Physically Based Distributed Hydrological Modelling

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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. 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, urbanization, 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 as well as for watershed management 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 practising 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 equations), logical statements, boundary conditions and initial conditions, expressing relationships between inputs, variables and parameters. Hydrological models may be broadly classified in two groups:

(i) Deterministic Hydrological Models
(ii) Stochastic Hydrological Models.

A deterministic hydrological model is one in which the proceses are modelled based on definite physical laws and no uncertainties 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 empirical, 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 models are formulated on the basis of a relatively small number of components, each of which is a simplified representation of the 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 processes 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.

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 focused on the physically based distributed catchment models since these have the potential to overcome many of the deficiencies associated with simpler approaches. On the other hand, 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) jointly developed 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.

2. O FULLY DISTRIBUTED, PHYSICALLY BASED MODELS

These are based on our understanding of the physics of the hydrological processes which control catchment response and use physically-based equations to describe these processes. From their physical basis such models can simulate the complete runoff regime, providing multiple outputs (e.g. river discharge, phreatic surface level and evaporation loss) while black box models can offer only one output. Also, almost by definition, physically-based models are spatially distributed since the equations from which they are formed generally involve one or more space coordinates. They can therefore simulate the spatial variation in hydrological conditions within a catchment as well as simple outflows and bulk storage volumes. On the other hand, such models make huge demands in terms of computational time and data requirement and are costly to develop and operate.

Unlike lumped conceptual models, physically-based distributed models do not consider the transfer of water in a catchment to take place between a few defined storages. Instead the transfers of mass, momentum and energy are calculated directly from the governing partial differential equations, for example the St. Venant equations for surface flow, the Richards' equation for unsaturated zone flow and the Boussinesq equations for groundwater flow. These cannot be solved analytically forcases of practical interest and solutions must instead be obtained using approximate numerical methods, an approach which has become feasible only with the introduction of powerful computers.

Physically based distributed models treating single components of the hydrological cycle have been developed and applied extensively over the last two decades. Almost all groundwater models, for instance, conform to this type. However, physically based distributed catchment models, integrating submodels of the major components of the hydrological cycle within one model, have progressed less rapidly. This is largely because of the heavy computer and data requirements of such models, although there are also numerical difficulties, such as mass balance errors, to be overcome in modelling the transfer of data between the separate submodels. Nevetherless, several physically based distributed models have been successfully developed and treated during the past decade, although not applied operationally on a routine basis for practical projects. Prominent among these is the SHE modelling system.

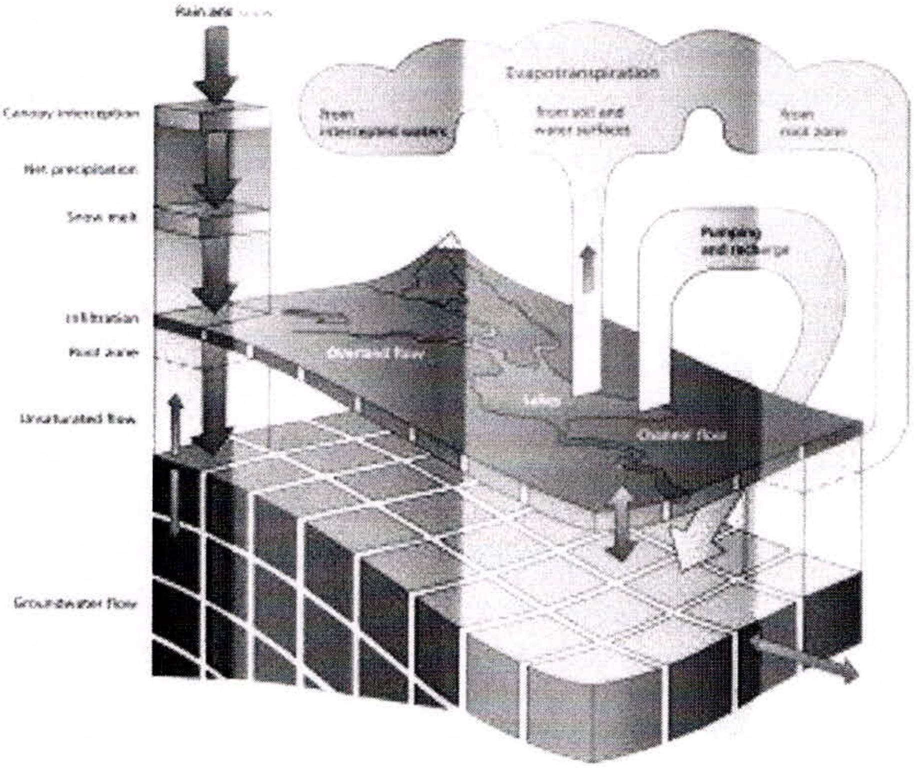
Other examples of models categorised as being physically based and distributed include the IHDM (Rogers et al., 1985), ANSWERS (Beasley et al., 1982) and SWAM (DeCoursey, 1982). In addition there are a number of models that, in the Hortonian tradition, treat only interacting infiltration and surface flow processes ignoring subsurface conditions.

Some models which are not quite fully distributed and physically based, but contain some degree of either lumping or conceptualization have been developed and successfully applied for practical purposes. One example is the SUSA model (Refsgaard and Hansen, 1982), which has been designed to anlayse the effects on the hydrological regime of groundwater exploitation forwater supply and irrigation purposes. Another example is the WATBAL model (DHI, 1985), which has been designed specifically for the efficient use of distributed data for water balance calculations - particularly satellite data - in a model computationally less complex than SHE.

3.0 A PHYSICALLY BASED DISTRIBUTED HYDROLOGICAL MODEL - SHE MODEL

3. 1 The 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.



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

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

The SHE model software has been transferred to the National Institute of Hydrology, Roorkee under a project financed by Agreement ALA 86/19 between the Commission of European Communities and the Government of India. Under the project, six NIH scientists have been trained in the theoretical and practical aspects of the SHE at Danish Hydraulic Institute, Denmark. The SHE model has been applied in close interaction with the Consultants to eight river basins of India, at NIH. The following section deals with one of such applications, viz. the application of SHE model to Ganjal basin of river Narmada.

3.2 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 hydrometeorological 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, coefficient of discharge for weir 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

Porosities or specific yields, saturated hydraulic conductivities.

ii) Input data

Impermeable bed elevations, 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

3.3 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 Organizational data
ii) Catchment Organizational 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 organization 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.

3.4 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.

3.5 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. Almost for any kind of hydrological problems, SHE model will 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, hydrometeorlogical 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 hydrometeorlogical records are sufficient to calibrate SHE model whereas for the conventional rainfall-runoff models this record length 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

iv) **Ground** water contamination
    - Industrial and municipal waste disposal
    - Agricultural chemicals
    - Erosion/sediment transfer

v) **Flood** Prediction

4.0 A CASE STUDY

An application study of the SHE Model to Ganjal Sub-basin of River Narmada was carried out and based on this study a technical report CS-28 has been prepared. This report discusses the results in comprehensive manner. However, the abstract of the study is discussed hereunder.

4.1 General Description of Ganjal Basin

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

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

4.2 Data Availability And Processing

The Ganjal basin is covered by the Survey of India Toposheets 55F and 55G in the scale 1:250,000 and 55F/7, 55F/8, 55F/11, 55F/12, 55G/5 and 55G/9 in the scale 1:50,000. Using the toposheets in the scale 1:50,000 the boundary of the catchment, the river system and contours were digitized. The digitized information was used to set up computational grid points, river network and topographic elevations.

Rainfall data of four ordinary raingauge stations namely Chicholi, Chhidgaon, Seoni and Makrai has been used. Daily rainfall data of the above mentioned raingauge stations has been converted in hourly values using the hourly rainfall data of Betul self recording raingauge. The Chicholi, Chhidgaon, Seoni and Makrai, raingauges represent 51%, 17.7%, 23.7% and 7.6% area of the basin respectively.

Discharge measurements for Ganjal basin are carried out by Central Water Commission at Chhidgaon. The flow velocity is measured by current meter. For Chhidgaon gauging site, hourly stage observations and daily discharge measurements were available for the monsoon months. The cross sections of the river at the gauging site was also available for the period 1977 to 1987. The rating curves for the gauging site over the period 1977 to 1987 were also available. However, these rating curves did not cover the range of stages observed in either of the years. To estimate the discharge values for the given hourly stages beyond the range of the rating curves; Manning's roughness coefficient was calculated for some of the high measured stage-discharge values, and average Manning's roughness coefficient was used to compute the discharges beyond range of rating curves.

Soil and landuse maps in the scale 1:250,000 were obtained from the Narmada Valley Development Authority (NVDA). These maps were digitized in order to specify soil type and landuse for each of the grids. Three types of soils viz. medium black, shallow black and laterite and four types of landuse pattern, viz. agriculture, dense forest, open forest and waste land were digitized. These landuses were further subdivided in low land (<400 m) semihilly (400m-550 m) and hilly (>550 m above msl). The hydraulic properties of the soils were not directly available and were derived from secondary sources. Soil depth and root zone depth was assumed to be dependent upon topographic elevation and landuse. Retention curve and leaf area index as adopted for Kolar Barna, and Sher basins in earlier simulation studies have been used, in the absence of any information. As the required information about soil moisture retention curve conductivity and other properties was not available, about all the three categories of soils, hence, only one type of soil was taken into consideration for simulation. The ground water levels are observed by the Madhya Pradesh State Ground Water Board at selected permanent observation wells usually two times a year. Nine groundwater wells lie within or near the boundary of the basin. The information on well levels was used as a general guideline about setting the groundwater table before and after the monsoon season. Pan evaporation data for stations at Powerkheda, Betul, Jabalpur and Pendra Road was obtained. After the analysis of pan evaporation data, it was decided to use Jabalpur pan evaporation data for simulation. Observed pan evaporation data was converted into potential evaporation by multiplying with a pan coefficient of 0.70. However, sensitivity analysis for the pan evaporation data of all the four stations was carried out.

4.3 The SHE Set Up for Ganjal Basin

The computational grids were initially 500 m x 500 m in size. Since the computational requirements for a set up of this size of grids are enormous, set up for grids sizes of 1 km x 1 km, 2 km x 2 km and 4 km x 4 km were also made.

In the model, rivers can be setup only along the grid boundaries, hence their course was approximated by straight lines. The river network representations for grid sizes of 1 km x 1km, 2km x 2km and 4km x 4km were prepared. The basin area was represented in the form of grids by raingauge stations, soil type and landuse, under various grids of the basin. The present simulation study was carried out for grid size of 2 km x 2 km.

In order to set up land use, soil depth and initial position of groundwater table, SHE overlay maker service programme was used in which different codes were assigned to the grids and the corresponding parameters were specified. As the unsaturated zone calculations require large CPU time, these calculations were carried out for representative grids. A classification scheme was followed to group the grids whose response was likely to be same based upon landuse, soil and rainfall station representing the grid. Then the computations were made for one grid in each group. In this study, unsaturated zone computations were carried out for 14 grids. The SHE array formatting routines were used to prepare the model setup according to the required format by various model components.

4.4 Calibration of SHE for Ganjal Basin

Data for the period March 1982 to February 1984 was used for calibration and March 1985 to

December 1987 for validation. The model was calibrated by comparing and analysing the simulated discharge hydrographs, monthly runoff volumes, monsoon volumes, monsoon peaks, baseflow and phreatic surface levels with the corresponding observed values.

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 soil cracks in soil, and surface detention storage. It may be stated that as SHE is a physically based model, theoretically, it should not require any calibration for the parameter values. However, in practice, variation in parameters is required because:-

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

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

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

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

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

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

In the final run, good fits were obtained for monthly and monsoon seasonal volumes and peak values. Hydrological regime of the catchment was reasonably well represented; though, representation of groundwater regime of the catchment had some scope for improvement.

4.5 Validation of the Model

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

In the validation run, the model set up and parameters were kept the same as during the calibration runs. The initial conditions were also kept the same as in the calibration runs and a continuous run for the period March 1982 to December 1987 was taken. The results show that there is some under simulation of discharge for the years 1985 and 1986, where as there is a little over simulation for the year 1987. The same trend is observed in case of peak discharges. The general trend of groundwater response is represented in similar way as that for calibration period, and it has a scope for improvement. The above referred results can be further improved based on correct input rainfall data and catchment characteristics parameters. At the same time it is important that the observed data including hourly stage/discharge values which are used for comparison of the results are reliable.

4.6 Sensitivity Analysis

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

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

The sensitivity analysis was conducted considering one typical grid of the catchment. The grid was taken to be under dense forest and represented by Makrai raingauge station. Thus, by performing the sensitivity analysis one on grid the consumption of CPU time was immensely reduced. The following sensitivity runs were taken using the record for the period March 1983 to Feb.1985.

a) Using calibration parameters (Reference run).
b) Using Betul pan evaporation data.
c) Using Powerkheda pan evaporation data.
d) Using Pendra Road evaporation data.
e) Reducing the exponent appearing in Averjanou's formula (for calculation of unsaturated conductivity) from 14 to 10.
f) Reducing water content at wilting point and residual water content from 0.21 and 0.21 to 0.12 and 0.12.
g) Increasing saturated conductivity of unsaturated zone from 0.1 to 0.5.

The results of the above mentioned runs are concluded in the following section.

4.7 Conclusions

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

a) The SHE model has been successfully used for modelling entire land phase of hydrologic cycle for Ganjal basin with a reasonable accuracy, within the constraints of data availability. The simulation study of the basin well represents the hydrological regime the basin, except the groundwater response which has adequate scope for improvement.

b) The values of soil parameters, which play a dominant part in the simulation in their absence have been derived from indirect sources for adjacent basins and available literature. Further, the spatial distribution of soil depth was also unknown. These were assumed based on the information collected during field visits. A accurate parameter values for the physical properties of soil alongwith the correct spatial distribution of soil depths can improve the simulation results.

c) The vegetation parameters have also been based on review of literature and general experience. The simulation results can be improved by input of accurate values of these parameters.

d) As sufficient information about spatially distributed parameters such as Strickler roughness coefficient for overland and channel flow and conductivity, etc. of unsaturated and saturated zones was not available. Such parameters were assumed uniform all over the basin. The simulation results can be refined by input of spatially distributed accurate parameter values.

e) The rainfall data does not provide the desired level of representation in the study. More than half of the basin area is represented by Chicholi raingauge, which itself lies in the south east part of the basin. Out of the considered four raingauge stations, two lie outside the basin. Further, the hourly rainfall data of Betul self recording raingauge has been used for distributing the daily data of the four raingauge stations representing the basin. As the Betul self recording raingauge lies far away from the basin, spatial and temporal representation of rainfall was not upto the desired level.

f) The computation requirement are dependent on the grid size used for simulation. In this study the model was set up on 2km x 2km grid size. Though the physical processes are accurately represented by smaller grid size.

g) It has been observed that potential evaporation data is not a much sensitive input parameter in simulation of the Ganjal basin.

h) The processes of soil evaporation, transpiration and canopy evaporation can be well simulated by the SHE model.

i) The well calibrated SHE model can be used to model the land phase of hydrologic cycle including the effect of land use changes on the hydrologic regime of the basin. However, extensive data and computational requirements of the model are its major limitations. Hence, the use of SHE is not warranted for dealing with routine hydrological problems.

5.0 CONCLUDING REMARK

Deterministic, distributed, physically based model structure provides a sophisticated hydrological modelling approach in simulating the land use change impact, ungauged basins, spatial variability in catchment input and ouputs, groundwater and soil moisture conditions, and the water flows controlling the movement of pollutants and sediments. However, for obtaining a worthwhile realistic results good quality data and information of various parameters both in space and time are necessary. Any uncertainty in the spatial and temporal distribution of the precipitation and runoff time series and in the values and distributions of other hydrological parameters would significantly affect the results. The physically based distributed model like SHE has very good potential for solving the hydrological problems particularly for Himalayan Region provided a good data base is available for developing a decision support system. At present as such the hydrological data base is not available for the Himalayan Region. Such data base may be created through the NRDMS programme launched by the Dept. of Science and Technology for promoting the development of spatial data management technologies for management of natural resources. This will enable the application of physically based hydrological modelling system for simulating the runoff and sediment characteristics of the Himalayan Rivers.

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