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

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ABSTRACT

At present water resources development activities in the Narmada Basin are on increase, resulting in changes in the hydrologic regime of the basin. The conventional rainfall-runoff models are often inappropriate to predict such changes to the desired accuracy. Now-a-days the physical based distributed catchment models are getting much attention as these models have potential to overcome many of the deficiencies associated with the conventional rainfall runoff models.

SHE model is a deterministic, distributed and physically based hydrological modelling system where-in all land phase components of hydrologic cycle are generally modelled either by finite difference representations of the partial differential equations of mass, momentum or energy conservation, or by introducing some conceptualisation in the form of empirical equations derived from individual experimental research. The catchment is represented by an orthogonal grid network in the horizontal and by a column of horizontal layers at each grid square in the vertical. The model is capable of simulating multi output of the catchment considering the spatial distribution of catchment parameters, rainfall and other meteorological inputs. The basin component processes which are being modelled include interception, evapotranspiration, over land and channel flow, unsaturated zone flow, saturated zone flow and snowmelt etc.

In the present study, SHE model is applied to simulate the rainfall-runoff process in the Barna sub-basin of river Narmada. The Barna river orginates from the Vindhya range in the Raisen district of Madhya Pradesh at an elevation of 450 metres. It is a right bank tributary of Narmada river. It contributes flow to Narmada river drain-

ing a total area of 1789 sq.km. But in this application study, the model is set up upto the Bareli gauging site of the Barna river having the catchment area of 1590 sq.km. At about 25 km u/s from the Bareli gauging site, a dam has been constructed in year 1976 across Barna river near village Bari of Tehsil Bareli in Raisen district to provide irrigation in the command area generally during non-monsoon season. Upstream to the dam site one more gauging site has been established by M.P. Irrigation Department and the flows at this gauging site are monitored only during monsoon months using float method for velocity measurements.

The available time series of daily gauge and discharge data, hourly gauge data (for monsoon months), daily and hourly rainfall data for the raingauge-stations located within or near the basin, evaporation data, ground water fluctuations for some observation wells, reservoir levels and reservoir operation data have been collected processed and used in the study. The relevant toposheets, on the scale of 1:50,000 procured from Survey of India have been manually digitized to provide the elevations at each node point on 500 m x 500 m grid scale map. The model has been set up on 2 km x 2 km grid scale for simulating the Barna sub basin. Data for the two year period of 1984-1985 have been used for the calibration and for two year period 1986-1987 have been used for validation of the model following the split sample test approach. Sensitivity analysis has been performed by taking simulation runs for seven different cases in order to investigate the sensitivity of simulation results with respect to the important calibration parameters. The computed inflows, based on observed reservoir levels and reservoir operation data, to the Barna reservoir have been used for calibration and validation of the model. Since the flow at Bareli gauging site is not virgin due to the existence of the dam upstream to the gauging site, and the flows at Sultanpur gauging site are erroneous because of the severe errors associated with the velocity measurements made by float method during the period of high flows. The physical parameters for the different types of soils and soil depths, roughness characteristics vegetation characteristics and aquifer characteristics alongwith their spatial distributions are needed for the successful model application. The information derived from indirect sources was utilized for deciding the range of those parameter values for calibration. Since information collected from various sources regarding these parameters were not to the extent needed for the application of the SHE model.

The performance of the model in simulating the inflows at Barna Dam site during calibration as well as validation phase seems to be reasonably well within the constraints of data availability and assumptions made about the parameter values and model structure. The reproductions of inflow volumes and peaks are quite encouraging. However, the performance of the model in simulating ground water response could not be judged because of most of the wells for which data were available are located in the command area of the Barna Dam and the levels for those wells are affected by the impounding of water in the reservoir. It is observed from the sensitivity analysis that the simulation results are much sensitive to the physical properties of soils such as saturated hydraulic conductivity and roughness characteristics. It is also seen in one of the sensitivity runs that a small error in rainfall input may largely affect the simulation results. A proper network of self recording raingauge stations are, therefore, needed in order to provide realistic representation of the spatial and temporal variations of the rainfall within the basin. The effect of land use changes on basin response is also investigated through a sensitivity run after changing the land use at all squares in the dense forest area to agriculture. The results are compared with the reference run which indicate higher volumes and peaks. This may be attributed to the changes in depth of root zone and leaf area index from one type of vegetation (deep forest) to the other (agriculture) which causes the reduction in water loss through transpiration even during dry season resulting more moist soil generating a greater runoff during the monsoon.

1.0 INTRODUCTION

Water is the most essential natural resource for life and is likely to become a critical scarce resource in the coming decades due to continuous increase in population. Precipitation in the form of rain, snow, hail, dew and even frost is the source of all water on earth. However, mainly rain and snow contributes to the usable waters on the surface of the earth. Water is a resource which can not be produced or added as and when required by any technological means. The total fresh and sea water content of the earth is essentially fixed. It has been estimated that out of the total precipitation of around 400 million hectare metres in the country, the surface water and ground water availability are about 178 million hectare metres and 42 million hectare metres respectively. Out of the available surface water about 50% can be put to beneficial use because of topographical and other constraints. On the other hand, additional energy in the form of hydropower is needed for potential utilisation of available ground water resources.

Water in all its forms solid, liquid and gaseous is constantly on the move in and around the globe along the paths of Hydrological cycle. The circulation of fresh water over the earth can be represented by a continuous process under the influence of solar energy and other climatic factors, where by water follows a cycle of evaporation from the earth's surface (mainly from the oceans), condensation, precipitation, flow over the land surface and below it and returning back to the oceans. Variations in climatic characteristics both in space and time are responsible for uneven distribution of precipitation. In India, precipitation is confined to only about three or four months in the year and varies from 10 cm in the western parts of Rajasthan to over 100 cm at Cherrapunji in Meghalaya. This uneven distribution of the precipitation causes highly uneven distribution of available water both in space and time, which leads to floods and drought affecting vast areas of the country. Man's activities such as land use changes, deforestation or afforestation, agricultural practices, urbanisation, constructions of water resources structures for irrigation, hydro-power, water supply and navigation etc. influence the hydrologic cycle to a certain extent which modify the pattern of natural availability of fresh water supplies, with respect to space and time. An accurate assessment of the available water, both on surface and ground is needed for optimum design, planning and operation of the water resources projects in order to meet the basic needs of the people in coming decades. Since the hydrological processes are continuous and quite complex, therefore, an accurate assessment of quantities of water simultaneously passing through all these processes is quite a difficult task. The problem becomes even more complex when the natural hydrological cycle is getting distributed by the man's activities. Mathematical modelling of hydrological processes provides a most powerful technique for an accurate assessment of the available water in space and time considering the physical processes to a certain extent close to the reality and incorporating the various factors affecting the natural hydrologic cycle due to man's influence. Such modelling exercises are very much helpful for both the research hydrologists and the practicing water resources engineers involved in developing the integrated approaches for planning, development and management of water resources projects.

A model is a simplified representation of a complex system. It aids in making decisions, particularly where data or information are scarce or there are large number of options to choose from. Hydrological models represents the physical/chemical/biological characteristics of the catchment and simulates the natural hydrological processes. Hydrological models are essentially mathematical models where the physical processes of hydrologic cycle are described by a set of mathematical equations (often partial differential equation), logical statements, boundary conditions and initial conditions, expressing relationships between inputs, variables and parameters. Hydrological model may broadly classified in two groups:

(i) Deterministic Hydrological Models

(ii) Stochastic Hydrological Models.

A deterministical model is one in which the proceses are modelled based on definite physical laws and no uncertainities in prediction are admitted. It has no component with stochastic behaviour i.e. the variables are free from random variation and have no distribution in probability. Deterministic models can be further classified according to whether the model gives a spatially lumped or distributed description of the catchment area, and whether the description of the hydrological proceses is emperical, conceptual or fully physically based.

Empirical or black box models contain no physically based transfer function to relate input to output. In other words no consideration of the physical processes is involved in such types of models. These models are basically input-output based models. Within the range of calibration such models may be highly successful. However, in extrapolating beyond the range of calibration, the physical link is lost and the prediction then relies on mathematical technique alone.

Lumped conceptual models occupy an intermediate position between the fully distributed physically based approach and empirical black box analysis. Such modelsare formulated on the basis of a relatively small number of components, each of which is a simplified representation of one process element in the system being modelled. Parameters of such type of models are calibrated using trial and error method or automatic optimisation technique or combination of both.

Fully distributed physically based models are based on our understanding of the physics of the hydrological process which control catchment response and use physically based equation to describe these processes. From their physical basis such models can simulate the complete runoff regime, providing multiple outputs (e.g. river discharge, phreatic surface level and evaporation loss) while black box models can offer only one output. Unlike lumped conceptual models, physically based distributed models do not consider the transfer of water in a catchment to take place between a few defined storages. Instead the transfers of mass, momentum and energy are calculated directly from the governing partial differential equations, for example the St. Venant equations for surface flow, the Richards equation for unsaturated zone flow and the Boussinesq equation for ground water flow.

Now a days engineers, scientists and planners involved in water resources development have become more concerned with the effect of land use changes related to agricultural and forestry practices, hazards of pollution and toxic waste disposal and general problem arising from conjunctive uses of water. Conventional rainfall runoff models (empirical as well as lumped conceptual models) are often not able to provide satisfactory solutions to such problems. Attention is, therefore, being focussed on the physically based distributed catchment models since these have the potential to overcome many of the deficiencies associated with simpler approaches. On the otherhand, such models are complex and considerable resources in human expertise and computing capability are needed for their development and applications. In the light of these concerns, three European Organisations (the Danish Hydraulic Institute, the British Institute of Hydrology and the French consulting company SOGREAH) joined forces to produce the European Hydrological System - Systeme Hydrologique European or SHE. This is a general, physically based, distributed modelling system for modelling all or any part of the land phase of the hydrological cycle for any geographical area.

1.1 SHE Model Project

A financial agreement entitled 'Hydrological Computerised Modelling System (SHE)' was signed in June/July 1987 between the European Economic Committee (EEC) and the Republic of India on the project to transfer SHE Model to National Institute of Hydrology, Roorkee by the Danish Hydraulic Institute (DHI), Denmark on behalf of DHI, Denmark, SOGREAH, France and NERC Water Resources System of University of New Castle (UK). The project is to contribute to India's capacity in formulating Water & Land Resources Development Strategies by the transfer of Hydrological Computerised Modelling System (SHE) (Systeme Hydrologique European). The project has been envisaged to contribute to finding solutions to more complicated hydrological problems which need a modelling approach. The project includes transfer of SHE model to the National Institute of Hydrology, Roorkee for its application on hydrological problems all over India. The project components are as below:

i) Data collection in India

ii) Date processing model adaptation work and training in Europe

iii) Model installation in India

iv) Model application, testing, training and workshops in India

v) Backup during running of normal operation

The Project commenced on November 18, 1987.

To start with the Narmada basin was identified for application of this model as a number of developmental activities are currently underway in this basin. Six sub basins of Narmada basin ranging from 1000-4000 sq.km. have been chosen for this purpose. As per the project schedule, the first group consisting of three NIH Scientists to undertake training at DHI, Denmark were identified during visit of consultants during November/Dec. 1987. Three sub-basins of Narmada namely Kolar, Sher and Barna were chosen for model applications during the training of these three scientists at DHI, Denmark. A number of trips were undertaken by NIH Scientists, Scientific staff and consultants to Narmada basin (M.P) for identification and collection of required data for model applications. Simultaneously, the processing of data was also carried out. This report describes the application of SHE model to Barna sub-basin of Narmada Basin, which is one of the sub-basin selected for the modelling studies under the project.

The following chapters described relevant aspects of the structure of SHE model, the data requirements and possible model applications. The simulations runs and results obtained from the application of SHE model to Barna sub-basin are also presented including the data processing and preparations in SHE format.

2.0 SHE MODEL

2.1 SHE Model Structure

She Model is a deterministic, distributed and physically based hydrological modelling system developed from the partial differential equations describing the processes of sub-surface, overland and channel flow solved by finite difference methods, and includes the processes of interception, evapotranspiration and snowmelt. 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 of specified grid size and in the vertical by a column of horizontal layers at each grid square. The channel system is represented on the boundaries of the grid squares. The model structure is illustrated in Fig. 1.

At present only the primary components of the land phase of the hydrological cycle namely snowmelt, canopy interception, evapotranspiration overland and channel flow and unsaturated and saturated sub-surface flow are being modelled using SHE. Secondary details, such as soil macropores and an under growth of the vegetation below the major vegetation, are not currently explicitly modelled because of the extra complexity and economic penalities which would be involved. Similar simplifications have been introduced in the computer software in order to reduce computing requirements. Thus, it is assumed that,

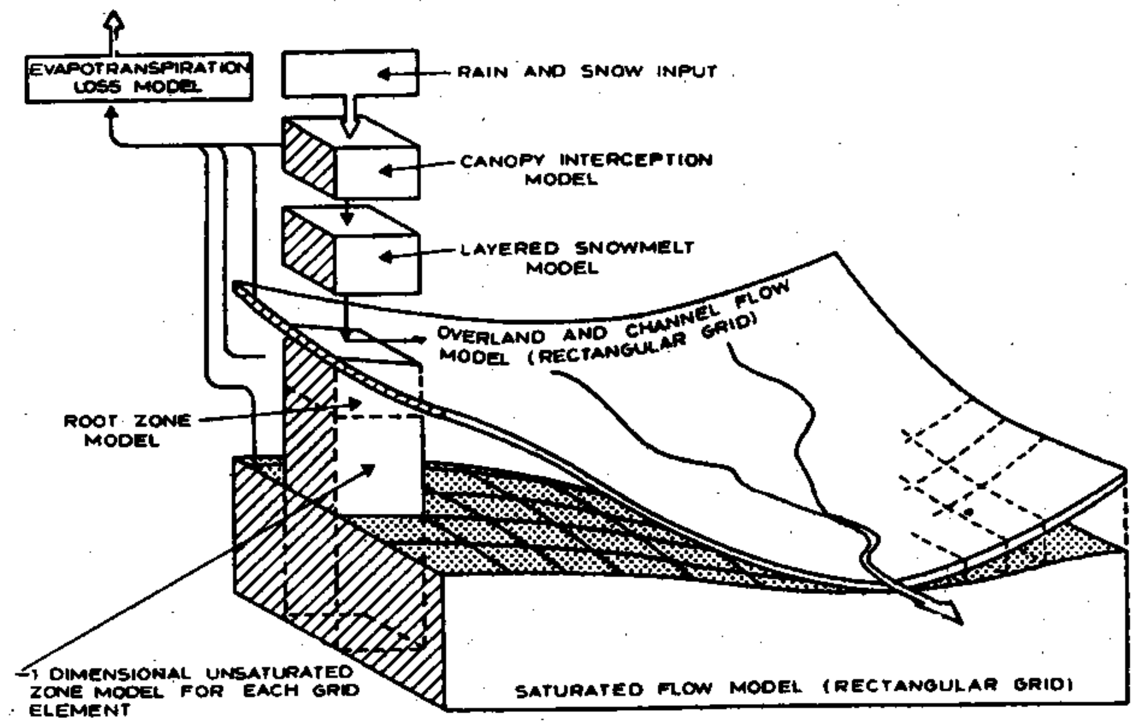


Fig. 1 Structure of the European Hydrologic System.

for most slope, flow in the unsaturated subsurface zone is essentially vertical and flow in the saturated sub-surface 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. Furthermore the unsaturated flow equations are solved only for some representative columns selected taking spatial variability into consideration and then the calculations are transferred to different grids. Such an arrangement ensures acceptable computing costs at an acceptable level of approximation of the catchment processes. However, it also poses the numerical problems of linking one dimensional and two dimensional sub-surface 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.

2.2 Data Requirement

A large number of parameters describing the characteristics of the catchment on a spatial distributed basis are required in addition to the hydrological and hydro-meteorological time series for successful running of the model.

Data required for SHE model may be obtained either from field measurements or from field measurements supplemented by the information from available scientific literature. The data and parameters required for each grid square (or channel link) in the SHE model for the most comprehensive calculation models are given below:

a)	Frame Component	
	i) Model Parameters	Ground surface elevation, Impermeable bed elevation, Distribution codes for rainfall and meteorological source stations, and Distribution codes for soil and vegetation types.
b)	Evapotranspiration/Interception Component	
	i) Model Parameters (for each vegetation type)	
	Option One	Canopy resistance, Aerodynamic resistance, ground cover indices (time varying), Ratio between actual and potential evapotranspiration as a function of soil moisture tension, Root distribution with depth, canopy storage capacity (time varying)
	Option Two	Evapotranspiration parameter Root distribution (time varying) Leaf area index (time varying) Ground over Indices (time varying) Canopy storage capacity coefficient
	ii) Input data	Meteorological data
c)	Overland and Channel flow component	
	i) Model Parameters	Strickler roughness coefficient for overland and river flows, co - efficient of discharge for wier formulae
	ii) Input data	Specific flows or water levels at boundaries, Man controlled diversions and discharges, Topography of overland flow plane and channel cross sections.

d) Unsaturated Zone Component

i)	Model Parameters (for each soil type)	Soil moisture tension/ content relationship, Unsaturated hydraulic conductivity as a function of moisture content Field capacity, wilting point and saturated hydraulic conductivity for unsaturated zone

e) Saturated Zone Component

i)	Model Parameters	Por-osities or specific yields, Saturated hydraulic conductivities,
ii)	Input data	Impermeable bed delevations, Specific flows or potentials at Boundaries Pumping and Recharge data

f) Snowmelt Component

i)	Model Parameters	Degree Day factor Snow zero plane displacement Snow roughness height
ii)	Input data	Meteorological and precipitation data

In order to provide ease in the data collection programme, the data requirement for SHE Model may be classified in the following categories:

a) Topography :

- Contour maps showing the elevation over the catchment

b) River Cross-sections, L-Sections and Roughness parameters

- River and channel cross sections and L-Sections for the important reaches

- Information about the width, depth and slope for different river reaches upstream to the gauging site.

- Roughness parameters for different river reaches as well as for overland flow plane.

c) Soil Data:

- Soil maps showing the spatial distribution of different types of soil over the catchment

- For each soil type a soil moisture retention curve and the hydraulic conductivities, soil texture analysis, volumetric water content at saturation, field capacity and wilting point.

d) Vegetation data:

- Vegetation (land use) maps showing the vegetation distribution over the catchment

- Canopy resistance, Aerodynamic resistance, and canopy storage capacity.

- For each vegetation type the typical variation of root depth and leaf area index over the year.

e) Meteorological data:

- Rainfall data (time series) from all daily and hourly recording stations in the area

- Snow related data, if the basin is snowfed

- Potential evapotranspiration data or daily climatological data (windspeed, humidity, temperature radiation or sunshine hours etc.)

f) Hydrological Data

- Stage and discharge (time series) from all daily and hourly recording stations

- Rating curve to convert the stage values into discharge values

g) Hydrogeological data

- A hydrogeological description of the aquifer system

- Aquifer geometry (thickness, boundary conditions etc.)

- Aquifer parameters (leakage, transmissivity, storage coefficient)

- Ground water level fluctuations
- Ground Water management (pumping etc.)

h) Man made influence (historical as well as proposed)

- Irrigation
- Reservoir regulation
- Water development
- Details of weirs, if any
- Afforestation or deforestation
- Urbanisation

2.3 Input Data Files Organisation for SHE Model

Application of SHE requires the provision of a large amount of parametric and input data organisation in an array of data files. To each component a data file is attached. The naming of the files is usually given in a way, which identifies the specific catchment followed by three letters indicating the component. The data input necessary to run SHE successfully are divided into four categories:

i) Program organisational data
ii) Catchment organisational data
iii) Physical characteristics data
iv) Meteorological data

The first three types of data are read in during the initialization phase, while the meteorological data are read during the simulation phase. The major part of the programme organisation data are read from the FRAME COMPONENT . This includes information about organisational and operation of the simulation, i.e. length of simulation,grid square set up and times at which data should be stored or printed. Codes describing the soil and vegetation type distribution, and rainfall and meteorological station network are also read from FRAME. The distributions are presented as an array of codes, allocated to each grid square. A code number signifies a particular characteristics. The physical data associated with these characteristics are read from the different process components where the data are used.

2.4 Running SHE Model

After preparation of the required SHE data files, SHE can be run by typing SHE. The user is then requested to type the catchment name, which would correspond to the name given to the data files.

If specified in the frame data file XXX. FRD results will be both printed and stored on a file respectively. The SHE output print file XXX. PRI contains various results and warning error messages. It is recommended in the initial phase of SHE application to print the initial conditions for checking of the Data. Stored results in the file XXX. RES may be retrieved and presented by applying the routines SHE. OR or SHE.GD.

2.5 Field of Application of SHE

SHE model has significant advantages over existing hydrological models for a wide range of applications due to its distributed model structure and physical interpretation of the hydrological processes. Almost for any kind of hydrological problems, SHE model wil be able to provide the answer, although further development and refinement is still needed to achieve the optimum goal of its general applications. Moreover, cheaper conventional rainfall-runoff models may be successfully applied to provide the solutions for many simple hydrological problems. But for the more complicated problems, the conventional models fail to provide the satisfactory results and hence there may be a little alternative but to use a system such as the SHE. Some of the possible applications are given in the following examples:

(a) Catchment changes:

Catchment conditions are non-stationery due to nature and man made changes in land use, such as the effects of fires, urbanisation and forest clearance for agricultural purposes etc. The parameters of SHE model have direct physical interpretation and can be evaluated for the new state of the catchment conditions before the change actually occurs. The new set of parameter values can be used to examine the possible effect of such changes in advance taking different alternatives of simulation runs.

(b) Ungauged catchments:

The parameters of SHE model can be easily derived from the short term field investigations. The model may be calibrated using much shorter and therefore more cheaply obtained, hydrometeorological record than is necessary for more conventional models. It means for an ungauged catchment in which a project has been proposed, one or two years of hydrometeorological records are sufficient to calibrate SHE model whereas for the conventional rainfall-runoff models this record langth is too short.

(c) Spatial variability in catchment input and output:

Distributed models can be used to study 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.

(d) Movement of pollutants and sediments:

Water flows provide the basic dispersion mechanism in the movement of pollutants and sediments. Thus, modelling the flows is prerequisite to model the movement of pollutants and sediments. Most water quality and sediment problems are distributed in nature, so distributed models are the most suitable for supplying the basin information on water flow.

In brief, some possible fields of application of SHE model are listed below:

i) Irrigation Schemes

. Irrigation water requirement

. Crop production

. Water logging

. Salinity/Irrigation management

ii) Land use change

. Forest clearance

. Agricultural practices

. Urbanisation

iii) Water developments

. Ground Water Supply

. Surface water supply

. Irrigation

- Streamflow depletion
- Surface water/ground water interaction

vi) Ground water contamination

Industrial and municipal waste disposal

- Agricultural chemicals
- Erosion/sediment transfer

v) Flood Prediction

2.6 Brief Review of Some Studies Using SHE Model

With the advent of high speed digital computers and considerable improvements in data base significant progress has been made in the application of physically based distributed models such as SHE model as modelling tool in a wide range of water resources studies. A brief review of the variety of studies which have been conducted or currently being undertaken with the SHE is given below:

2.6.1 Simulation of water flow and soil erosion, Thailand

DHI (1985) in cooperation with the Royal Irrigation Department in Thailand applied SHE model to quantify the hydrological behaviour and effects of land use changes on the hydrological regime of small and medium size catchment in Thailand with special emphasis on high flows and soil erosion aspects. Three catchments located north east of Bangkok were used in the study. The model simulation runs were taken and the results were encouraging. In order to analyse the effects of land use changes over the years some hypothetical test runs were taken for the two small catchments, khlong Yang and Khlong Samo Pun, using SHE Model after calibrating and validating it for those catchments based on records of streamflow in the wet season (June-October) and some observations of water table elevations in a well adjacent to the Khlong Yang stream gauge station. A comparative study of these tests runs with the existing situation in the two catchments yielded compatable results with respect to hydrological regime and soil erosion.

2.6.2 Environmental impacts of fertilizer application:

At DHI (1986), a comprehensive Danish Research and Development Programme was initiated with an objective to reduce the pollution from nutrients and organic matters in agriculture. Other than DHI, a number of Danish Research and governmental institutions are involved in this integrated multidisciplinary research programme including National Agency of Environmental Protection. The development of a regionally distributed hydrological model for describing water and nutrient losses from farming areas through the unsaturated and saturated zone to the streams envisaged at DHI. For this purpose, the SHE model would provide the hydrological framework for the model simulations incorporating sub models for simulating the nitrogen.

SHE model is applied to two catchments namely Karup and Lang Vad catchments which represent the typical conditions with respect to geology, hydrogeology and hydrochemistry in Denmark Preliminary runs were taken for these catchments.

2.6.3 Application of SHE in the country of Aarhus, Denmark

SHE model, set up for multilayer aquifer system consisting of one unconfined and two confineu aquifer separated by aquitards, is being applied at DHI for the country of Aarhus, Denmark with the following objectives:

- i) Estimate tne water availability and ground water development potential at various sites.
- ii) Predict the impact of ground water abstraction on the river flow and meadow areas.
- iii) Establish an optimal control and monitoring programmes.
- iv) Modelling of transport and geochemical procecess of pollutants from waste disposal.

2.6.4 Sensitivity Analysis of SHE for an Upland catchment in Mid-Wales

Bathurst (1987) carried out a sensitivity analysis of SHE model based on simulations of two stream flow hydrographs for an upland catchment in mid wales. For each hydrograph, a single parameter was varied at a time and the simulation sensitivity was assessed quantitatively in terms of the change in peak discharge and in the root mean square value of the differences between measured and simulated discharges taken at intervals through the hydrograph. An important qualitative assessment was provided through interpretation of the changes based on physical reasoning. The results show that the simulations can be as sensitive to model grid spacing and time step as to catchment parameters and that these "structural" parameters should therefore be small by comparison with the scales of the variations which they are used to represent. The simulation results were more sensitive to the soil parameters and flow resistance co-efficients which can be evaluated by point measurements at a few representative field sites.

3.0. GENERAL DESCRIPTION OF STUDY AREA AND DATA AVAILABILITY

3.1 General Description of Barna Sub-Basin

The Barna river rises in the Vindhya range in the Raisen district of Madhya Pradesh, east of Barkhera village, at an elevation of 450 metre at north latitude 22°55' and east longitude 77°44' . It is a right bank tributary of Narmada river. It drains a total area of 1987 sq.km. The distance of confluence with Narmada from the source is 605 km. The index map of the sub basin is shown in fig. 2.

In the sub-basin, a dam has been constructed in year 1976 across Barna river near village bari of Tehsil-Bareli District-Raisen, located near National High Way (NH-12) connecting Bhopal to Jabalpur. The total drainage area of the Barna river upto the dam site is 1176 sq.km. There is a small tank namely Palakmati Tank situated in the catchment which intercepted the runoff of an area of 85.47 sq.km. The gauging of the Barna river is being carried out at Bareli gauging site and Sultanpur gauging site. The Bareli gauging site is situated over the Barna river basin at about 25 km d/s of the dam site having the catchment area about 1590 sq.km. The Sultanpur gauging site is located u/s of the dam site and the catchment area upto the gauging site is about 414 sq.km.

In the sub-basin, four distinct seasons occur during each year. They are i) cold weather, ii) hot weather

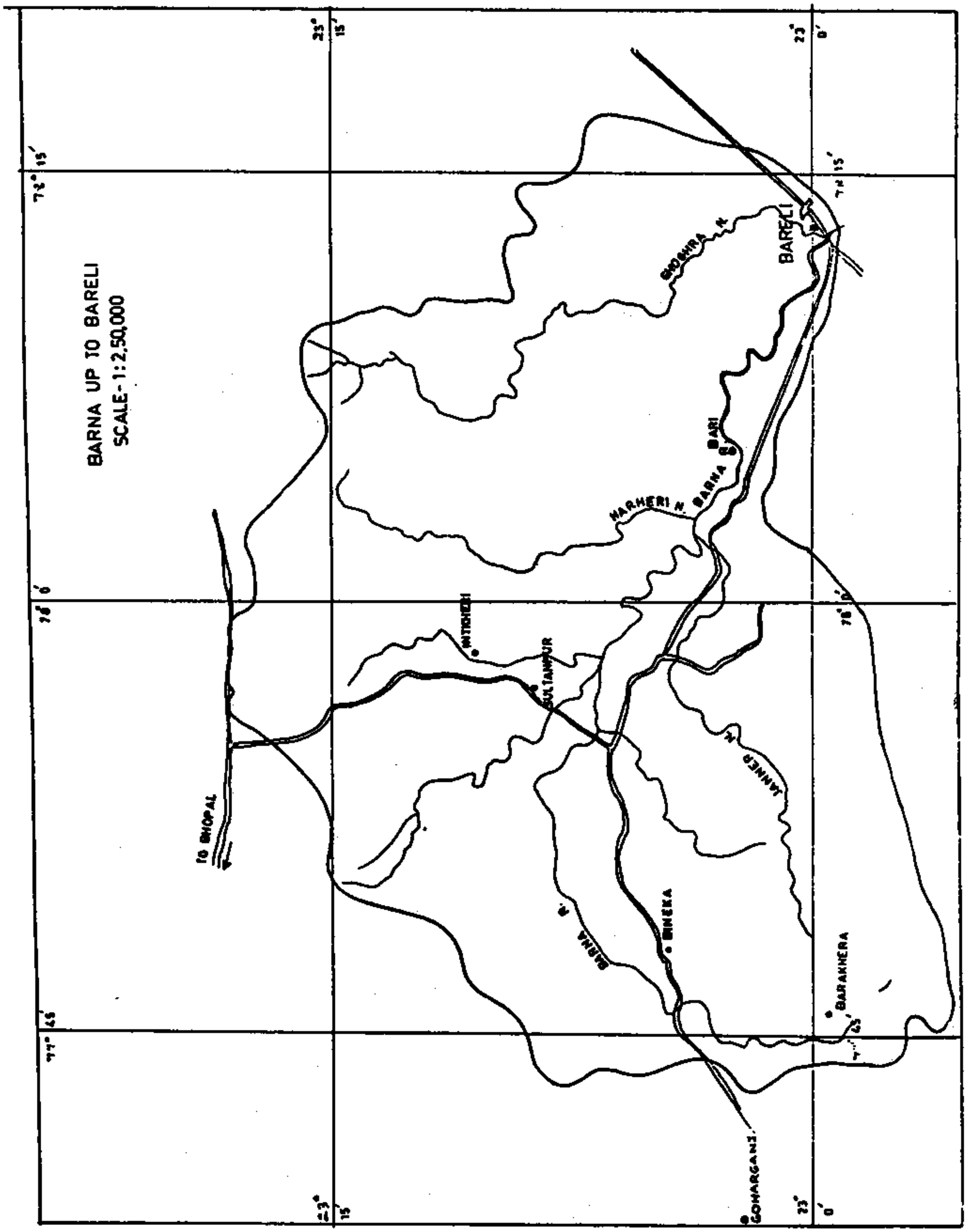


FIG. 2 : INDEX MAP OF BARNA SUB-BASIN UPTO BAREILLY.

iii) south west monsoon and iv) post monsoon. The cold weather season commences in December and continues till the end of February. It is characterised by bright cloudless days and clean nights and piercing winds. Frost is known to occur occasionally. Hail too is not uncommon. There is a slight precipitation in the basin during this season. The mean annual temperature in the cold weather varies from 17.5°C to 20°C. 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 mean annual temperature during the hot weather varies from 30°C to 32.5°C, with maximum temperature some times exceeding to 48°C. The south west monsoon sets in by the middle of June and withdraws by the first week of October. June to September are the rainiest months. Nearly 90% of the annual rainfall is received during the five monsoon months from June to October. In the south west monsoon the temperature ranges 27.5°C to 30°C. In the post monsoon season temperature between 25°C to 27.5°C are experienced. Average annual rainfall in the sub basin is about 1130 mm.

The topographic elevations in the basin ranges from 300 m near the Bareli gauging site to 630 m in the upper most part of the basin. The hilly portion of the basin is predominantly covered by dense decidous forest The portion of the catchment d/s to the Barna Dam site comes under its command. The soils in the basin are medium to deep black cotton soils except on the hilly region where skelton soils have been reported. In the command area, the agricultural practices are carried out. During monsoon months, the water is impounded in the agricultural bounded fields. The response of this area to input rainfall is likely to be quite slow.

The discharge at the Bareli gauging site mostly depend on the discharge from the Barna dam during non-monsoon season. However, during monsoon season, a major river, Ghoghar river, which joins the Barna river at 8 km. u/s from the gauging site, also contributes to the Barna River. At Sultanpur gauging site, discharge measurements are carried out only during monsoon months as the river is usually dry during the non-monsoon months.

Barna project is one of the important Irrigation Projects of M.P. which envisage construction of Masonary Dam across Barna river near Bari village. The salient features of Barna project are given below:

A. HYDROLOGY

i)	Drainage area of the river above dam site.	1176 sq.km.
ii)	Average annual rainfall	1132 mm
iii)	Maximum annual rainfall	2068 mm (Year 1973)
iv)	Minimum annual rainfall	535 mm (Year 1920)
v)	Mean annual runoff at the dam site.	56500 hect.metre
vi)	Observed maximum flood at the dam site	11480 cumec. (Year 1965)

vii)	Design flood	13557 cumec
viii)	Moderated flood	6825 cumec

B. RESERVOIR

i)	Gross storage capacity at F.R.L. 348.55 m.	55900 hect.
ii)	Dead storage at F.R.L. 338.1 m	8320 hect. m
iii)	Live storage at F.R.L. 348.55 m	45580 hect.m
iv)	Area submerged at F.R.L. 348.55 m	7700 hect.
v)	a) Area under cultivation	2430 hect.
	b) Area not under cultivation	2190 hect.
	c) Forest Area/	3080 hect.
	village affected	25 Nos.

C. MAIN DAM

i)	Type of dam	Straight gravity Stone masonary
ii)	Normal pondage level	348.55 m
iii)	Maximum water level	351.45 m
iv)	Dead storage level	338.10 m
v)	Top level of dam	352.70 m
vi)	Deepest river bed level	315.6 m
vii)	Length of dam	432.0 m
viii)	Top width of dam	460.0 m
ix)	Maximum height	47.7 m

D. CENTRAL SPILLWAY

i)	Crest level of the spillway	341.7 m
ii)	Length of the spillway	115.1 m

iii)	Type of crest gates	Radial crest gates
iv)	No. and size of gates	8 Nos. 12.2 m.x 6.85 m
v)	Top level of crest gates	348.55 m

E. SADDLE DAM (Including head regulator of combined canal)

i)	Type of dam -Straight gravity stone masonary	Block 1 to 3&5 Block 4 (Regular block)
ii)	Length of Dam	94.50 m
iii)	Top width of dam	4.6 m
iv)	Maximum height	20 m

. CANAL SYSTEM

i)	Gross commanded area	0.72 lakh hect.
ii)	Culturable command area	0.55 lakh hect.
iii)	Annual Irrigation	0.61 lakh hect.
	a) Rabi	0.34 lakh hect.
	b) Kharif	0.27 lakh hect.
iv)	Total length of canal	318.55 km.
	a) Main canal	38.56 km.
	b) Distributary	86.30 km.
	c) Minors	193.69 km.
v)	Nos. of villages benefitted and proposed irrigation	
	a) In Raisen Distt.	156 Nos. 48.6 hec. Lakh
	b) In Sehore Distt.	42 Nos. 12.0 hect.Lakh

3.2 Data Availability

The topographic maps procured from Survey of India on 1:50,000 scale were used to prepare a base map of the Barna Basin upto Bareli gauging site. The toposheets with the following numbers were required to draw the catchment of the Barna River upto Bareli Gauging site:

i)	55F/12	(ii)	55E/15	(iii)	55E/16
iv)	55F/19	(v)	55F/13	(vi)	55I/3
vii)	55I/4	viii)	55J/1	(ix)	55I /8
x)	55J/5				

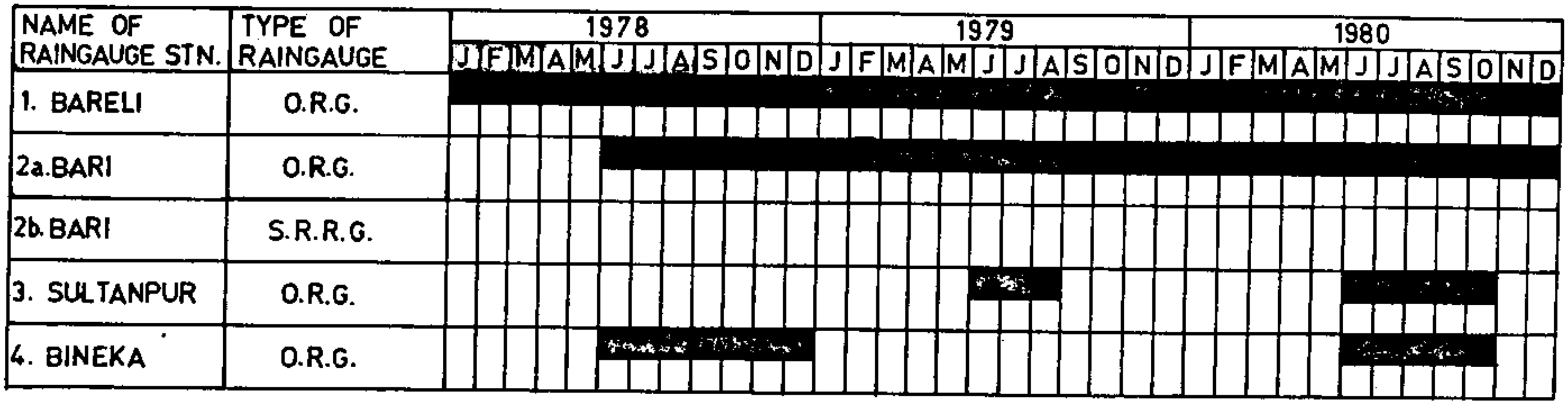
The numbering of the above toposheets are based on the standard procedure being followed by Survey of India. Since, SHE model is a physically based and distributed hydrological model where all the major components of the hydrologic cycle are being modelled separately using governing differential equations, information about a large number of variables is needed for a successful model application. In order to collect the required information, a data collection programme was launched and a large number of data collection agencies, both central and from the state of Madhya Pradesh, were approached to colect the required data. Frequent field visits were made to collect the relevant data. However, the data collected from the different agencies were not to the extent needed for SHE model application studies. The availability of rainfall data for Barna River Basin upto Barelli, gauging site is given in Table 1. The rainfall data for four non recording raingauge stations and one recording station were available for the period indicated in the table 1. Table 2 and 3 provide information regarding data availability status for daily gauge and corresponding discharge and hourly gauge values respectively at Bareli and Sultanpur gauging sites. The hourly river stages and corresponding discharge were available for Sultanpur G-D site. The flow velocity at this site is measured using floats and because of this, the discharge estimates are highly uncertain. The Bareli gauging site was started from 16th July 1984. However, both gauge and discharge measurements were started from 7th August 1985. As mentioned earlier, the Bareli gauging site is about 25 km d/s of the Barna Dam Site. Therefore, the discharge at Bareli gauging site would be affected by spillway releases. There is no module available in SHE model programme to simulate the reservoir effects. As such, some indirect computations for reservoir inflow were made using the available reservoir operation, releases and evaporation data. The availability of reservoir data collected from the Barna Dam Site is given in Table 4. The Barna Dam is built to provide the irrigation in the command area mostly during non monsoon months when the inflow to the reservoir is not that significant. The major inflow to the reservoir usually occurs during monsoon months. At that time the releases for irrigation are negligible and the inflow entering into the reservoir are stored and surplus water is released through spillway in the river.

TABLE 1 STATUS OF RAINFALL DATA—BARNA RIVER BASIN

NAME OF RAINGAUGE STN.	TYPE OF RAINGAUGE	1984												1985												1986											
		J	F	M	A	M	J	J	A	S	O	N	D	J	F	M	A	M	J	J	A	S	O	N	D	J	F	M	A	M	J	J	A	S	O	N	D
1. BARELI	O.R.G.																																				
2a. BARI	O.R.G.																																				
2b BARI	S.R.R.G.																																				
3 SULTANPUR	O.R.G.																																				
4 BINEKA	O.R.G.																																				

NAME OF RAINGAUGE STN.	TYPE OF RAINGAUGE	1987												1988											
		J	F	M	A	M	J	J	A	S	O	N	D	J	F	M	A	M	J	J	A	S	O	N	D
1. BARELI	O.R.G.																								
2a. BARI	O.R.G.																								
2b. BARI	S.R.R.G.																								
3. SULTANPUR	O.R.G.																								
4. BINEKA	O.R.G.																								

TABLE 1 STATUS OF RAINFALL DATA – BARNA RIVER BASIN



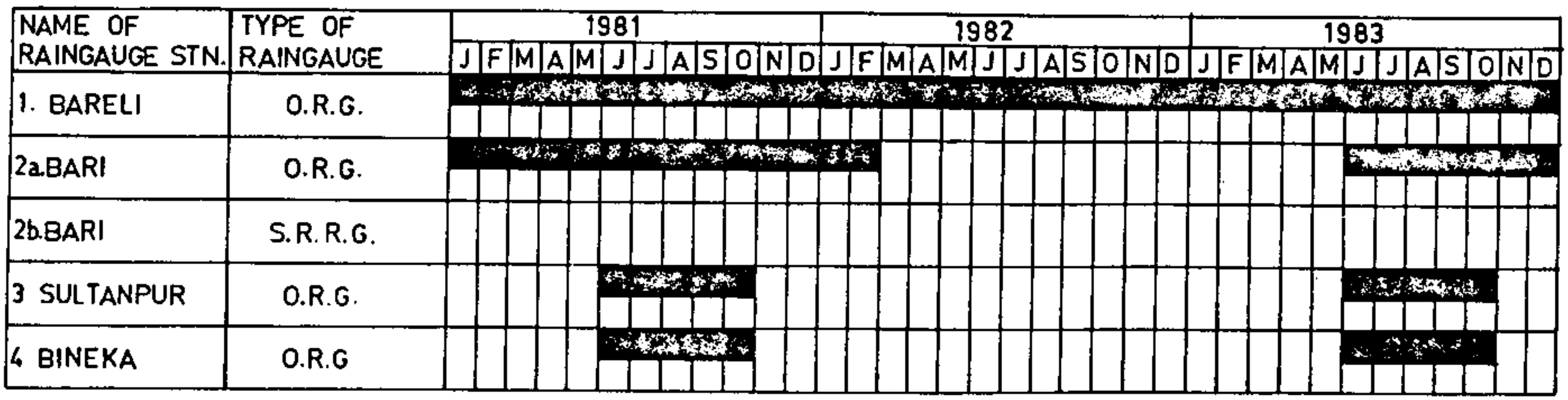


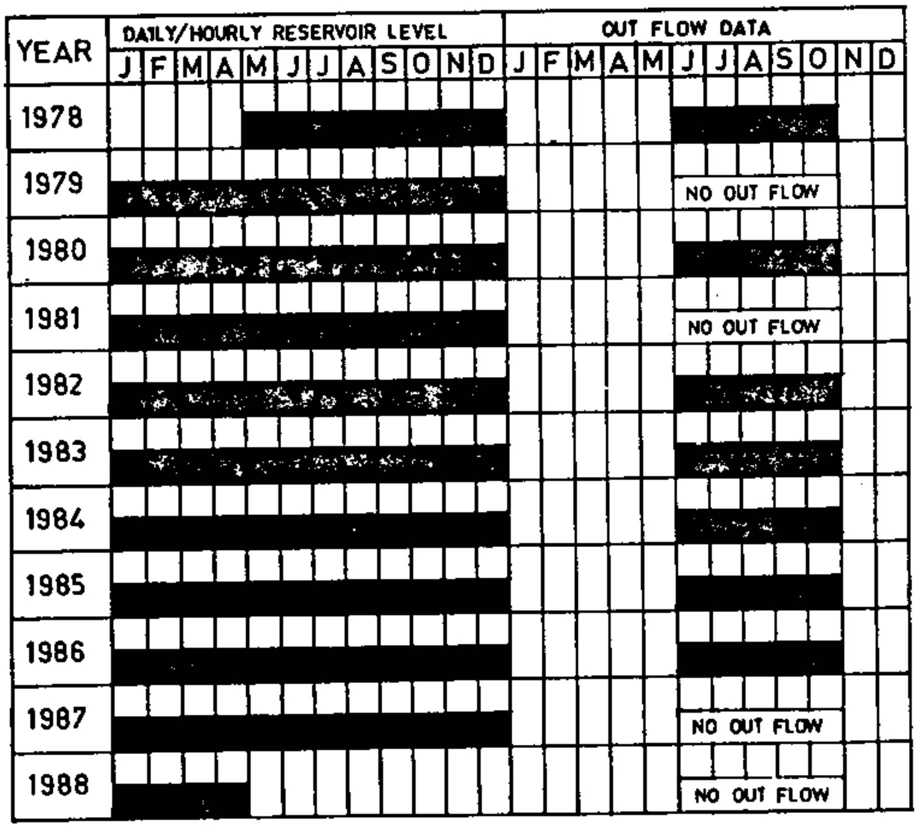
TABLE 2 STATUS OF GAUGE AND DISCHARGE DATA AT BARELI GAUGING SITE

YEAR	DAILY GAUGE DATA												DAILY DISCHARGE DATA												HOURLY GAUGE DATA											
	J	F	M	A	M	J	J	A	S	O	N	D	J	F	M	A	M	J	J	A	S	O	N	D	J	F	M	A	M	J	J	A	S	O	N	D
1984																																	■	■		
1985						■	■	■	■	■	■	■						■	■	■	■	■	■	■							■	■	■	■		
1986	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■						■	■	■	■	■		
1987	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■												
1988	■	■	■	■	■								■	■	■	■	■																			

TABLE 3 STATUS OF HOURLY GAUGE AND DISCHARGE DATA AT SULTANPUR GAUGING SITE

YEAR	J	F	M	A	M	J	J	A	S	O	N	D
1982							■	■	■	■		
1983							■	■	■	■		
1984							■	■	■	■		
1985							■	■	■	■		
1986							■	■	■	■		
1987							■	■	■	■		
1988							■	■	■	■		

TABLE 4 STATUS OF RESERVOIR DATA AT BARNA DAM SITE



The reservoir inflow computations were made during monsoon months neglecting the releases from the reservoir for irrigation.

The cross sections of the river, required for river set up at Bareli and Sultanpur gauging sites were collected. The soil and land use maps on scale 1:250,000 were procured from the Narmada Valley Development Authority (NVDA). No systematic soil survey has been carried out in the basin to determine the hydraulic properties of the different types of soils and spatial distribution of soil depths. However, the hydraulic properties of different types of soils were derived from secondary sources available in the form of project reports and research papers and the soil depths were assumed to be dependent on the land use and slopes. The ground water levels were observed by the M.P. State Ground Water Board for selected permanent observations wells two or three times in a year. The ground water level observations for those permanent observation wells which are either in side the basin or near the periphery of the basin were collected from the office of M.P. State ground Water Board. There were about nine to ten wells satisfying this criterion. However, majority of these wells are near the periphery of the basin. As such, this information was used as general guidelines about the position of water table during the year. Furthermore, the groundwater level fluctuations data were also used to specify the initial conditions for SHE model.

The evaporation data for a research station namely power-kheda located near the basin was available from 1983 onwards (weekly during 1983-87 and daily during 1987-88) and used in the study.

4.0 DATA PROCESSING AND PREPARATIONS

The rain data collected from various state and central government agencies can not be used as such for running SHE Model. It is necessary to process the field data in order to bring them in SHE model format. Processing of different types of data have been carried out as follows:

a) Processing of Topographic data

In the first stage of data processing, a topographic map of the sub basin was prepared on 1:50,000 scale using the relevant toposheets procured from Survey of India. A transparent overlay consisting of square grids of 500m x 500m was prepared and later superimposed over each one of the toposheet maps of the sub-basin. Then the topographical elevations for each node of the grids were obtained from interpolating the nearest contours and bench levels manually. In case electronic degitizer is available, the contour of each topographic map of the sub basin may be degitized and the elevations of each node of the grids may be estimated using a suitable interpolation software. It provides an alternative method to the manual procedure. The digitizer method is less subjective and involves the computation of the nodal elevation values based on the values of the nearest contours. The interpolated nodal elevation values are used to draw grid net work for square grids oi uifferent sizes which are integer multiple of 500mx500m grid size. The mean elevation for a grid, computed and used in the model, are average of the point elevations falling within that grid.

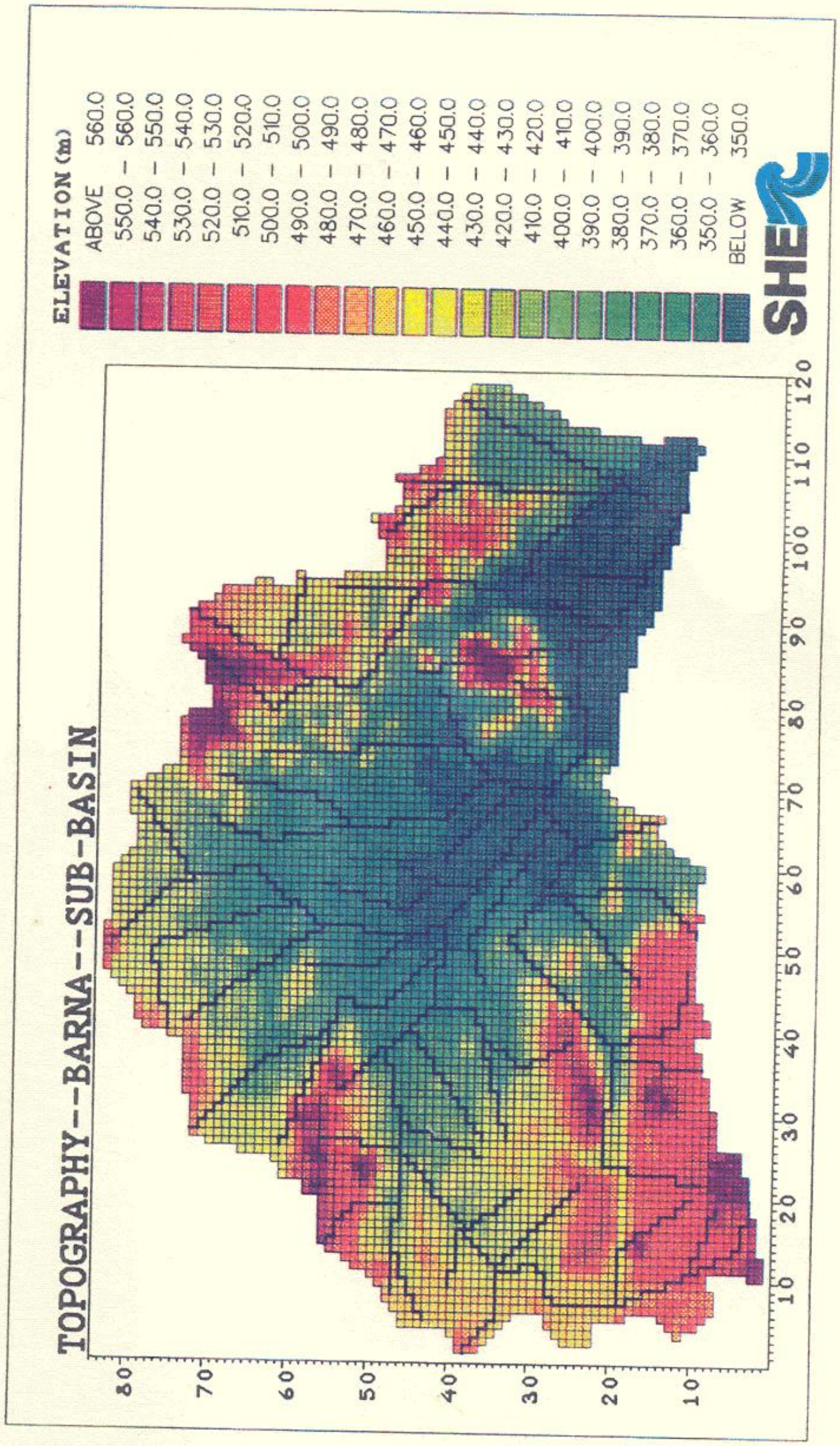
Fig. 3 to 5 illustrate the topographic maps prepared on 0.5km, 1km and 2km grid sizes.

b) Processing of River System Data

The next step was to process the river system data in order to set up the river on the grid maps of different scale. The river system marked on 1:50,000 scale basin maps was approximated into a series of linear sections for which an array of points were defined with systematiac numbering. A file RIVER. DAT, having a series of data points defined in the cartesian coordinate system, table defining the cross section at each end of the river sections, the bank levels and strickler roughness coefficients, was prepared and created on computer. Alternatively, electronic digitizer can be used to digitize the river system and the river cross sections. The cross sections available at Bareli and Sultanpur gauging sites were supplied. Wherever cross sections were not available efforts have been made to define the rough cross sections depending upon the order of the streams and information gathered during the field visits. In case no information about the cross section is available a provision has been made through a service programme, SHE.AF, to interpolate the intermediate cross-sections utilising the cross section information available at two ends of a river section.

c) Processing of Vegetation Data

The land use map, supplied by NVDA, was used to prepare a grid map on 1km x 1km size grids. The land use



G. 3 : TOPOGRAPHY OF BARNA BASIN ON 500 m x 500 m GRID MAP

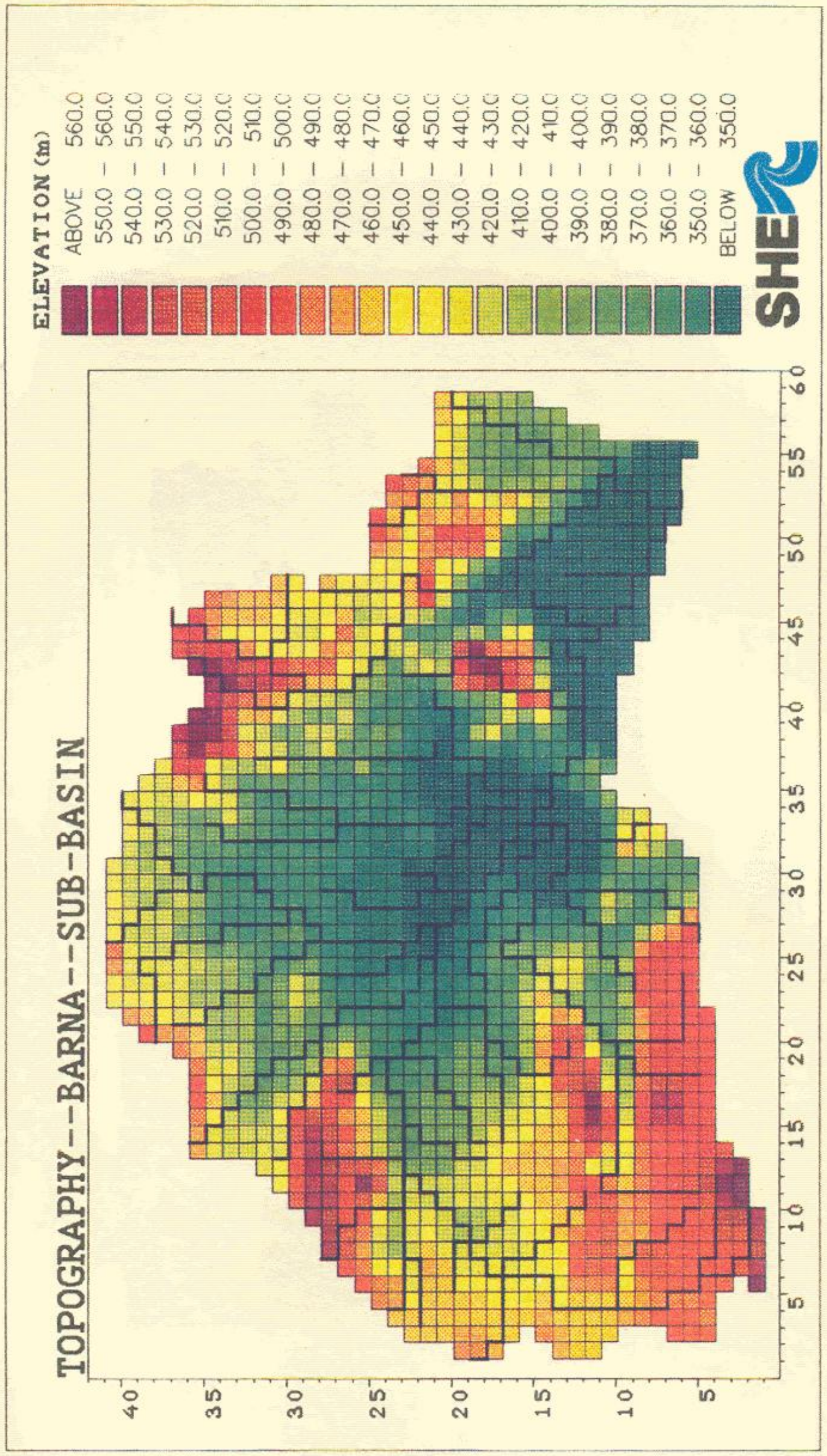


FIG. 4 : TOPOGRAPHY OF BARNA BASIN ON 1 Km x 1 Km GRID MAP

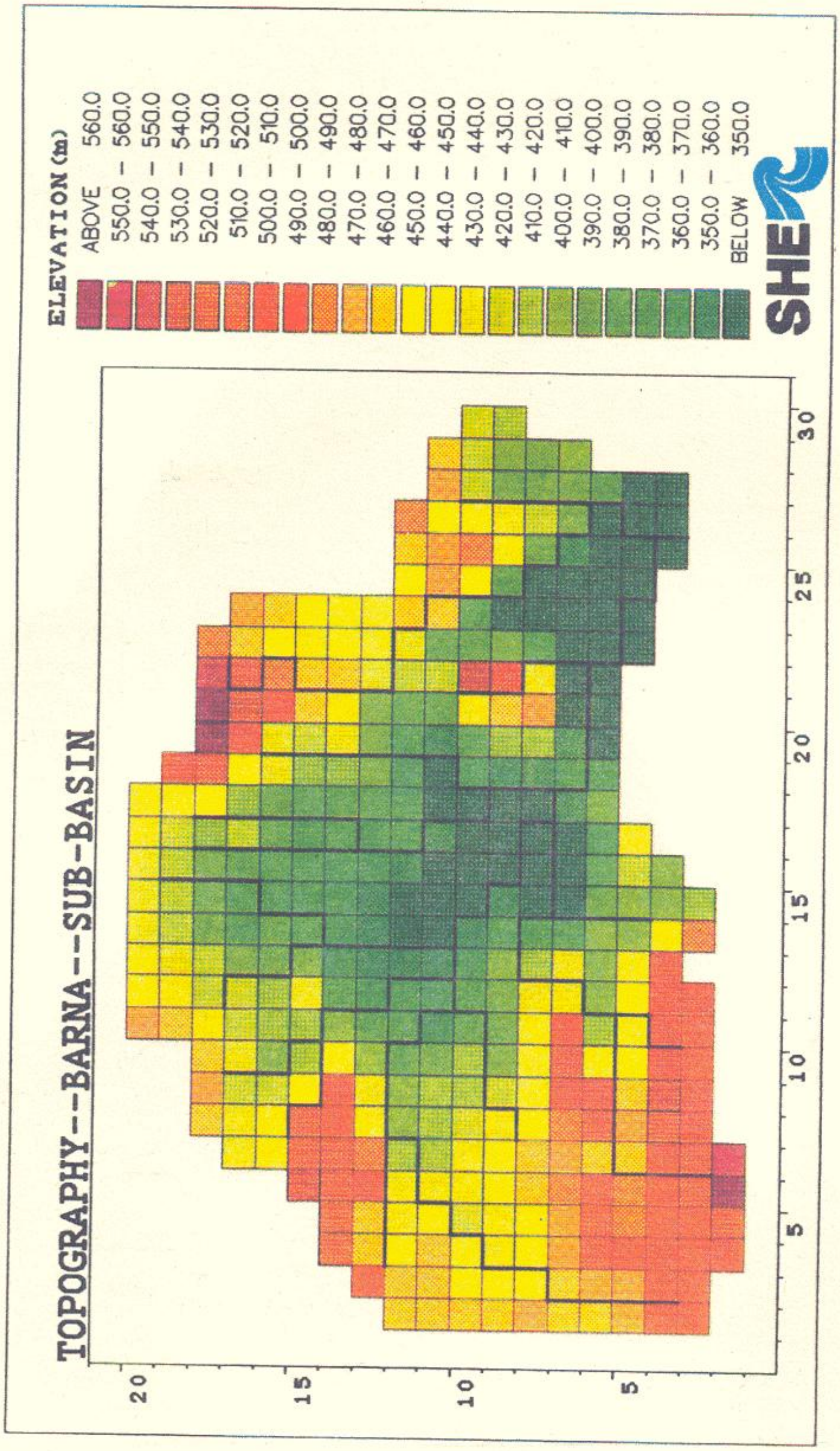


FIG. 5 : TOPOGRAPHY OF BARNA BASIN ON 2 Km x 2 Km GRID MAP

was classified in six categories - dense forest on uplands, dense forest on slopes, open forest, agriculture on uplands, agriculture on low lands and waste land. If more than one land use category was falling in any grid, the dominant land use type was assumed to be the representative for that grid type. Defining identification code data file LAND. 1000 was prepared for 1km x 1km grid set up.
Similarly, the grid identification code file LAND.2000 was also prepared in order to set up the model on 2km x 2km grids scale. For each categories of vegetation, the model also requires information about variation of leaf area index with time. This information was derived using the literature available from ICAR, discussions with agriculture wing of NVDA and M.P. Agriculture Deptt. and field visits. The typical curves developed and used for this study are shown in fig. 6.

Similar curves for root zone depth are also required for different land uses.

d) Processing of Soil data

The soil map procured from Narmada Valley Development Authority shows eight different types of soils. Due to lack of information on soil properties, this was viewed as too detailed for the purupose of simulations. Therefore, the soil classification is made based on the land use map. Different types of soils were assumed within and beyond the root zone depths respectively. Two different grid identification code files were prepared representing the types of soils in two different layers. In absence of the soil physical properties, they were derived from the available literature for the neighbouring basins. A typical retention curve developed for the black cotton soil is illust-rated in Fig. 7. The same retention curve was assumed to be valid throughout the basin. The spatial distribution of soil depth was introduced through a grid identification code file prepared based on type of land uses considered in the basin.

e) Processing of Hydrometeorological Data

Proper network of recording raingauges is needed for better representation of the spatial and temporal rainfall data inicates only one hourly recording station and three ordinary raingauge stations providing daily rainfall observations in Barna sub basin. The rainfall records for different stations were scrutinised and it was found that some daily rainfall values were missing. In order to provide the regular records of daily rainfall values, the missing rainfall values were estimated using the distance power method. The stations rainfall at shorter interval, for example hourly interval are required as input to the model to take care of temporal distribution of rainfall in the catchment. In absence of any other recording station, the hourly rainfall data available at Bari raingauge station was used to distribute the daily rainfall values of Sultanur, Binaka and Bareli stations assuming the same temporal variation in rainfall at all the raingauge stations. Hourly rainfall, thus obtained, at Sultanpur, Bineka, Bari and Bareli were used as input to the Model. Grid identification code files were prepared on different

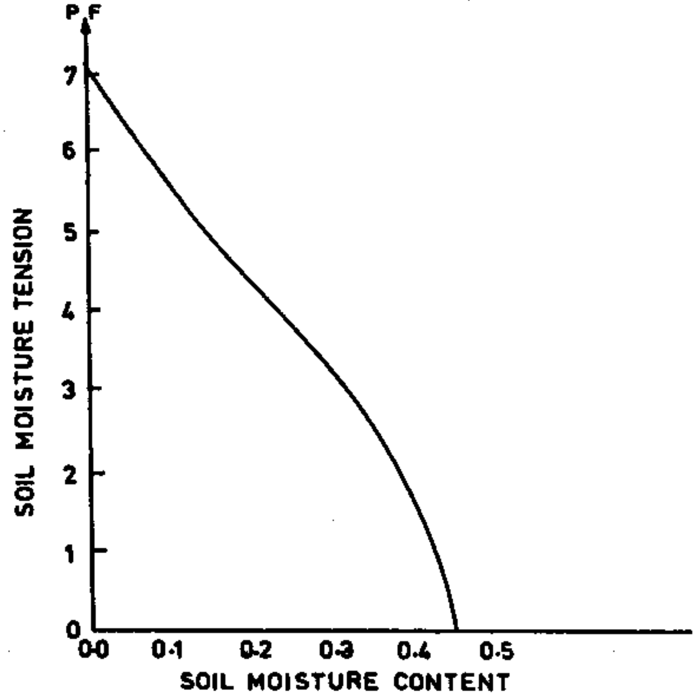


Fig. 7 : Soil moisture retention curve used for all soil types in the simulations. Based on data from ICAR (1984).

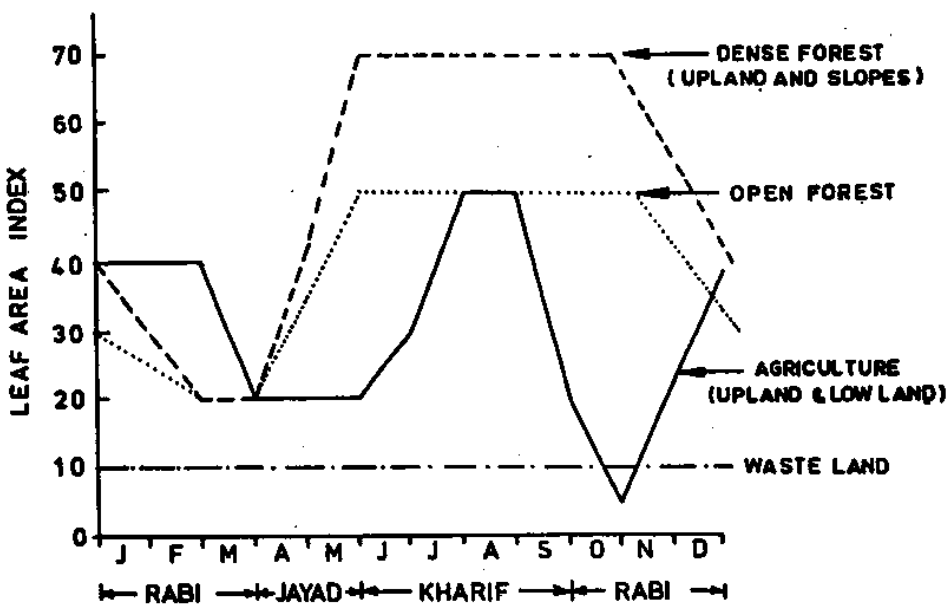


Fig. 6 : Time variation of leaf area index for the six landuse types used in the simulations.

grid scales assigning the codes for the nearest representative raingauge stations to different grid squares.

The pan evaporation data available at Powerkheda Research station was processed and brought in SHE format. The processed evaporation values were multipled by a pan coefficient equal to 0.7 to get potential evapotranspiration input for SHE model in order to estimate the actual evapotranspiration using the second option which is based on soil moisture control. If the climatological data such as sunshine hours, radiation data, wind speed, vapour pressure and aerodynamic resistance etc. are available, then the potential evapotranspiration and acatual evapotranspiration values are computed using the option one of SHE model which is based on Penman-Montieth Model. Grid identification code for meterological observatories would also be needed if more than one observatories are reporting the climatological data for the basin. This code file may be prepared in the same way as the raingauge stations grid identification code file was prepared.

f) Processing of Hydrological Data and Reservoir Data

The available gauge discharge records at Sultanpur and Bareli gauging sites were scrutinised. At Sultanpur gauging site, velocity measurements are made using float method. During high flood period, the float method provides unrealiable measurements for the velocity resulting erroneous discharge values. Therefore, the available records at Sultanpur gauging site were not considered for calibration and validation of the model. The Bareli gauging site is located at the

Barna river down stream to the Barna Dam. The flows at Bareli gauging site, are, therefore, depend upon the reservoir releases and contributions from the intermediate catchment between dam site and the gauging site. Since SHE model is not capable of simulating the reservoir effects directly, the flows at bareli gauging site could not be used in simulation studies. Inflows to the Barna reservoir, computed on daily basis using observed reservoir levels, reservoir released, evaporation from the reservoir, area capacity and elevation capacity curves, are used for model calibration and validation. Mathematically, the daily inflows to the reservoir are expressed as:

$$I_2 = S_2 - S_1 + Q_2$$

where,

S_1 and S_2 are the reservoir capacities computed for the two consequtive days using observed reservoir levels and elevation capacity curve.

and

Q_2 is the outflow from the reservoir which include the reservoir releases and evaporation from the reservoir sub-merged area

g) Water Balance Studies

Before using the processed rainfall runoff records in the model, it is necessary to check whether the rainfall and runoff data are consistent or not. In this regard the computation of runoff coefficients in different time periods provides useful inferences about the portion of precipitation appeared at the outlet of the catchment during that period. The runoff coefficient is simply defined as the ratio of runoff and rainfall within the specified period. In order to check the consistency of the rainfall-runoff records, monthly runoff coefficients are computed for the five months of the monsoon period upto Barna Dam site. The monthly rainfall, runoff and runoff coefficients for five monsoon months are given in table 5 to 8 for the years 1984 to 1987. Runoff co-efficients for monsoon season are also computed and given in table 5 to 8. It is observed from the tables that the runoff coefficients are always less than one and are considerably small in the beginning of the monsoon period indicating that a large portion of the rainfall is lost for fulfilling the soil moisture deficits, evaporation and other demands. The estimated recharge rate for monsoon season varies between 14% to 28% which seems to be reasonable.

From such studies, definite conclusions cannot be drawn regarding the consistency of the rainfall-runoff records at shorter time interval such as daily, hourly et. as the hydrologic pro-cesses become much more complex and the simple water balance studies would not be able to describe the processes within the reasonable accuracy, at the shorter time interval. However, the rainfall runoff data used in the water balance studies are consistent on monthly and seasonal basis. These data may, therefore, be utilised for calibration and validation of SHE model for the application study wherein the observed

TABLE 5: WATER BALANCE COMPUTATIONS

YEAR:--1984

MONTH	RAINFALL (P) (P)	OBSERVED RUNOFF (Q) (Q)	POTENTIAL EVAPORATION (E)	RUNOFF COEFF. (R)	S=P-Q-0.7*E.
(1)	(2)	(3)	(4)	(5)=(3)/(2)	(6)=(2)-(3) -0.7*(4)
JUN	75.20	0.00	230.0	0.00	-85.80
JUL	134.90	10.60	141.0	0.08	25.60
AUG	991.10	471.50	98.0	0.48	451.00
SEP	23.20	19.40	85.0	0.84	-55.70
OCT	15.80	0.00	112.0	0.00	-62.60
MON	1240.20	501.50	666.0	0.40	272.50

TABLE 6. WATER BALANCE COMPUTATIONS

YEAR:--1985

MONTH	RAINFALL (P) (P)	OBSERVED RUNOFF (Q) (Q)	POTENTIAL EVAPORATION (E)	RUNOFF COEFF. (R)	S=P-Q-0.7*E.
(1)	(2)	(3)	(4)	(5)=(3)/(2)	(6)=(2)-(3) -0.7*(4)
JUN	111.10	5.50	260.0	0.05	-76.40
JUL	440.90	37.50	121.0	0.09	318.70
AUG	498.60	339.50	89.0	0.60	96.80
SEP	255.30	217.10	149.0	0.85	-66.10
OCT	137.10	121.80	85.0	0.89	-44.20
MON	1443.00	721.40	704.0	0.50	228.50

TABLE 7: WATER BALANCE COMPUTATIONS

YEAR:--1986

MONTH	RAINFALL (P) (P)	OBSERVED RUNOFF (Q) (Q)	POTENTIAL EVAPORATION (E)	RUNOFF COEFF. (R)	S=P-Q-0.7*E.
(1)	(2)	(3)	(4)	(5)=(3)/(2)	(6)=(2)-(3) -0.7*(4)
JUN	178.80	7.90	113.0	0.04	91.80
JUL	820.00	607.50	90.0	0.74	149.50
AUG	225.30	185.00	79.0	0.82	-15.00
SEP	110.10	14.20	90.0	0.13	32.90
OCT	4.80	0.00	110.0	0.00	-72.20
MON	1339.00	814.60	482.0	0.61	187.00

TABLE 8 : WATER BALANCE COMPUTATIONS

YEAR:--1987

MONTH	RAINFALL (P) (P)	OBSERVED RUNOFF (Q) (Q)	POTENTIAL EVAPORATION (E)	RUNOFF COEFF. (R)	S=P-Q-0.7*E.
(1)	(2)	(3)	(4)	(5)=(3)/(2)	(6)=(2)-(3) -0.7*(4)
JUN	6.80	2.80	179.0	0.41	-121.30
JUL	133.90	5.10	146.0	0.04	26.00
AUG	535.70	161.70	79.0	0.30	318.70
SEP	144.70	52.30	105.0	0.36	18.90
OCT	69.20	3.80	88.0	0.06	3.80
MON	890.30	225.70	597.0	0.25	246.70

and simulated runoff values may be compared on monthly and seasonal basis.

h) Processing of Geohydrological Data

Based on the fluctuations in water table of the observation wells, a grid identification code file was prepared in order to specify water table fluctuations as initial conditions in the beginning of the simulation period. In the absence of information about the aquifer characteristics in space, same value of saturated hydraulic conductivity, derived from relevant literature, was adopted throughout the basin.

4.1 SHE setup for Barna sub basin

As mentioned in the previous section, the computational grids were initially drawn of 500mx500m size. Since, the computational requirement for a set up on this size was enormous, the setup for grid size of 1km x 1km and 2km x 2km were made. Later on, the set up for the computational grid size of 2km x 2km was found to be the computationally efficient for this size of the basin based on sensitivity runs and the same has been adopted in further simulation studies. Fig. 8 illustrates the representation of the basin on the computation grid size of 2km x 2km. In SHE model set up, the rivers can run only along the grid boundaries. Manually, it would be too tedious to set up the rivers in SHE format. A service programme SHE. AF, which utilised the information about the coordinates of the series of points

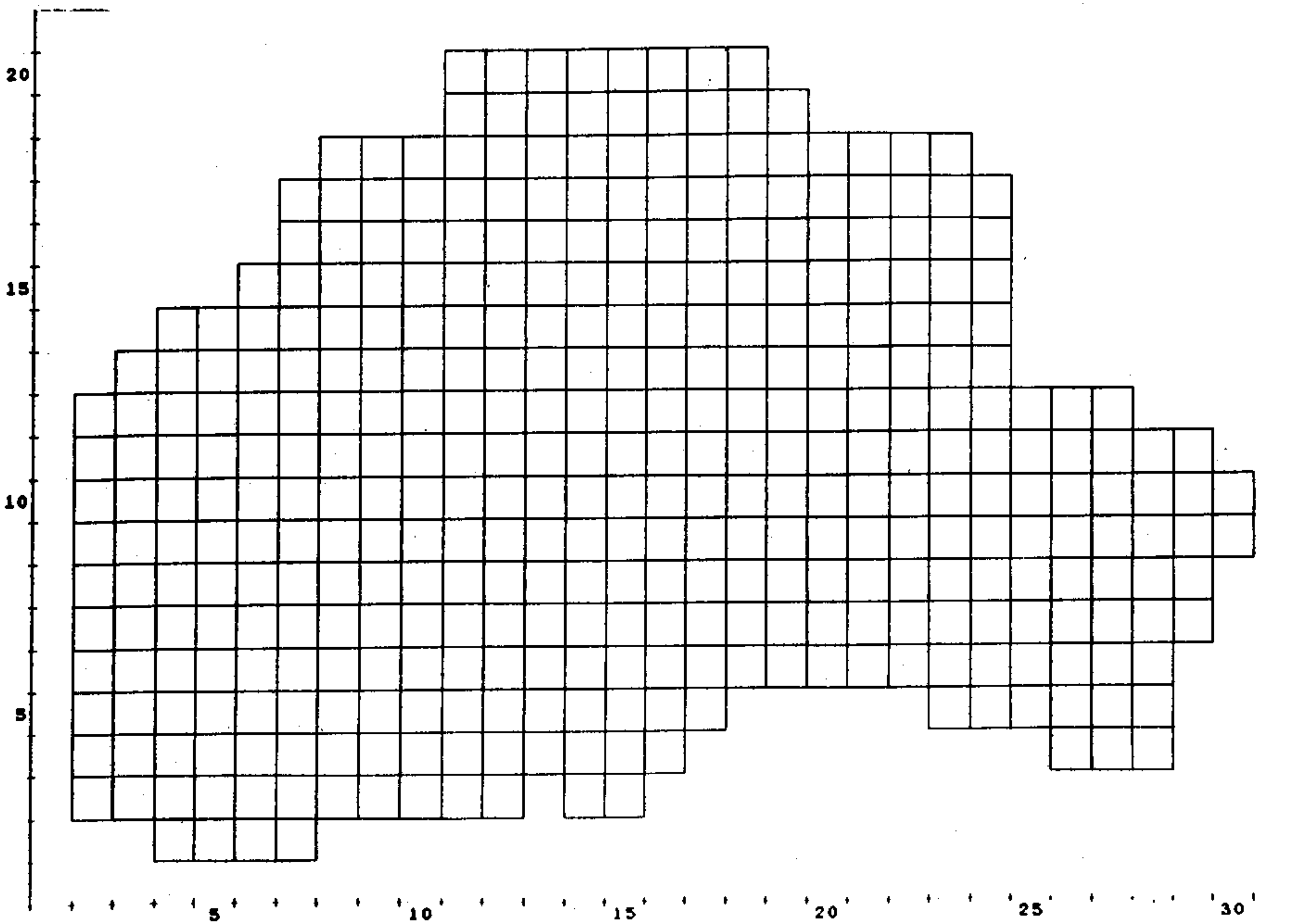


FIG. 8 : REPRESENTATION OF BARNABASIN ON THE COMPUTATION GRID SIZE OF 2 Km x 2 Km.

defining the river channel by straight line and bank levels, Strickler roughness coefficients and some points defining the river cross sections, was used for this purpose. The river network representations for grid size of 2km x 2km is shown in fig. 9. The grid and channel network dimensions for the basin for different grid scales at which the set up were made are given in table 9.

Further,for setting up land use and soil depth, a grid map was prepaared in which codes were assigned to different grids and corresponding parameters were specified. The initial position of water table was also specified in similar way using the available historical information about the fluctuations in ground water observation wells. Since the unsaturated zone component of SHE model consume considerable C.P.U. time, these calculations are not made for all grids. The compu-tations involved in UZ component are considerably reduced after classifying the selected grid squares in different groups whose response is likely to be the same. Such classification was made following a classification scheme where the variability in land use, soil meteorologic characteristics and ground water fluctuations etc. was taken into account for each square grid. Then the computations are made for one grid in each group and the calculated results at each time steps are transferred to the other grids of the same group. Lastly, the SHE array formatting routine, which utilised the information about land use, soil types, soil depth, initial conditions, raingauge net work, represented

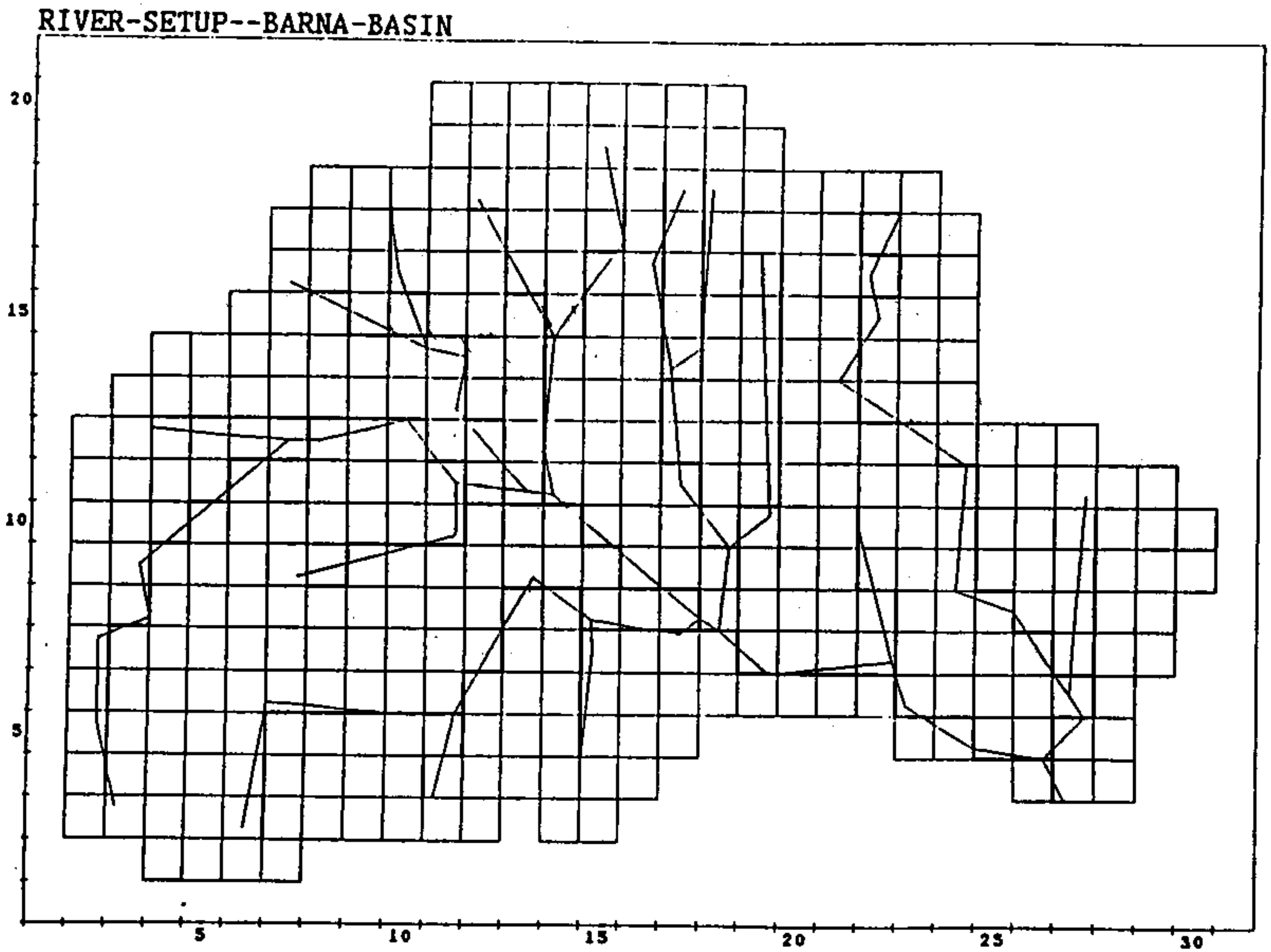


FIG. 9 : REPRESENTATION OF RIVER SET UP ON GRID SIZE OF 2 Km x 2Km GRID MAP

TABLE 9 : GRID AND CHANNEL NETWORK DIMENSIONS FOR THE BARNA BASIN FOR DIFFERENT GRID SCALES

Grid Square size km x km	Represented basin area (sq. km.)	Number of grid squares representing the basin	Number of river links representing river systems	Ratio of number of links to number of squares
.5 x .5	1531	6124	1303	0.21
1 x 1	1543	1543	592	0.38
2 x 2	1532	383	165	0.43

in the form of grids and river set up etc. was used to make the model set up according to format required by the different components of SHE.

5.0 CALIBRATION

Model calibration involves the manipulation of the model parameters to reproduce the response within some range of accuracy. The calibration procedure provides the estimates for those parameters which can not be assessed directly from field data. The fully distributed physically based models contain only parameters which can be assessed from field data. In theory, therefore, calibration should not be necessary if sufficient data are available from the field. However, for all practical purposes, some kind of calibration is also needed for physically based distributed models restricting the parameter values to relatively narrow intervals compared with those for the empirical parameters in empirical or lumped, conceptual models.

When the model is applied to simulate the physical system response, it produces the output containing the effects of the input deficiencies. The simulation output is compared with the recorded output containing the output deficiencies in order to test and varify the accuracy of the model. During the calibration the parameters are adjusted until the close agreement between simulated and recorded output is satisfactorily achieved. Basically four sources of uncertainity occur in deterministic simulation:

i) Random or systematic errors in the input data

ii) Random or systematic errors in the recorded output data

iii) Errors due to non optional parameter values

iv) Errors due to incomplete or biased model structure

During the calibration phase only error source (iii) is minimised, whereas the disagreement between simulated and recorded output is due to all four errors sources.

In principle three different calibration methods can be applied i) 'trial and error' or manual parameter assessment, ii) numerical optimisation methods, and iii) a combination of manual and numerical optimisation methods. Trial and error method involves a number of simulation runs before arriving at the final parameter values. In this study the trial and error method was used for parameter calibration.

Since the hourly rainfall data for one of the raingauge stations was available for the period of 1984-1988, it was decided to use the data for the period of 1984-1988 for calibration and validation. Subsequently, the discharge data available at Sultanpur gauging site (u/s to the dam site) and at Bareli gauging site (d/s to the dam site) were also scrutinised. It was found that the discharge data at Sultanpur gauging site was not reliable due to the errors in velocity measurements which were made using floats.Furthermore, the discharge at Bareli gauging site as such could not be used for calibration as the site is located at the down stream of the Bari Dam. Therefore, it was decided to use the inflow to the sreservoir of Bari Dam.for the calibra- and validation of the model. However the inflow to the reservoir are not observed but computed on daily basis using the daily reservoir levels, releases and evaporation data. Thus, the reliability of the inflow data depends upon the accuracy of the data used in their computations. Since the reservoir levels were available upto the year 1987, the inflow computations could be made only upto that period restricting the available records for the period of 1984-87 for calibration and validation. Finally, the data for the period of 1984-85 were used for calibration and years 1986-87 used for validation.

During the inflow computations, the large number of negative inflows were obsered specially during the periods when the catchment is receiving very little or no rainfall. These may be attributed to the errors in measusring the reservoir levels at which the inflow computations would largely depend. Other source of errors could be due to using the evaporation data available at Powerkheda Research Station (nearby station) in absence of the evaporation data at the dam site. Due to the above limitations the scope of the calibration and validations, based on the computed inflow at Bari Dam site is some what limited. The possibility of using the fluctuations in water table of the observation wells for the purpose of calibration and validation was examined. There were four observation wells, located in the basin in the d/s of the dam site, whose fluctions would also be significantly affected due to the existence of the dam. In addition to this these wells are located in command area of Barna Dam and information about pumping etc are not at all available.

Therefore, as such one can not rely on the water table fluctuations data of these wells for model calibration and validation.

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

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

b) Even some degree of lumping is being done at the level of grid size in the SHE model which is considered to be fully distributed and physically based model.

In general It has been observed that the Strickler coefficient has strong influence on hydrograph peaks, unsaturated zone hydraulic conducativities affect the infiltration rate and runoff hydrograph, saturated zone hydraulic conductivity affects the base flow, the soil cracks and detention storage modelling affect the hydrograph peaks and infiltration during the initial period of monsoon rains.

The range of values for the parameters were decided based on the literature and the information collected during the field visits made prior to this study. The parameters were tuned up within the acceptable range during the calibration. The observed and simulated volumes of runoff were comparable within the reasonable accuracy. However, since the inflow have been computed on daily basis, it would be rather difficult to draw any definite conclusion about the timing of peaks and their magnitudes. Nevertheless, the peaks of the inflow hydrograph computed on daily basis and the peaks of the simulated hydrograph are given in Table 10 for comparison. The timings of the peaks of the simulated hydrograph and inflow hydrographs seem to be within the acceptable range. It was also observed during the calibration runs that the runoff volumes in the beginning period of the monsoon period were being over estimated. It may be attributed to the cracking and swelling effects exhibited by the black cotton soils in the early part of the monsoon period.

At this stage the soil cracking consideration was introduced in the model. Modifications were made in the code for improved modelling of the basin response to the rainfall in presence of soil cracks by specifying a fracation of input rain, which directly goes to the bottom of the root zone rather than contributing to the overland flow, along with the cumulative rainfall beyond which it is presumed

TABLE 10: MONTHLY WATERBALANCE FOR BARNA BASIN UP TO DAM SITE-- CALIBRATION RUNS

YEAR:-1984

MONTH	RAINFALL	OBSERVED RUNOFF	COMPUTED RUNOFF	OBS.RUNOFF COEFFICIENT	COMP.RUNOFF COEFFICIENT	POTENTIAL EVAPORATION	RATIO
	(MM)	(MM)	(MM)			(MM)	
(1)	(2)	(3)	(4)	(5)=(3)/(2)	(6)=(4)/(2)	(7)	(8)=(3)/(7)
JUN	75.2	0.0	7.3	0.00	0.10	230	0.00
JUL	134.9	10.6	6.3	0.08	0.05	141	0.08
AUG	991.1	471.5	423.1	0.48	0.43	98	4.81
SEP	23.2	19.4	15.9	0.84	0.69	85	0.23
OCT	15.8	0.0	8.9	0.00	0.57	112	0.00
MON	1240.2	501.5	461.5	0.40	0.37	666	0.75
PEAK (CUMEC)		2109.0	2557.0				

YEAR:-1985

MONTH	RAINFALL	OBSERVED RUNOFF	COMPUTED RUNOFF	OBS.RUNOFF COEFFICIENT	COMP.RUNOFF COEFFICIENT	POTENTIAL EVAPORATION	RATIO
	(MM)	(MM)	(MM)			(MM)	
(1)	(2)	(3)	(4)	(5)=(3)/(2)	(6)=(4)/(2)	(7)	(8)=(3)/(7)
JUN	111.1	5.5	2.3	0.05	0.02	260	0.02
JUL	440.9	37.5	53.3	0.09	0.12	121	0.31
AUG	498.6	339.5	281.1	0.68	0.56	89	3.81
SEP	255.3	217.1	167.9	0.85	0.66	149	1.46
OCT	137.1	121.8	102.7	0.89	0.75	85	1.43
MON	1443.0	721.4	607.3	0.50	0.42	704	1.03
PEAK (CUMEC)		1300.0	2052.0				

that the cracks disappear. This together with a surface detention storage led to better matching of monthly discharge volumes. The parameters were changed systematically within the feasible zone identified from the preliminary runs taken with their extreme values. This manual optimisation procedure was continued till the best fit objective is achieved.

The Strickler roughness co-efficient for overland flow could be changed to match the simiulated peaks and computed inflow hydrograph peaks. The conductivities in saturated and unsaturated zones were varied to match the baseflow. The representative set of parameter values werefound following the above manual optimisation procedure.

In the final run, good fit was obtained for monthly volume during the monsoon season but the peaks could not be compared due to non-availability of inflow hydrograph ordinates within the twenty four hour duration (inflow hydrographs are computed on daily basis). The monthly volumes for the non monsoon season could not be compared due to lack of an accurate information about the inflow during this period. However, this runoff volume is only 2 to 3% of the volume of the monsoon season runoff as indicated by the simulated hydrographs and also supported by the literature. The final parameter values adopted are given in table 11. A comparison of volumes and peaks of inflow hydrographs and simulated discharges is shown in Table 10.

TABLE 11 DETAILS OF SOIL AND VEGETATION PARAMETERS AND DISTRIBUTIONS USED IN THE SIMULATIONS

LAND USE	PROPORTION OF BASIN COVERED (%)	SOIL TYPE	SATURATED SOIL CONDUCTIVITY (M/DAY)		SATURATED SOIL MOISTURE CONTENT (M**3/M**3)	SOIL DEPTH (M)	INITIAL DEPTH TO PHREATIC SURFACE (M)	VEGETATION ROOT ZONE DEPTH (M)
	(%)		UN SATURATED ZONE	SATURATED ZONE				
1	20.0	1	0.02	14.0	0.45	15	10.0	0.60
2	35.0	2	0.01	14.0	0.45	3	2.8	1.50
3	19.0	3	5.14	14.0	0.45	1.5	1.3	1.00
4	11.0	4	0.06	14.0	0.45	2.0	1.8	0.50
5	6.0			14.0		3.2	2.5	0.60
6	9.0			14.0		6.0	4.5	2.0

OVERLAND FLOW PLAIN STRICKLER'S ROUGHNESS COEFFICIENT =2.00

NOTE:---

TYPE	LANDUSE
1	AGRICULTURE ON LOW LANDS
2	DENSE FOREST ON UPLANDS
3	OPEN FOREST
4	WASTE LAND
5	DENSE FOREST ON SLOPES
6	AGRICULTURE ON UP LANDS

6.0 VALIDATION

If the model contains a large number of parameters, it is nearly always possible to produce a combination of parameter values which permits a good agreement between measured and simulated output data for a short calibration period. In order to find out whether a calibration is satisfactory, or which of the several combination of parameters values is the most correct, the calibrated parameters should be tested (validated) against data different from those used for calibration. Klemes (1986) stated a systematic procedure to test the performance of a simulation model in its application to the kind of task for which it is intended. The satisfactory model operation should not only be judged based on the performance characteristics derived from the calibration data set. The model must be validated using the independent data sets different from those used for calibration. The data sets used for validation must represent a situation similar to that to which the model is to be applied operationally. Usually, in hydrology, it is a standard approach to split the available records in two parts and use one part for calibration and other for validation. As mentioned in section 5.0, the data for the period 1986-87 was used to validate the model. During the validation phase, the calibrated parameter values are used to reproduce the discharge hydrographs and compare with the observed discharge hydrographs for the period not considered for calibration.

The calibrated parameter values given in table 11 were used during the validation runs. The monthly volumes are compared in table 12 for the validation period. An analysis of the results shows that the volumes of discharge hydrograph for the year 1986 were somewhat underestimated. However, it matches well for the year 1987. The peaks of the inflow hydrograph computed for daily interval were also compared with the simulated hydrograph for the validation period in table 12. However, the ground water fluctuation data could not be used in validation due to the constraints imposed by the existence of dam. It is seen that the calibrated model is a reasonable representation of the Barna Basin within the constraints of data availability.

TABLE12: MONTHLY WATERBALANCE FOR BARNA BASIN UP TO DAM SITE-- VALIDATION RUNS

YEAR:-1986

MONTH	RAINFALL	OBSERVED RUNOFF	COMPUTED RUNOFF	OBS.RUNOFF COEFFICIENT	COMP.RUNOFF COEFFICIENT	POTENTIAL EVAPORATION	RATIO
	(MM)	(MM)	(MM)			(MM)	
(1)	(2)	(3)	(4)	(5)=(3)/(2)	(6)=(4)/(2)	(7)	(8)=(3)/(7)
JUN	178.8	7.9	14.8	0.34	0.88	113	0.07
JUL	820.0	607.5	455.9	0.74	0.56	90	6.75
AUG	225.3	105.0	158.5	0.82	0.70	79	2.34
SEP	110.1	14.2	24.4	0.13	0.22	90	0.16
OCT	4.8	0.0	11.5	0.00	-	110	0.03
MON	1339.0	814.6	635.1	0.61	0.50	482	1.69
PEAK (CUMEC)		4842.0	3279.0				

YEAR:-1987

MONTH	RAINFALL	OBSERVED RUNOFF	COMPUTED RUNOFF	OBS.RUNOFF COEFFICIENT	COMP.RUNOFF COEFFICIENT	POTENTIAL EVAPORATION	RATIO
	(MM)	(MM)	(MM)			(MM)	
(1)	(2)	(3)	(4)	(5)=(3)/(2)	(6)=(4)/(2)	(7)	(8)=(3)/(7)
JUN	6.8	2.8	3.3	0.41	0.49	179	0.02
JUL	133.9	5.1	3.6	0.04	0.03	146	0.04
AUG	535.7	161.7	144.5	0.30	0.27	79	2.05
SEP	144.7	52.3	28.2	0.36	0.20	105	0.50
OCT	69.2	3.8	9.8	0.06	0.14	88	0.04
MON	890.3	225.7	189.[illegible]	0.25	0.21	597	2.65
PEAK (CUMEC)		792.0	1020.1				

7.0 SENSITIVITY ANALYSIS:

A sensitivity analysis was performed to examine the sensitivity of simulation results with respect to the important calibration parameters. Such analysis provides an useful way for identifying the parameters for which additional field measurements are required within the certain accuracy. During each of the sensitivity runs, the response of the basin was simulated by changing just one parameter value and keeping other parameters same as the calibrated parameter values. This response was then compared with the results of calibration or validation runs referred to as the reference run in the further discussions. Furthermore, some runs were also taken after changing the landuses from one type to the other and using mean areal rainfall (MAR) instead of distributed rainfall as input to study the influence of these changes on the simulated basin response. The ability of SHE model in simulating the basin response due to change in basin characteristics is useful feature which is not generally available in simpler models.

For sensitivity analysis the following runs were taken using the records for the year 1984 and 1985.

Case-1 Using calibrated parameters value (Reference Run)

Case-2 Double the strickler co-efficient (overland flow)

Case-3 Double the saturated conductivities in UZ

Case-4 Double the saturated conductivity in SZ

Case-5 Without using the soil cracks modelling

Case-6 Using Mean Areal Rainfall (MAR) instead of distributed rainfall as input

Case-7 Using 1.1* MAR as input

Case-8 By changing landuse for Grids Lying in Dense Forest area to Agriculture

A comparison of simulated and observed peaks and volumes of discharge for the above sensitivity runs is given in Table13.

The results of these runs are discussed below:

i) The strickler roughness coefficient for overland flows was made twice as big as the calibrated value in order to study the effect of the change in the strickler roughness coefficient over the simulation response. Increase in the value of the Strickler Roughness Coefficients results increase in the smoothness of over land flow plains giving more flashy basin response. A comparison with reference run shows that the new peaks are 25 to 30% higher. However, there is slight increase in the volume of the discharge for the year 1984. On the other hand, there is a little reduction in the volume of the discharge for the year 1985. It indicates that the peak flows are much sensitive to the Strickler Roughness Coefficient. A correct estimate of this parameter is therefore essential for simulating the basin response properly during the periods of high flows.

ii) The saturated soil conductivities in the unsaturated zone were doubled everywhere. The simulated discharge volumes and peaks were less than with that of the reference

TABLE 13: SENSITIVITY RUNS FOR BARNA BASIN-COMPARISON OF VOLUMES AND PEAK DISCHARGES

YEAR	MON	OBS. INFL. (MM)	SIMULATED INFLOW (MM) CASE-1	CASE-2	CASE-3	CASE-4	CASE-5	CASE-6	CASE-7	CASE-8
1984	6	3.0	7.3	7.3	7.4	10.5	7.3	7.4	7.4	7.5
1984	7	13.6	6.3	6.3	6.1	7.7	6.5	6.2	6.3	6.4
1984	8	471.5	423.1	428.9	388.1	422.6	419.8	462.5	547.6	443.8
1984	9	19.4	15.9	16.3	10.9	24.6	26.3	17.0	1[illegible].2	13.1
1984	10	0.0	8.9	8.4	10.7	10.6	8.0	9.4	9.7	9.3
SUM		501.5	461.6	467.2	431.2	476.0	467.9	502.5	592.2	480.1
PEAK(CUMEC)		2189*	2557	3204	2400	2567	2560	3450	3926	2670

YEAR	MON	OBS. INFL. (MM)	CASE-1	CASE-2	CASE-3	CASE-4	CASE-5	CASE-6	CASE-7	CASE-8
1985	6	5.5	2.3	2.2	3.5	1.7	2.1	2.3	2.5	2.4
1985	7	37.5	53.3	62.7	34.4	52.4	56.9	40.4	60.6	55.2
1985	8	339.5	281.1	282.2	251.3	277.1	379.6	308.7	363.6	297.4
1985	9	217.1	167.9	161.1	166.0	153.1	180.0	161.3	193.6	167.6
1985	10	121.8	102.7	90.3	108.4	102.3	86.9	99.5	115.0	101.6
SUM		721.4	607.3	598.5	563.6	586.6	705.5	612.2	736.1	624.2
PEAK(CUMEC)		1303*	2052	2668	1006	2043	2063	2194	2753	2152

*PEAKS FOR INFLOW HYDROGRAPHS ARE INDIRECTLY COMPUTED USING DAILY RESERVOIR DATA runs. The reduction in the simulated discharge volume and peak is attributed to the higher soil conductivities which allow more water to infiltrate leaving less water for overland flow. However, river aquifer interaction would also play an important role in generating the flow. If the water table position is higher than the water level in stream, the ground water contributes to the stream as base flow resulting an increase in the flow. On other hand, the stream contributes to the ground water in case if the water table position is lower than the water level in stream reducing the flow rates. The results of these runs demonstrate the sensitivity of the results to the soil parameters. For simulating the response of the sub-surface zone as well as overland flows properly, a correct tuning of these parameters is must. Note that correct modelling of sub-surface response of a basin is essential for SHE type models which integrate surface and sub surface responses.

iii) The saturated zone conductivity was doubled for all grid squares. In this case, the simulated discharge volume and peak were higher for the year 1984 and lower for the year 1985, with respect to the reference runs. The reduction or increase in the volume of the discharge and peak were only 4 to 5% of the reference runs indicating the basin response is not much sensitive to this parameter.

iv) In order to examine the effect of soil crack modelling of the simulation, one run was taken without the soil crack modelling i.e. considering no cracks developed in the soil prior to the monsoon period. After comparing the results of the run with the reference run, it was observed that the volumes of discharge and peaks were higher than the reference run. The reason for this increase is due to the more water available at the surfae for overland flow and less is observed by soil without cracks. However, the increase in peaks are not significant suggesting that the peaks are not much sensitive to the soil cracks modelling specially when they occurred during the middle of monsoon period. The peaks of the early period of the monsoon would be somewhat effected due to soil cracks modelling.

v) A sensitivity run for Barna basin was taken where in the mean areal rainfall was used as input for all grid squares instead of the distributed rainfall. A comparison of the results reveals that the volume of the discharge as well as peaks were higher than the reference run. The increase in volume of the discharge is due to the increase in average intensity of rainfall over the basin and decrease in losses through evaporation and infiltration. The peaks were higher because during the period of peak flows, the entire catchment area contributed to the discharge at the outlet. In case of distributed rainfall, the portion of the catchment contributing to the peak would depend upon the spatial rainfall pattern. These results indicates the importance of the proper representation of spatial distribution of rainfall for which there should be an adequate network of raingauge stations uniformly distributed over the whole catchment. In order to achieve the correct temporal distribution of rainfall, it is also necessary to have enough self recording stations in the network of the raingauges.

vi) One run was taken using the input rainfall which was 10% higher than the mean areal rainfall. The objective of this run was to examine as to how errors in rainfall measurement might affect the simulated basin response. When the volume of the discharge and peaks were compared with reference run a sharp increase was observed. It reflects that even a small error in measurement of rainfall can produce a significant change in the simulated output. Furthermore, the calibration of the parameters using erroreous rainfall data may lead to erroneous parameter values.

vii) In order to demonstrate the effect of land use changes on basin response which is a vary useful capability of the physically based models, one run was taken after changing the land use at all squares in the dense forest area to agriculture. A comparison of the results with the reference run indicates higher volume as well as peaks. This behaviour was observed because the depth of root zone and leaf area index for crops is less than the same for the tree. It causes the reduction in water loss through transpiration during dry season giving relatively more moist soils which support a greater runoff when the monsoon arrives.

8.0 CONCLUSIONS

SHE Model was satisfactorily applied to simulate the response of Barna sub basin. Keeping in views the computational limitation, the model was set up on 2km x 2km grid scale. Since large amount of data of varying nature were needed for the SHE Model application, a systematic data collection programme was launched and various State and Central Government organisations concerned with Barna sub-basin were contacted. As far as possible efforts were made to collect most of the parameter values, required for SHE Model application, from the visits made to focus basin and associated offices located in Madhya Pradesh prior to the study. However, the informa-collected from all possible sources were not adequate for the SHE Model application. Inspite of data limitations, lack of information about the parameter values, computational constraints and assumptions involved in model structure, the model with simplified structure provides encouraging simulation results. Based on the this application study the following conclusions can be made:

i) SHE model application has been successful for simulating the response of Barna Basin within the constraints of data availability and inconsistencies associated with the data. The simulation response of the basin shows usually good match with the inflow volume and peaks for both calibration and validation periods even though the inflows to the reservoir are computed using observed reservoir levels and reservoir operation data.

ii) Model set up on smaller grid scale provides better simulation results. However, depending on the speed and memory of the computer, considerable computer time is involved in taking up simulation runs which may not be always practically feasible. Thus, the computational constraints imposed by the type of computer available necessitates the set up of the model on some coarse grid scale which may be decided after making appropriate sensitivity runs.

iii) The simulation results and accuracy are somewhat affected by the grid scale used in setting up the model. The ratio of the number of channel links to grid squares seems to be one of the imortant parameters which require further investigations.

iv) Available rainfall data should be adequate to represent the spatial and temporal distribution within the basin. Unfortunately, only one self recording raingauge data was available at the time of study. Therefore, the daily rainfall data for three other stations namely Bineka, Bareli and Sultanpur were distributed into hourly rainfall values based on that station. It implies that the temporal distribution of rainfall at different raingauge stations has not been properly represented. Further more, the locations of the four raingauge stations are such that they are not enough to provide the proper spatial distribution of rainfall data for the basin of this size. The errors in simulation results and in the parameter values may also be attributed to the poor network of raingauges which was unable to represent the proper spatial and temporal distribution of rainfall within the basin.

v) Major portion of the basin has black cotton soil which exhibits cracking and swelling effects during early part of the monsoon when prolonged hot weather precedes the rainy season. It is very important to model this effect properly in order to provide better simulation in early part of the monsoon. Although indirect provisions have been made in SHE code to simulate this effect, but it is not physically described due to lack of the proper understanding of the cracking and swelling effects exhibited by black cotton soils.

vi) Sensitive parameters of the model include the physical properties of different types of soils and spatial representation of soil depths. Efforts should be made to evaluate those parameters more accurately. An extensive and systematic field investigations are needed to provide the physical properties of different types of soil such as saturated hydraulic conductivity in unsaturated zone, field capacity, wilting point, tension at field capacity, saturated soil moisture content·residual soil moisture content, spatial distribution of soil depths and retention curves ($\theta-\psi$ curves) etc. In absence of the physical properties of soils in detail the same were derived from indirect sources such as research papers, reports etc. for adjacent basins and also from discussions held with the concerned officers of M.P. Government during the field visits. An accurate parameter values for the physical properties of soils alongwith the correct spatial distribution of soil depths would definitely improve the calibrated parameter values and simulation results.

vii) Strickler roughness coefficient is found to be one of the most sensitive parameters during the sensitivity analysis Due to lack of sufficient information about the spatial distribution of Strickler roughness coefficient, a constant value was assumed throughout the basin. Extensive field investigations are needed to determine spatial distribution of Strickler roughness co-efficients for overland flow plane as well as for different reaches of the channel beginning from the first order stream. In addition to this channel cross sections and L-sections for some important channel reaches should also be collected during the planned field investigations.

viii) A constant value of saturated hydraulic conductivity for saturated zone was assumed in absence of the aquifer characteristics in space. This, parameter is somewhat less sensitive than the physical properties of soils and roughness characteristics. The simulation results would definitely improve if the spatially distributed parameter values are used in the model.

ix) Choice of an accurate initial condition is a important consideration for the entire simulation excersie. The initial conditions was specified in the form of phreatic surface level at the time of taking simulation runs. The data base in this regard must be improved. Alternatively, the initial conditions may be decided for a given monsoon period by running the model from the previous monsoon period.

x) There is no consideration of the reservoir and other utilisations in the present codes of SHE model. A separate module is needed to enable the direct simulation of the reservoir outflows and flood hydrographs at the gauging site down stream of the reservoir.

xi) In order to have the better simulation results using SHE model, the required data base must be improved to the extend possible before taking up the application studies. The proper net work of self recording raingauges may be designed and installed within the catchments in order to provide a better representation of spatial and temporal distribution of rainfall input for the focus basins. Further-more, the focus basin must be well represented by adequate no. of meteorological observatories so that an accurate estimate for potential evapotranspiration values may be obtained.

xii) Physical properties of soils and soil depths are found to be most sensitive parameters of the model during the sensitivity analysis. In absence of the requisite information about the soil properties and soil depths, an extensive field investigation followed by laboratory experiments must be planned before going for simulation runs.

xiii) In the present code of SHE Model, there are some processes which has been conceptually relpresented in the absence of the proper understanding of their physics. Efforts should be made to understand the physics of these component processes and modify accordingly in the SHE code.

xiv) As such no direct provision has been made in the present code of SHE model to simulate the effect of water bodies if present in the basin. It is, therefore, become essential to incorporate a separate module in SHE code to model the effect of water bodies on different components of hydrologic cycle.

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