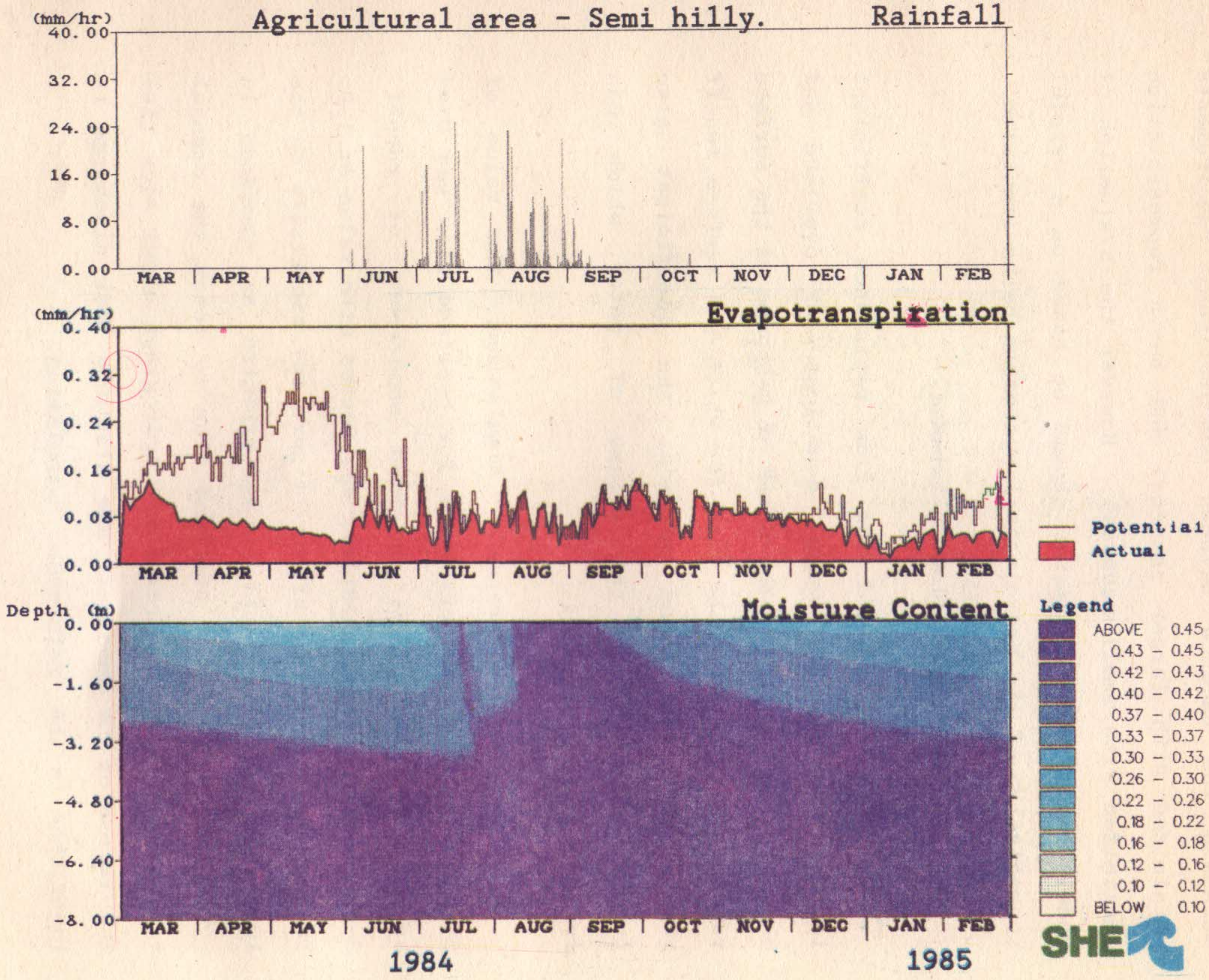


FIGURE 45 - UNSATURATED ZONE CONDITIONS IN THE AGRICULTURAL, SEMI-HILLY AREA (SENSITIVITY 1)

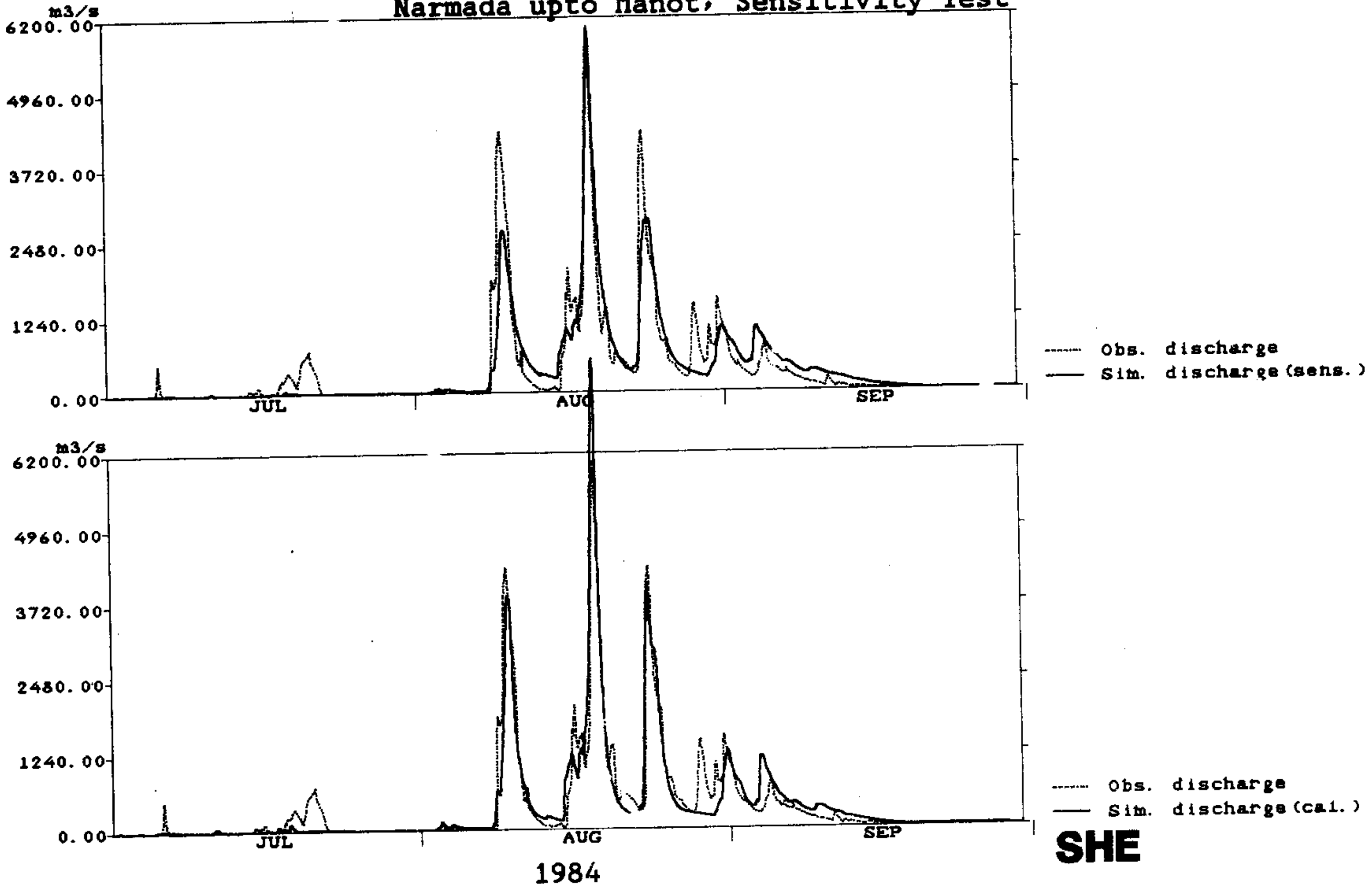
spacing of 4 km can further be investigated in order to maintain the balance between computational requirements (minimized with larger squares) and basin representation (maximized with small squares). However the evaluation of model 'structural' parameter should be based on a careful appreciation of the hydrological processes being simulated.

(b) Sensitivity to flow resistance

The magnitude of the flow resistance coefficient included in the St. Venant equations for overland and channel flow determines the speed of response of the surface runoff. By affecting the time for which the surface runoff remains on the ground surface, the coefficient also partially determines the volume of water which can infiltrate into the soil.

For the "reference" simulations, the value of Strickler roughness coefficient for overland flow was used as 2.5 reflecting the observed occurrence of runoff. Sensitivity of the simulations was tested with value of 1.0. There is a significant effect (figure 46) especially on the intensity of the runoff. As expected an increase in resistance enables the overland flow to reach the channel system slower, so the resultant hydrograph shows slow rise and recession is smoother; and also the peak discharge is lower than in the "reference" simulation.

Narmada upto Manot, Sensitivity Test



Sensitivity to the channel flow resistance was examined by reducing the Strickler roughness coefficient for channel flow from 30 to 15 (same value applied to all river links). This decreased the flashiness of the simulated response (figure 47). By increasing the flow resistance the rate of surface runoff is reduced with smoother recession. Peak discharges were decreased but change in the total hydrograph volume for monsoon season was insignificant. However the use of a constant coefficient value at a site (i.e. not changing with depth or discharge) results in minor errors in the time to peak of the simulated hydrograph. This is because in reality the flow resistance varies at a site. Thus observed low magnitude peaks tend to occur later than predicted while observed high magnitude peaks tend to occur earlier than predicted.

6.4 Remarks

Before physically-based, distributed catchment models can be used with confidence, it must be established that their performance is adequate and that preparation and calibration of the parameter sets do not pose overwhelming practical difficulties. These points have been addressed in the sensitivity analysis of SHE with generally encouraging results.

Those catchment parameters to which the simulations are most sensitive, need to be evaluated with relatively high accuracy. This can be provided by field measurements

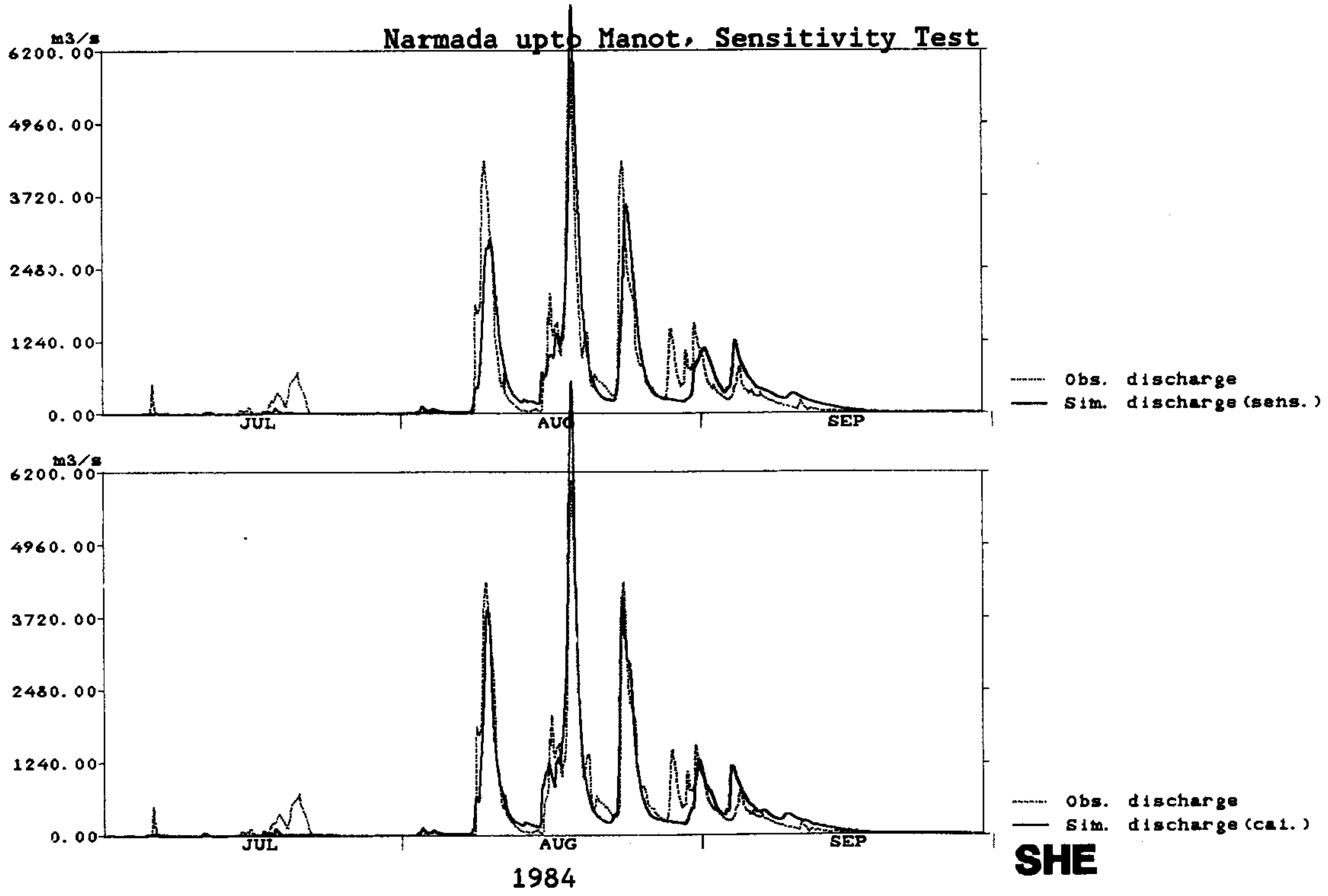


FIGURE 47 - OBSERVED AND SIMULATED HYDROGRAPHS (1984) AT THE MANOT GAUGING SITE (CALIBRATION AND SENSITIVITY 3)

at a few representative sites. Point measurements are suitable for representing average conditions in a grid square. The less important parameters need to be evaluated with only moderate accuracy which can often be satisfied by data available in the literature.

Grid spacing and time steps should be small in comparison with the scales of the spatial and temporal variations which they are used to represent. Errors may otherwise be comparable with those resulting from inaccurate evaluation of the more important catchment parameters. The scope for achieving equally satisfactory calibrations based on different combinations of parameter values can be reduced by considering several different events. Further research is needed to delineate the likely ranges of the various catchment parameters for different soils, vegetations and catchments. Sensitivity tests should also be carried out for different catchments in order to show how sensitivity varies with catchment type.

7.0 CONCLUSIONS

The aim of the present study has been to implement a physically-based, distributed catchment model and to simulate a variety of catchment responses. Application of the SHE to the Narmada (upto Manot) catchment indicates a few deficiencies but the results are generally encouraging. Based on the above simulation study, the following conclusions are drawn -

1. The SHE has been successfully used for modelling the Narmada (upto Manot) basin within the constraints of data availability. The patterns of catchment response, with regard to calibration and validation, accord well with the observed catchment behaviour.

2. There remain considerable uncertainties in the input data and the model parameters, notably in the spatial distributions of rainfall, soil depths and soil parameter values. Reduction of the uncertainty will depend on improved data availability.

3. The availability of only one hourly rainfall station outside the basin, with which to distribute the daily rainfall records on hourly basis, contributed significantly to uncertainty in the calibration results. In order to reduce the uncertainty attached to the basin simulations, it is particularly important to have proper spatial coverage with self recording raingauges.

4 Improvement of the calibrations will require a more extensive spatial and temporal coverage of rainfall input, more accurate evaluations of the model parameters (especially for the soil properties) and their spatial distribution (through field measurements), a careful consideration of the initial phreatic surface depths and careful specification of grid sizes, and river channel representation.

5. Based on the sensitivity analysis, it can be concluded that the grid spacing of 4 km can be investigated for the basin, in order to maintain the balance between computational requirements and basin representation.

Model Limitations

In SHE, a physically-based, distributed modelling system, a balance is required between adherence to the physical basis on the one hand and computing requirements on the other and the system therefore incorporates a number of approximations and assumptions. The followings are some of the model limitations:

1. Computer requirements are heavy. A large memory capacity is needed to store the data arrays associated with the large number of calculation nodes.

2. The evaluation of a large number of parameters describing the physical characteristics of the

catchment (e.g. topography, soil, vegetation) are required on a spatially distributed basis. For most of the field situations, it may not be practicable to measure these parameters directly in the quantity required.

3. Parameters are likely to be sampled and evaluated at spatial scales significantly different (generally smaller) from those of the model grid scale. The parameter values may not then be representative of conditions as they are simulated in the model.

4. **Inspite of physical base of SHE model, conceptual understanding of complex interaction of hydrological processes may not be sufficient for it to be expressed mathematically in the model.**

5. The large amount of data required by the model means that new operation methodologies must be evolved. A lack of data may create significant uncertainties in the values of the catchment parameters used in a simulation. These uncertainties will give rise to corresponding uncertainties in the predictions.

6. In the SHE, the channel network is represented by an orthogonal system along the boundaries of the grid squares, which is not truly representative of the actual channel, system.

7. At present only single-layer, unconfined aquifers can be modelled. However, the saturated zone component is designed so that it can easily be expanded to account for confined and multilayer aquifers in the future.

8. There is no consideration of the hydraulic structures like dams and reservoirs and their operation in the present codes of SHE. A separate module is needed to enable the direct simulation of the outflows and flood hydrograph at the gauging site downstream of the hydraulic structure.

9. In order to support the application of the SHE to the irrigation command area, an irrigation subcomponent needs to be added to the modelling system. This must account for looped networks, dispersal of canal irrigation water on the land surface and irrigation involving ground water pumping.

Suggestions for Further Work

Lack of information on basin parameters and hydrological response is a significant source of uncertainty in the simulation results It is therefore necessary that a simple programme of field measurements be carried out with the aim of improving the parameter base as follows:

Soil parameters

Soil type and distribution, hydraulic properties (saturated conductivity, retention curve and related information), depth to bed rock. Distribution of soil type is obtained from a close analysis of existing soil and topographic maps and visits to representative sites in the basin. Hydraulic properties are determined from a number of sampling sites for each soil type - infiltration measurements are made in situ and soil cores collected by hand-auger for analysis in the laboratory. Soil depths are obtained from wells, road and channel cuts and from the test and construction drill data collected around dam and barrage construction sites. Information is particularly needed for the forest areas.

Vegetation parameters

Vegetation type and distribution, cropping patterns during and after the monsoon, root depth (especially for forest areas). Obtaining this information will require detailed discussions with relevant agencies including agricultural institutes, supported by visits throughout the basin.

Channel parameters

Cross-sectional data. These are obtained by surveying the channel at representative locations.

Basin response

Areas of soil saturation, spatial and temporal distribution of surface runoff including flow in ephemeral channels, variation in water table elevation, differences between agricultural and forest areas. Detailed investigations of basin response would require an extensive field survey. However, useful information can be obtained from visits to the basin in dry and wet seasons, measurements at wells and general observations.

It is important that the techniques of measurement should, as far as possible, correspond to the structure and scale of the model. A potentially enormous impact on the provision of spatially distributed data can be obtained by remote sensing techniques, by providing average parameter values on a grid basis. Similarly, tracers can be used to provide information on the integrated characteristics of overland and channel flow over given reaches. However, while remote sensing can currently give surface distributions of catchment properties, especially vegetation, further research into the provision of information on soil type and subsurface soil conditions is still required.

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