NIH_Basin – A WINDOWS Based Model for Water Resources Assessment in a River Basin

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ABSTRACT

A detailed spatially distributed model has been developed at NIH to assess various components of hydrological cycle in a river basin. The model incorporates spatial variation of land-use, soil type, rainfall, evapo-transpiration, physiographic characteristics, cropping pattern, irrigation development, groundwater conditions, river network and hydraulic structures in a river basin. GIS is employed to link the spatial data with the simulation model and to project model results in map form. The model is under continuous development. In the present report, an effort has been made to make some modifications in the model methodology and develop a WINDOWS interface (named as ***NIH_Basin*** – **NIH_Basin-Simulation**) of the model for easy application by the user groups.

For approximating the EAC relationships for a reservoir, the approach developed by J. Mohammadzadeh-Habili et. al (2009) has been adopted. The method has been programmed and linked to river basin model for computation of EAC table for a reservoir. This method avoids the necessity of obtaining EAC tables for various reservoirs in the river basin. The basin model has been modified to include rule curve based operation for the storage reservoirs so that control on basin water resources utilization can be analyzed and water management issues can be addressed. The option of hydropower simulation of a reservoir has also been added. An important modification of the current study is the simpler representation of GW system for long-term simulation. The revised model can now work in two modes: a) monthly mode (in which the simulation is carried out at daily time step for a month and then the spatial recharge and discharge pattern are externally used to find the revised water table in the basin with groundwater simulation model, say Visual MODFLOW, and the revised groundwater table is used for the analysis in subsequent month), and b) continuous mode (in which the simulation is carried out at daily time step for the complete period, say for 30 years of record, for which hydro-meteorological data are available). In the second case, a simplified methodology to represent GW conditions has been adopted. For each sub-basin, average groundwater elevation is computed from data of a large number of observation wells. A procedure, defined by DHI, Denmark in DSS under HP-II has been adopted for computing average GW elevation in a sub-basin from irregular groundwater depth observations in different wells. A FORTRAN program has been developed for the purpose and added in the WINDOWS interface.

In addition, a number of modifications have been adopted some of which include: increase in number of landuse classes from 6 to 61 and increase in number of dimensions of other variables for model application to a large river basin, separate consideration of industrial demands, inclusion of date of commissioning of projects in long-term simulation so that their effects are considered only after their occurrence, consideration of variable GW development, variable human and cattle population etc. In WINDOWS interface of the model, various data input forms have been developed for easy preparation of data files by the user groups. Four important modules of the software include: a) Database preparation, b) GIS analysis, c) Model execution, and d) Results. Now, it is planned to apply the modified model to a large basin and develop the User’s Manual for effective technology transfer to large group of users.

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Chapter - 1

Introduction

1.1 General

India is bestowed with rich water resources but more than 80% of the annual rainfall over this country falls in the four monsoon months from June to September. Because of the high time and space variability of rainfall and uncertain nature of monsoon, reservoirs form one of the most important components of water resources development project in India. More than 4500 major and medium dams have already been constructed all over the country to tap the available water resources so that the water can be utilized in accordance with the requirements of mankind.

Any water-related activity, that takes place in one part of a river basin, may have consequences in the other part. Effective management of water and related environment in a river basin requires proper assessment of spatial and temporal availability of surface and ground water resources and water demands for various purposes and subsequently, integrated and co-ordinated planning and utilization of available water within the basin so that various water demands in the basin can be satisfied to the maximum extent and sustainability of surface and groundwater resources can be maintained. In the present approach of water availability assessment at river basin scale, it is difficult to account for the effect of various developmental activities and climate sensitive parameters on the water resources scenario in a river basin. Groundwater is not given enough attention in the assessment of total water resources in the basin and the water requirement for different purposes is not precisely estimated. Discharge is considered as the basic unit for water availability estimations which may be affected by a number of basin parameters and developmental activities.

With this need in view, a detailed spatially distributed model has been developed at NIH [Goel et al. (2008)] to assess various components of the hydrological cycle in a river basin. In this model, focus is given to incorporate spatial variation of land-use, soil type, rainfall, evapo-transpiration, physiographic characteristics, cropping pattern, irrigation development, groundwater conditions, river network and hydraulic structures in a river basin. GIS is employed to link the spatial data with the simulation model and to project the model results in map form for easy visualization. The basin is divided into grids of uniform size (~ 1 km) and model computes various components of hydrologic cycle such as actual evapo-transpiration, overland flow, groundwater recharge, and residual soil water content at monthly time step for each grid. The model brings out total water availability in the basin; water consumed by different uses; and water storage in different hydraulic structures, in soil water zone, and in groundwater aquifer in a river basin. By taking repeated runs of the model for longer time periods, sustainability of various water resources management plans can be examined. The model can be used to: a) visualize impact of land use or cropping pattern change, climate change (in terms of rainfall, temperature, humidity etc.), and population and industrial growth on the basin water resources, and b) analyze various management options like inter-basin transfer of water, development of new water resources projects etc.

1.2 Scope of Present Study

In this study, efforts have been made to make some modifications in the model methodology and develop a WINDOWS interface (named as ***NIH_Basin – NIH_Basin-Simulation***) of the model for easy application by the user groups. The model is in continuous phase of development. Some of the present limitations of the model which have been addressed include: i) specification of EAC tables or corresponding relationships for various storage structures, ii) rule-curve based operation of reservoirs so that different operation policies of the system can be simulated, iii) option of hydropower simulation in the basin, and iv) simplified representation of groundwater computation at the sub-basin scale.

For approximating the EAC relationships for a reservoir, the approach developed by J. Mohammadzadeh-Habili et. al (2009) has been adopted, avoiding the necessity of specifying EAC tables for various reservoirs in the river basin. The method has been programmed within the FORTRAN code of the model. It is also possible to specify the known EAC table for some projects. Rule-curve based approach has been added in the FORTRAN code for simulating the reservoir operation as per specified operation policy. Earlier, reservoir operation was simulated only with standard linear operation policy (SLOP) only. The option of hydropower simulation of a reservoir has also been added and eight different methods of supply of water through the power plants have been considered. Tail water elevation is also considered as a function of discharge.

Model is planned to work in two modes: a) monthly mode (in which the simulation is carried out at daily time step for a month and then the spatial recharge and discharge pattern are externally used to find the revised water table in the basin with groundwater simulation model, say Visual MODFLOW, and the revised groundwater table is used for the subsequent month), and b) continuous mode (in which the simulation is carried out at daily time step for the complete period, say for 30 years of record, for which hydro-meteorological data are available). In the second mode, grid-wise pumping and recharge estimations are accumulated over each sub-basin and then divided by the S_y of the sub-basin to convert water withdrawal/ recharge to corresponding change in groundwater level which can be applied to initial groundwater surface to find the revised surface in the sub-basin, thus avoiding the necessity of detailed groundwater simulation. For each sub-basin, average groundwater depth is computed from data of a large number of observation wells (a procedure, defined by DHI, Denmark has been adopted for converting irregular observations in different wells in a sub-basin) has been programmed and is being added as a module in the software.

In WINDOWS interface of the model, various data input forms are being developed. Four important modules of the software include: a) Database preparation, b) GIS analysis, c) Model execution, and d) Analysis of results. In addition, a number of modifications are being made as described below:

a) Number of landuse classes has been increased from 6 to 61 for more detailed representation.
b) Option has been included to consider industrial demands separately (earlier, it was merged with domestic demands) and the same has been linked to city attributes.
c) Date of commissioning of hydraulic structures has been included and in the long-term simulation, their effects are considered only after their commissioning.

d) Now, variable GW development is considered (which was taken constant previously) by specifying the parameters of a 2nd order equation.
e) Provision of observed EAC table specification for a hydraulic structure has been added.
f) Baseflow computation is now made depending on the actual GW storage in upstream basin above a gauging site.
g) Rather than considering constant population for human and cattle population, population growth is considered as per defined rate and for long-term simulation, revised population is estimated at the beginning of each year.
h) In the command area of hydraulic structures which are commissioned in intermediate stages during long-term simulation, option has been included for considering the revised cropping pattern while computing irrigation demands.

The present report describes the modifications made in the modeling methodology for more detailed simulation of the river basin while simplifying some other aspects. In the report, Chapter – 2 describes the previous modeling methodology of the river basin model and brief description of its application to Tapi river basin. The data requirements and description of computations under various modules are also described. Chapter – 3 describes the modifications made in the modeling methodology while chapter – 4 describes the WINDOWS interface that has been developed for the model and layout and detailed description of input data forms.

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Chapter - 2

Description of Basic River Basin Model Developed at NIH

2.1 Description of Model

The aim of developing the model was to link various components of water resources in a river basin (rainfall, evapo-transpiration, runoff, groundwater recharge, soil moisture, irrigation, domestic and industrial demands, reservoirs, diversion weirs, groundwater movement etc.), to incorporate sufficient details (spatial and temporal) for realistic representation of a basin, and to suit to the data availability constraints in our country for assessing the water resources availability and demands. Model operates at daily time step to bring out in quantitative terms the hydrological variables (rainfall, evapo-transpiration, groundwater contribution, runoff, soil moisture status, deep percolation) and water demands and supply at sub-basin scale, working tables of various hydraulic structures, and generated runoff in various streams and rivers.

2.1.1 Model Methodology

The model adopts the simulation approach for assessing the spatial and temporal availability and demands of water in the river basin. The model incorporates computation for runoff generation, soil moisture balance, domestic and industrial demands, irrigation demands, flow movement through drainage network, reservoir operation, and groundwater recharge and discharge. For simulating groundwater dynamics in the basin, model generates monthly pumping and withdrawal outputs that can be directly imported in the Visual MODFLO groundwater modelling system. Before taking up various components of water resources in detail, salient features of the model are presented below:

- The model takes precipitation as the basic input in the basin. It is possible to import/export water from outside the basin in a reservoir or a river segment. It is also possible to move water directly from any stream/ reservoir to any other stream/reservoir within the basin through a link.
- The basin is assumed to be divided into grid cells of uniform size (say, 1 km) and hydrological analysis is carried out for each cell. Remote sensing data (say IRS or NOAA satellite) are used to spatially characterize the land use/land cover, cropping pattern, cities and hydraulic structures in the river basin.
- GIS environment is used for spatially distributed modeling. The model is linked to the ILWIS (Integrated Land and Water Information System) GIS System, developed by the ITC, The Netherlands. This GIS is in public domain. A special module of the GIS (DEM Hydro Processing) is used to generate the slope, flow direction, drainage network, and contributing sub-basins at various gauging locations in the basin from the digital elevation map of the basin. Digital elevation map can either be obtained from the interpolation of the digitized contours and spot levels from the SOI toposheets or from the geo-referenced SRTM data.

- The model is developed for daily time step. Though a finer time step (hourly) can simulate the hydrological conditions in much greater detail, daily time step is considered adequate for river basin planning analysis that needs to be carried out for longer span of time (of the order of years) to arrive at some meaningful conclusion for policy evaluation. This time step also conforms to the frequency of data collection at various hydro-meteorological and hydrological stations in India. Weekly/monthly time steps are considered too coarse for soil moisture accounting, groundwater recharge, reservoir operation, and flow in river network. The model runs at daily time step for one full month and estimates various hydrological components in different sub-basins during the month. The soil moisture status and reservoir contents at the end of the month are saved in a separate file using which analysis for the subsequent month can be carried out.

- Modified SCS curve number method is used to estimate the overland flow at each grid which is routed through intermediate grids up to the river depending on the flow direction. Overland flow generation at a grid depends on the land use, crop type (if any), soil type, slope, rainfall amount, and the antecedent moisture condition (cumulative rainfall of past five days). Curve number estimated at a grid keeps on modifying daily depending on the moisture conditions.

- Soil moisture accounting is carried out for each grid. Balance rainfall (after deducting overland flow), overland flow from upstream grids, irrigation application, and groundwater contribution (in case of water logging) are considered as input to a grid. Outputs include evapo-transpiration and deep percolation. Using the crop evapo-transpiration demands at each agricultural grid and soil moisture status, irrigation demands are computed after accounting for surface water and groundwater efficiencies.

- Various demands considered by the model include domestic and industrial demands, irrigation demands, evapo-transpiration demands for different land uses, minimum releases required from reservoirs, and artificial water transfer from any reservoir/stream.

- Domestic demands are computed using district-wise statistical records of rural and urban population and the cattle population. The population at each grid is worked out on pro-rata basin after accounting for the area of a district within the basin, the area of cities (for urban population), and the area of barren/agricultural land (for rural and cattle population). Per capita water demand for urban, rural, and cattle population is used to find domestic demand which is met from groundwater or a reservoir. Industrial demand (urban areas) is taken equal to the domestic demand.

- The model is linked to a groundwater simulation model (Visual MODFLO) for computing revised groundwater conditions for subsequent month corresponding to the estimated spatial pumping/recharge pattern in the month. Using the results of groundwater model, groundwater surface is generated in GIS which is used for the analysis of subsequent month. Groundwater conditions are considered constant during a month. Depth to groundwater at each grid is used to compute base flow contribution at various gauging sites in the basin, available groundwater for satisfying various demands, maximum recharge that can occur, and groundwater contribution to evapo-transpiration.

- Operation of different reservoirs/weirs is simulated using the standard linear operation policy. After accounting for the evaporation losses (based on water spread area), first priority is given to domestic and industrial demands, second priority to downstream minimum flow demands, and third priority to the irrigation demands. Any export from a reservoir is accorded last priority.
- Calibration and validation of the model includes matching of monthly runoff volume at different gauging sites in the basin and the comparison of observed and simulated groundwater levels at different times in the observation wells. Parameters for different sub-basins for different land uses are calibrated to adjust the curve numbers so as to match the observed and simulated river flows. Similarly, a parameter is calibrated to estimate groundwater contribution to river flows in different months.
- Output of the model includes spatial and tabular results. Spatial maps include: monthly accumulation of groundwater pumping and recharge in the basin (for input to VMOD) and soil moisture status at the end of the month. Tabular output includes: a) daily and monthly flows in different rivers, b) daily and monthly working tables for all the reservoirs and diversion structures, and c) for each sub-basin - hydrological components for different land uses for the month, various demands and their supply from different sources, and cumulative results for different reservoirs in the sub-basin.
- The model can be used to: a) visualize the effect of land use change, cropping pattern change, climate change (in terms of rainfall and its distribution, temperature, humidity etc.), and population and industrial growth on the basin water resources, and b) analyze various management options like inter-basin transfer of water, development of new water resources projects etc.

2.2 Input Data Requirement of the Model

Various types of spatial, attribute, and dynamic data are integrated by the model to perform the water balance analysis of a given basin. Input data requirements of the model are given below.

a) Spatially distributed data

Spatially distributed information about the basin is obtained as geo-referenced maps either from remote sensing analysis (land use/land cover map and cropping pattern in the basin in Kharif, Rabi, and Hot-weather season) or from digitization of topographic maps and field survey records in GIS, or from topographic analysis. Different types of distributed information used by the model include:

- Land use map – six different land uses are specified (urban land/cities, rainfed agriculture, irrigated (SW or GW) agriculture, forest, barren land, and water body). This map can be obtained either from remote sensing analysis or from River Basin Authority (RBA).

- Crop map – different maps can be specified for different seasons (Kharif/Rabi/Hot-weather). These maps can be obtained either from the multi-temporal remote sensing analysis or from RBA.
- Soil map – can be obtained from the NBSSLUP and digitized in GIS or can be obtained from field survey.
- Thiessen polygon map of rainfall stations - obtained from the location of various rain gauge stations in the basin from GIS analysis.
- Thiessen polygon map of ET stations - obtained from the location of various climate stations in the basin using GIS analysis.
- District boundary map – can be obtained from the SOI toposheets.
- Cities map – can be obtained from the SOI toposheets. Different cities are given different numeric identity.
- Water bodies map – can be obtained from the remote sensing analysis. Each water body is assumed to be created by a hydraulic structure. Different water bodies are given different numeric identity.
- Sub-basin map for different gauge stations - can be obtained from the DEM Hydro processing module of ILWIS.
- Digital elevation map (DEM) – can be obtained by interpolation of contours and spot levels from SOI toposheets in GIS or from the SRTM data.
- Slope map – can be generated from the DEM in GIS.
- Flow direction map – can be generated from DEM Hydro processing module of ILWIS.
- Groundwater depth map – can be obtained by subtracting the groundwater surface (obtained by interpolating groundwater levels in different observation wells) from the DEM.
- River network map – can be obtained either by digitization from the SOI toposheets or can be generated from the DEM Hydro processing module of ILWIS.
- Irrigated command area map of different hydraulic structures - can be obtained either by trial and error by knowing location of hydraulic structures, their GCA/CCA and their downstream agricultural area or can be obtained from different project authorities under RBA and digitized in GIS.
- Aquifer characteristics map (storage coefficient and transmissivity) – can be obtained from the groundwater department.

Land use map and crop map is used to define the effective soil depth at a grid (taken as the root depth of crop/forest at that grid). For barren and urban land, it is taken to be 200 mm as evapo-transpiration generally takes place from upper 200 mm of the soil layer. The model keeps track of the root depth development of a crop depending on the type of crop and its growth stage in the simulation period. Water demand of a crop depends on the crop coefficient which varies with its growth. Soil map is used to specify the storage and transmission properties of different type of soils in the basin. Thiessen polygons of rainfall and climate stations account for the spatial variation of rainfall and potential ET in the basin. District boundary map is used to transform the statistical information (rural/urban/cattle population, irrigated area, crop acreage, groundwater development etc.) available from the Department of Economics and Statistics (DES) of a State to different grids in the basin under a particular district. Map of different cities is used to locate the urban population and industries in the basin and to link their supply with any hydraulic structure. Irrigation source map is used to decide the surface water use or groundwater pumping at a grid. For surface water irrigated areas, demands are accumulated to estimate irrigation demands from a reservoir. Elevation, slope and flow direction maps are used to estimate the overland flow generation and its movement in different grids in the basin. Groundwater depth map is used to compute base flow contribution at various gauging sites in the basin, maximum recharge that can occur, and groundwater contribution to soil moisture for satisfying evapo-transpiration demands.

River network map is used to accumulate the flow in different rivers, to compute the surface flow at various gauging stations, and to estimate the inflows at different hydraulic structures. These hydraulic structures are then operated with standard linear operation policy [Supply = Minimum of (water availability, demand); Spill = Maximum of (0, Initial storage + inflow – evaporation – demands – storage at FRL)]. Residual moisture at each grid at the end of a day is stored in a temporary file and is used as initial moisture map for the subsequent day. Aquifer characteristic map is used in the groundwater simulation model to estimate revised groundwater conditions corresponding to the pumping/recharge in the basin.

b) Attribute data

Various attribute information are attached to different types of crops, soils, hydraulic structures, river network, gauging sites etc. The attribute details required by the model are:

Crop attributes: Various crop details that are specified for each crop include: identification number, maximum root depth, time to reach maximum root depth, fraction of available water that is readily consumed by the crop without stress, water depth required for land preparation before planting the crop, time of land preparation, starting week of crop, total number of weeks for which crop remains in the field, depth of standing water requirement (if any), time of standing water requirement, bund height around the crop field, and the crop carryover.

Soil attributes: Various soil parameters that are used by the model include: identification number, soil class, specific gravity, porosity, field capacity, permanent wilting point, and averaged hydraulic conductivity between field capacity and saturation.

Domestic and Industrial (D&I) demand attributes: District-wise statistical and other details that are used by the model for estimating D&I demands include: human/cattle population, total district area and the area within the basin, forest area, water spread area, urban area, percentage of urban population, per capita demands of human (urban and rural) and cattle population, percentage of surface water supply and groundwater use, percentage of consumptive use, and percentage of used water that is drained into the surface water source/groundwater source.

City attributes: For each city, that is given a different identification number, various other attributes included: the district in which it is located and the hydraulic structure identity from which it receives water supply.

River network attributes: River network is divided into different segments. The segmentation depends on the break in continuity of a reach due to the presence of a hydraulic structure, a gauging station, or due to the joining of another river segment with the present segment. For each segment in the river network, attribute data includes the identification number, stream order (for each successive stream, it is one higher than the highest stream order of upstream segments), type of structure located at the downstream (0 – nothing, 1 – gauging site, 2 – diversion, 3 – storage), its node number, number of segments immediately upstream and their node numbers.

Hydraulic structure attributes: Each hydraulic structure in the basin is represented by a unique identification number. In addition, various other attributes that are specified for a hydraulic structure include: the ET station whose data are used for estimating evaporation from the reservoir, sub-basin in which it is located, diversion capacity of the structure (in case of a diversion structure, otherwise 0), live storage of the reservoir, initial storage at the beginning of simulation, surface water and groundwater use efficiency in its command areas, proposed profitable area, water spread area at FRL, and minimum flow requirement (cumec) for 12 months from the reservoir.

Gauging station attributes: Each gauging station in the basin is represented by a unique identification number. In addition, various other attributes that are specified for a gauging station include: the river segment on which it is located, bed level (m), number of sub-basins upstream of the gauging station and their identification numbers.

c) Dynamic data

Dynamic information that is used by the model include: daily rainfall at different raingauge stations, daily reference evapo-transpiration at different climatic stations, weekly water import/export (either from/to outside the basin or water transfer within the basin) for each river segment in the basin, weekly water import/export (either from/to outside the basin or water transfer within the basin) for each hydraulic structure in the basin.

In addition, observed monthly water flows at various gauging sites and groundwater levels in different observation wells in the basin are used by the model for calibration and validation purposes.

d) Model parameters

Model is calibrated by: a) comparing the observed and simulated monthly runoff volumes at different gauging sites in the basin, and b) comparing the observed and simulated groundwater levels at different times in the observation wells. One set of parameters (CNFAC) are specified for different land uses for each sub-basin. These parameters adjust the CN values so as to match the observed and simulated flows. However, if their modification (within a range) does not lead to a satisfactory match in the observed and simulated flow values, then another parameter (SBFAC - specified for each sub-basin) is adjusted to modify the sub-basin output. Another parameter (GWFAC) is specified for different months for each sub-basin. GWFAC accounts for the groundwater contribution to base flow at different gauging sites depending on the upstream groundwater storage.

2.3 Various Modules of the Model

Since a number of water related activities are involved in a river basin, these have been represented as separate modules in the model. These modules include: Overland flow generation module, D&I demand estimation module, soil water balance module, overland flow movement module, irrigation demand estimation module, reservoir operation module, and groundwater recharge/withdrawal module. The computations under these modules are briefly described below.

a) Overland flow generation module

The USDA Soil Conservation Service (SCS) has developed a widely used curve number method for estimating runoff. The effects of land use, soil types, and antecedent moisture conditions are embodied in it. Recently, the method has been revised to include the effect of slope also. The procedure was empirically developed from the studies of small agricultural watersheds. The procedure consists of selecting a storm and computing the direct runoff by the use of curves founded on field studies of the amount of measured runoff from numerous soil cover combinations. A runoff curve number, which is dependent on the type of cover and antecedent conditions, is extracted from the standard tables. According to the SCS method, the SCS runoff equation is

$$Q = \frac{(P - I_a)^2}{(P - I_a) + S} \qquad \ldots(2.1)$$

where Q is the runoff depth, P is rainfall depth, S is maximum potential retention depth after runoff begins, and I_a is the initial abstraction which represents all losses before runoff begins. I_a includes water retained in surface depressions, water intercepted by vegetation, evaporation, and infiltration. I_a is highly variable but it has been approximated by the following empirical formula:

$$I_a = 0.3 * S \qquad \ldots(2.2)$$

By eliminating I_a as an independent parameter, the combination of S and P produces a unique runoff amount given by the following equation:

$$Q = \frac{(P - 0.3S)^2}{P + 0.7S} \qquad \ldots(2.3)$$

where the parameter S is related to the soil and cover conditions through the curve number CN. CN has a wide range for different land uses over different soil types and S is related to CN by:

$$S = \frac{25400}{CN} - 254 \qquad \ldots(2.4)$$

Eq. 2.4 calculates S in depth units. Major factors that determine CN are the hydrologic soil group, land cover type and treatment, hydrologic condition, and the antecedent moisture condition. Based on the infiltration rate, all soils are classified into four hydrologic soil groups: A (High infiltration rate and low runoff potential with infiltration rate greater than 0.76 cm/h), B (moderate infiltration rate between 0.38 to 0.76 cm/h), C (slow infiltration rate between 0.13 to 0.38 cm/h), or D (very slow infiltration rate and high runoff potential with infiltration rate less than 0.13 cm/h). Treatment refers to the cover type modifier (such as contouring, terracing, crop rotation etc.) to describe the effect of cultivated agricultural land management on CN. Hydrologic condition indicates the effects of cover type and treatment (density of plants, residue cover etc.) on infiltration and runoff. A good hydrologic condition indicates that the soil has low runoff potential for the given soil group, cover type, and treatment. Antecedent moisture condition is an index of runoff potential for a storm event. For details on the SCS method, Maidment, D. R. (1992) can be referred.

In the study, the SCS method has been used to compute the daily runoff at a grid corresponding to the daily rainfall amount. The stepwise procedure adopted is described below:

a) The study area is divided into grids and for each grid, the land use, the soil type, the slope, the rainfall amount (based on the Thiessen polygon and amount of daily rainfall at that station), and the total rainfall in past five days are ascertained.

b) Based on the land use and the hydrological soil group, Curve Number (CN) is assigned to different grids for a day as specified in Table below.

Table - 1.1

Curve Number (CN) assigned for different land use and the hydrological soil group

Landuse	**Hydrologic Soil Group**			
	Group A	**Group B**	**Group C**	**Group D**
Urban land	72	80	86	92
Agriculture	60	68	76	84
Forest	28	44	60	76
Barren land	40	60	75	84

For rice crop in the agricultural area, CN value of 10 has been used. For water body, all of the rainfall is taken as input to the storage in the water body. The parameter CNFAC adjusts (increases or decreases) the CN values so as to match the observed and simulated flows at different gauging sites in the basin. Maximum possible values of CNs for various land uses and under different soil types have been limited to a specified maximum.

c) The CN value derived in step 'b' is then modified for slope. If the slope (SL) is in percentage, then the slope adjusted curve number CN_{sad} is calculated as per the following equation:

$$ICN = CN * e^{(0.00673*(100-CN))}$$

$$CN_{sad} = CN + (\frac{ICN - CN}{3}) * (1 - 2 * e^{(-13.86*SL)}) \qquad \ldots(2.5)$$

d) Slope adjusted curve number is then modified for antecedent moisture conditions (AMC). To account for the AMC, the rainfall depth in the past five days at the grid is accumulated. For the cropping season (Kharif – July, August, September, October; and Rabi – December, January, February, March), if 5-day rainfall lies in between 36 to 53 mm, then curve number derived in step 'c' represents normal AMC and is not modified. If rainfall is less than 36 mm, it is AMC1 condition and if it is more than 53 mm, then it is AMC3 condition. For these conditions, the revised curve number (RCN) is calculated as follows:

For AMC1, $$RCN = \frac{CN_{sad} - (2000 - 20 * CN_{sad})}{(100 - CN_{sad} + e^{(2.533-0.0636*(100-CN_{sad}))})} \qquad \ldots(2.6)$$

For AMC3, $$RCN = CN_{sad} * e^{(0.00673*(100-CN_{sad}))} \qquad \ldots(2.7)$$

For non-cropping season (April, May, June, and November), lower limit of 13 (in place of 36) and higher limit of 28 (in place of 53) are used for representing normal, dry, or wet hydrological conditions and modifying the CN accordingly as per Eq 2.6 and 2.7.

e) Knowing the revised curve number (RCN) after accounting for the slope and AMC, the surface retention 'S' is calculated as per Eq. 2.4.

f) Knowing 'S', the rainfall excess is calculated. If rainfall on a day is less than 0.3 * S, then rainfall excess is taken to be zero. Otherwise, it is calculated by the formula:

$$Runoff = \frac{(Rain - 0.3 * S)^2}{Rain + 0.7 * S} \qquad \ldots(2.8)$$

g) If the basin factor for a sub-basin (SBFAC) is other than 1, then the runoff (rainfall excess in depth units) is modified accordingly but limited to the rainfall amount of the day at the grid. The rainfall excess, so derived at different grids, is then moved in the downstream direction according to flow direction and moisture status at the downstream grid.

b) Soil water balance module

Soil water balance equation is a mathematical statement of law of conservation of mass as applied to the hydrologic cycle. It states that in a specified period of time, all water entering a specified volume must either go into storage within its boundaries, be consumed therein, or be exported therefrom either on surface or underground. Soil water balance approach allows a basin planner to compute a continuous record of soil moisture, actual evapo-transpiration, ground water recharge, and surface runoff. The storage volume in the basin soil cover provides an effective storage of water in a river basin. The model accounts for the water content in the basin soil cover by simulating the moisture status in the soil at all the grids and on all days of simulation period. Figure - 2.1 shows schematic sketch of water balance components. The soil column at a grid is divided in three sections:

i) *uppermost root zone* – Its effective depth is taken equal to the root depth of the crop. For an agricultural grid, since the root depth varies with crop growth, this zone varies from time to time. For forest land, it is given a fixed value, say 4 m. For urban land, barren land or for an agricultural grid not having any crop in a particular period, it is assumed to be equal to 200 mm. Water balance accounting is carried out for this zone only.

ii) *intermediate unsaturated zone* – This zone lies below the root zone and above the groundwater table. This zone is assumed to be at field capacity and it acts as a passage for any recharge from the root zone to the lowermost saturated zone.

iii) *lowermost saturated zone* – This is the lowermost zone that represents the occurrence of groundwater. Any recharge from the root zone is received here. Any movement of water in this zone is simulated by using the groundwater simulation model.

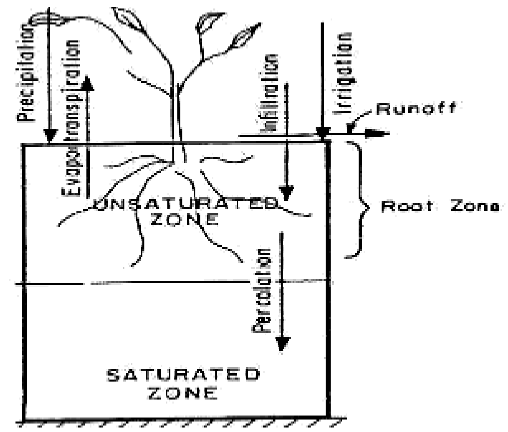


Figure – 2.1: Schematic sketch of soil water balance components

Effective soil depth at a grid during a day is taken as the average crop root depth during that week. The root depth of a crop increases in the initial stages of development till it attains a maximum value. Root growth with time is simulated in the model by a sigmoidal model [Eq. (2.9)] as proposed by Borg and Grimes (1986). The value of root depth on any day (t) is given by:

$$RD_t = RD_m \left[0.5 + 0.5 \sin \left\{ 3.03 \left(\frac{t}{t_m} \right) - 1.47 \right\} \right] \qquad \ldots(2.9)$$

where RD_t is the root depth of crop on t^{th} day after planting, RD_s is the starting root depth [taken as 200 mm since soil evaporation can occur from top 200 mm soil layer (Rao (1987) and Panigrahi and Panda (2003)], RD_m is the maximum root depth, and t_m is the duration of full development of the root zone (days).

Since rainfall, evapo-transpiration, recharge etc. are expressed in depth units, water content (w) of soil in percent on dry weight basis is converted into equivalent water depth. Consider a soil reservoir (Figure – 2.2) of surface area ‘A’ sq. m and soil depth ‘H’ meter.

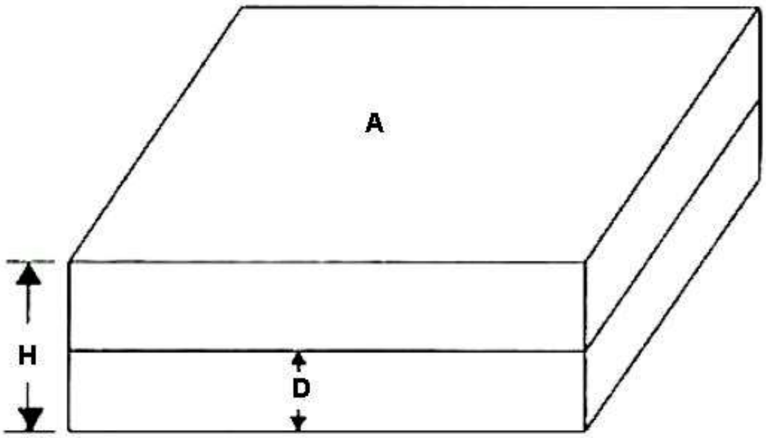


Figure – 2.2: A grid representing soil reservoir

Let ‘G_a’ be the apparent specific gravity of the soil (a dimensionless parameter equal to bulk density of soil in gm/cc) and ‘D’ be the equivalent water depth in mm corresponding to water content of ‘w’ percent on dry weight basis. Then,

w = weight of water/weight of soil solids = $W_{water}/W_{solid} * 100$ …(2.10)

W_{water} = Volume of water * specific gravity of water = (A.D/1000) * 1

W_{solid} = Volume of soil * apparent specific gravity of soil = (A.H) * G_a

Therefore, $$w = \frac{A.D}{1000.A.H.G_a}.100$$

and $$D = 10.w.G_a.H \qquad \text{…(2.11)}$$

Let ‘η’ represent the porosity of the soil (volume of voids per unit volume of soil) and ‘w_S’ represent the water content of saturated soil in percent on dry weight basis. Using Eq. 2.11, equivalent water depth at saturation (WDS) is calculated as:

$$\text{WDS} = 10 . w_S . G_a . H$$

$$= 10.\frac{W_{water}}{W_{solid}}.\frac{W_{solid}}{V}.H$$

$$= 10.\frac{W_{water}}{V}.H = 10.\frac{V_{water}}{V}.H$$

$$= 10. \eta. H \qquad \text{…(2.12)}$$

Similarly, water depth at field capacity (WDFC) and at permanent wilting point (WDO) is computed as:

$$WDFC = 10 * w_{fc} * G_A * H \qquad \text{…(2.13)}$$

$$WDO = 10 * w_{pwp} * G_A * H \qquad \text{…(2.14)}$$

where 'w_{fc}' is soil water content at field capacity and 'w_{pwp}' is water content at permanent wilting point, both expressed as % on dry weight basis. In addition, upper limit of water depth (UL) is defined to represent maximum water depth that can be stored in a grid before generating overland flow. UL is represented as:

$$UL = WDS + D_{max} \qquad \text{…(2.15)}$$

where 'D_{max}' is maximum standing water depth required by the crop (say, paddy) at any time. Further, lower limit of water depth (D_{min}) is defined to represent stress conditions under which, actual crop evapo-transpiration rate decreases below the normal rate. Lower limit of water depth represents the lower bound of the readily available moisture (FC-PWP) and indicates the level at which the crop just starts to respond to the shortage of the soil moisture. A plot showing the variation of ratio of actual to reference crop evapo-transpiration with soil water content (Shuttleworth, 1993) is shown in Figure – 2.3.

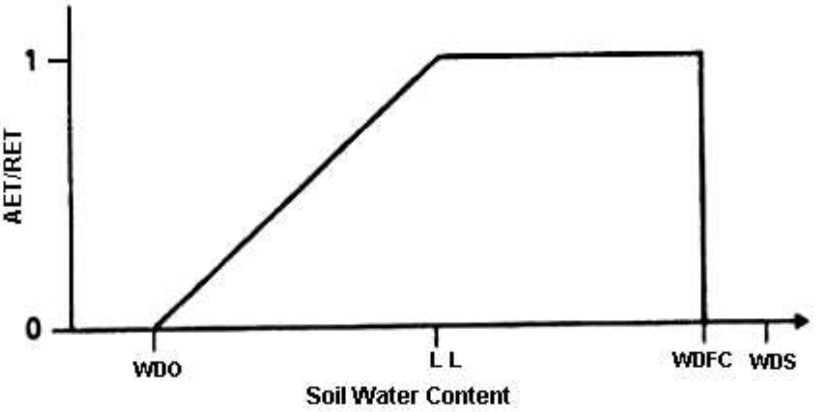


Figure – 2.3: Variation of actual crop evapo-transpiration with soil water content

Let 'p' represents the fraction of available water utilized by the plant without any stress. Then, D_{min} in equivalent water depth in mm is given by:

For Paddy: $D_{min} = WDFC$ …(2.16)

For other crops: $D_{min} = 10 * [FC - p * (FC-PWP)] * G_A * H$

or $D_{min} = WDFC (1- p) + WDO * p$ …(2.17)

For urban and barren land, D_{min} is assumed to be at WDO. For forest land, it is assumed to lie between WDFC and WDO. Definition sketch of equivalent water depths corresponding to specific water contents (saturation, field capacity, wilting point etc.) that are useful in SWBM is presented in Figure – 2.4.

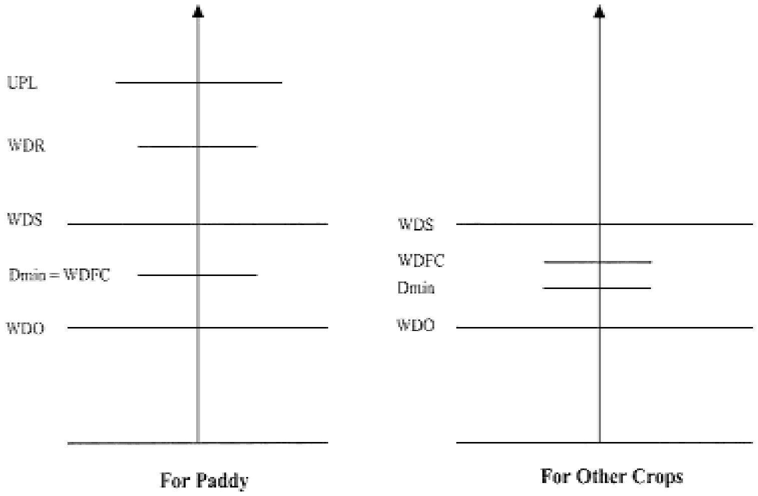


Figure-2.4: Definition sketch of specific equivalent water depths

Various inputs to the uppermost root zone are: balance rainfall after deducting overland flow, irrigation, and overland inflow from any upstream surrounding higher elevation grid. Various outputs from this zone are: evapo -transpiration, groundwater recharge, and overland outflow to downstream surrounding lower elevation grid (if any). Based on the land use type (crop type and its attributes in case of agricultural land) and the soil type, equivalent water depths corresponding to saturation (WDS), field capacity (WDFC), and permanent wilting point (WDO), upper water depth limit (UPL) and lower limit (D_{min}) are determined. Depending on the crop type and its growth stage, its crop coefficient and evapo-transpiration demand are determined. Initial moisture at the grid is read from the data file. If water table at any grid lies within the root zone, then the initial moisture is modified. Soil water balance equation is executed for each grid as follows:

$$WD_t = WD_{t-1} + ERF_t + IRR_t + OLFI_t + GWC_t - AET_t - DPER_t - OLFO_t \qquad ...(2.18)$$

where WD_t is the equivalent water depth in root zone at end of t^{th} day; WD_{t-1} is the initial equivalent water depth; ERF_t is effective rainfall on t^{th} day (Rainfall – Overland flow); IRR_t is the depth of irrigation applied on t^{th} day; $OLFI_t$ is the overland inflow to the grid cell from adjacent higher elevation grid on t^{th} day; GWC_t is groundwater contribution on t^{th} day; AET_t is actual crop evapo-transpiration on t^{th} day; $DPER_t$ is deep percolation going out of root zone on t^{th} day; and $OLFO_t$ is the overland outflow on t^{th} day.

Initially, evapo-transpiration is considered at potential rate (ETO) and $DPER_t$ and $OLFO_t$ are not considered. If WD_t lies below D_{min}, then AET_t is determined as per following:

$$AET_t = ETO * [1 - [\{D_{min} - WD_t\}/\{D_{min} - WDO\}]] \qquad ...(2.19)$$

AET_t is determined recursively in Eq. 2.18 till its value stabilizes. If the WD_t in the grid exceeds the WDFC, then $DPER_t$ is determined as:

$DPER_t$ = min. of (hydraulic conductivity, WD_t - WDFC) …(2.20)

For ponded crops (such as paddy), moisture content is kept above the equivalent depth at saturation in the field. For such crops, higher initial values of hydraulic conductivity of the underneath soil stabilize to lower values after a hard pan is formed below the crop roots. Phien (1983) used a value of 3 mm/day for sandy loam soil and 1 mm for clay soil. CWC and INCID (1995) suggest that percolation rate for paddy field may vary from 3 to 16 mm/day depending upon the type of soil and the time elapsed after the introduction of irrigation. Further, if the groundwater table lies very near or within the effective soil zone, it may restrict the deep percolation of excess water from the effective soil zone. To account for this effect, deep percolation is restricted to the water depth equivalent to the water content which will saturate the soil column below the root zone up to the water table. If the groundwater table lies within the root zone, deep percolation is assumed to be zero. Model considers these scenarios for determining deep percolation at a grid.

If the balance water after accounting for the AET_t and $DPER_t$ exceeds the WDS + bund height (for a crop, if any), then saturation excess overland flow is generated at the grid ($OLFO_t$) which is then routed to the surrounding lower elevation grid. The flow direction for each grid is estimated on the basis of DEM.

Based on the residual water content (after accounting for the evapo-transpiration, recharge, and overland outflow), the irrigation demands at an irrigated agricultural grid are worked out. If it is the land preparation week of the crop and residual water content is below UPL, then minimum of Palewa water demand or water required for saturating the field is taken as the irrigation demand. Palewa water is given only once in a week. If the land preparation phase is over for a crop field, then its irrigation demand (SWR) is computed as:

$$SWR_t = ETC_t - ERF_t - GWC_t - OLFI_t \qquad \ldots(2.21)$$

where SWR_t is supplementary irrigation demand on tth day and ETC_t is potential crop evapo-transpiration demand (crop coefficient * ETO) on tth day. Since rice crop requires standing water in field, percolation at prevailing rate from bed is also added to irrigation demand.

This module computes actual evapo-transpiration, saturation excess overland flow, recharge, supplementary irrigation demand, groundwater contribution, and residual soil water content at each grid. At each grid, daily recharge of each day is accumulated for the whole month which is then used with the groundwater simulation model to find revised groundwater table for the subsequent month. Irrigation demand, after accounting for the water use efficiency, is transferred to the connected reservoir for supply of irrigation water. Residual water content at each grid at the end of a day is stored in a temporary file which is then read as the initial moisture for the subsequent day.

c) Domestic & industrial demand module

A river basin supports large quantum of human and cattle population and their water requirements are met from the basin water resources. In addition, there may be lots of industrial activities that might require lots of water for their operation. Domestic and industrial demand module computes the water demands for these purposes in the basin. Human population can be further categorized as urban or rural, each having different standards of supply. Further, population changes with time and the records of district-wise human and cattle population are obtained during each census survey which is carried out every ten years. Such records can be obtained from the Statistical Directorates of States associated with the river basin.

This module uses the district-wise statistical records of human and cattle population, land use map, district map, map showing various cities in the river basin, and the water supply and drainage standards adopted in the river basin. Urban population is assumed to be concentrated in the cities while rural population is assumed to be uniformly distributed in agricultural and barren land area. First, the number of urban grids (cities) and rural grids (agricultural and barren land) within the river basin in each district are computed. Cattle population is also assumed to be uniformly distributed in the rural area. For each district (within or outside the river basin), the net area ($NARE_{Dist}$) excluding forest and water bodies is computed. Then density of human population per grid is calculated as:

$$Pop_R = \frac{TPOP_{Dist} * NGRD_{Bas} * (100 - PERUR_{Dist})}{100 * NARE_{Dist} * NGRD_R} \qquad \ldots(2.22)$$

where Pop_R is rural population per rural grid (agriculture and barren land use) of district within basin, $TPOP_{Dist}$ is total district population, $NGRD_{Bas}$ is total district area within basin, $PERUR_{Dist}$ is percentage of urban population in the district, and $NGRD_R$ is the total number of rural grids in the district within the basin. Similarly, urban population per urban grid and cattle population per rural grid in the district are calculated as:

$$Pop_U = \frac{TPOP_{Dist} * NGRD_{Bas} * PERUR_{Dist}}{100 * NARE_{Dist} * NGRD_U} \qquad \ldots(2.23)$$

$$Pop_C = \frac{TCPOP_{Dist}}{(NARE_{Dist} - TURB_{Dist})} \qquad \ldots(2.24)$$

where Pop_U is urban population per urban grid within the district in the basin, Pop_C is cattle population per rural grid within the district in the basin, $NGRD_U$ is the total urban grids within the district in the basin, $TCPOP_{Dist}$ is total cattle population in the district, and $TURB_{Dist}$ is the total urban area in the whole district.

After computing human and cattle population density at all the grids, domestic water demand at a grid is computed by multiplying the per capita water demand per day (specified for the district) with the grid population. At present, industrial demand has been associated with each urban grid and its demand has been taken equal to the domestic demand of the grid. In the rural area, water demand has been assumed to be met from groundwater withdrawal only. For the urban demand, if a city is connected with a reservoir, then its water supply is met from the reservoir. For other cities (not connected to any reservoir), water supply is met from groundwater withdrawal only. In all cases, groundwater withdrawal is limited to the groundwater potential at the grid.

Of the total water used for domestic and industrial supply, a part is consumed by the community and rest is drained in to the groundwater and surface water. Total water drained in the surface water and groundwater is computed by using the consumptive use factor which is specified for each district. For rural area, total drainage is assumed to return to groundwater whereas in urban area, factors specifying percentage drainage to surface and groundwater (for each district) are used to compute return drainage of domestic & industrial supply to surface and groundwater systems. Effective withdrawal of groundwater for domestic and industrial water use is then taken to be the groundwater withdrawal minus groundwater drainage at a grid. Surface drainage from the urban area moves as overland flow through intermediate low elevation grids towards the river segments and contributes to the river flow.

Total domestic and industrial demands and their supply from surface water (reservoir) or groundwater are computed for all sub-basins and presented in the output. Effective groundwater withdrawal for meeting these demands and surface water drainage for all sub-basins are also presented in output.

d) Overland flow movement module

Using this module, overland flow generated through various components (surface drainage of domestic supply, saturation excess overland flow calculated using soil water balance, and rainfall excess overland flow calculated using SCS method) is moved from a grid through subsequent lower elevation grids towards the river network or a storage reservoir.

The computations are started from the highest elevation grid in the river basin and total overland flow generated at the grid through various components (specified above) is computed. Using the flow direction map, the overland flow is moved in the flow direction and total inflow at the receiving grid from higher elevation grids is calculated. If the receiving grid has any component of overland flow, then the total inflow at this grid from upstream higher elevation is added to the total overland flow generated at this grid and it is moved further in the flow direction. However, if the receiving grid does not have a component (surface drainage of water supply or rainfall excess overland flow) of overland flow, then the total inflow at this grid is assumed as inflow for the soil water balance computation.

While moving the flow from higher to lower elevations, if a downstream grid happens to be a water grid (water surface of a reservoir), then the overland flow (converted from depth to volume units) is added to reservoir storage as “Peripheral Flow”. If the downstream grid happens to be a river grid, then overland flow (converted from depth to volume units) is added as flow to river segment. At this point, any imports to a river segment are also added to its flow.

e) Irrigation demand estimation module

Using this module, daily irrigation demands for each reservoir or diversion structure are estimated. Initially, irrigation demand (SWR) for each irrigated agricultural grid is computed using soil water balance module. Depending on the hydraulic structure (in the command of which the grid is located), on-field demands are divided by the surface water use efficiency (specified for each hydraulic structure) to represent the at-reservoir demands. At-reservoir irrigation demands of all the irrigated agriculture grids located within the command of hydraulic structure are accumulated to estimate the total irrigation demands from the hydraulic structure for a day.

It is quite possible that all the agricultural grids within the command area of a reservoir may or may not be supplied with irrigation water from the reservoir. Secondly, it is also possible that there are some discrepancies in marking the boundaries of a command area. To adjust for these possible anomalies, a parameter "Proposed Profitable Area (PPA)" is specified for each hydraulic structure. Total irrigation demands at the reservoir (computed above) are multiplied by the PPA to get the actual irrigation demands from the reservoir. Based on the analysis for a number of years, PPA is adjusted so that the annual total irrigation demands from the reservoir match with its design demands. At the time of irrigation supply to the individual grids, their demands are modified with PPA so that modified demands of all grids within the command area of the reservoir can be served.

f) Reservoir operation module

Using this module, operation of a storage reservoir or diversion weir is simulated. In the first step, daily flows in the river network are accumulated to estimate the inflows to the hydraulic structures. In the overland flow movement module, flows in individual river segments from their contributing areas have been estimated. Next, the flows in the river network are accumulated starting from the most upstream segments. If a river segment has two or more upstream river segments, then their flows are accumulated to get total flows at a river segment on each day. River network attributes (representing river network connectivity) are used for such accumulation. If a river segment has a hydraulic structure at its downstream end, then the flow in the river segment becomes the inflow to the reservoir. Similarly, if any immediate upstream river segment has a hydraulic structure located on it, then the release from the reservoir is considered as the flow from that river segment for flow accumulation. After the accumulation of flows and estimation of inflows at individual hydraulic structures, their operation is simulated using standard linear operating policy as shown in Figure-2.5.

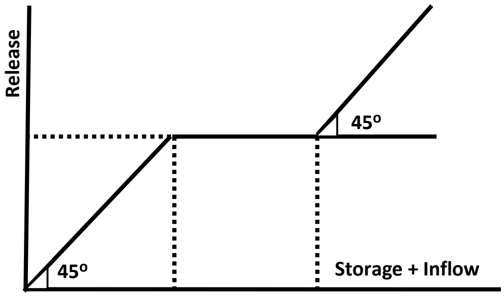


Figure-2.5: Standard linear operating policy

Different variables considered for reservoir operation are: river inflows; peripheral inflows to reservoir; rainfall on the reservoir surface; imports to the reservoir, evaporation losses; domestic and industrial water demands; minimum flow demands; irrigation demands;

supply for domestic demands, minimum flow, and irrigation; export from reservoir, spill from reservoir; and initial and final storages. The steps involved for reservoir operation are:

i) Total storage in the reservoir is determined as follows:

$$Stor_t = Stor_{t-1} + Rivflo_t + Iprt_t + Perin_t + Rfc_t \qquad \ldots(2.23)$$

where $Stor_t$ is total storage considering only inflows, $Stor_{t-1}$ is initial storage at beginning of t^{th} day, $Rivflo_t$ is river flow to reservoir, $Iprt_t$ is any import to the reservoir, $Perin_t$ is peripheral inflow, and Rfc_t is rainfall contribution to storage on t^{th} day.

ii) Water spread area (WSA) is assumed to have linear relationship with the storage. Knowing the maximum WSA corresponding to full reservoir level for a reservoir, the WSA_t corresponding to $Stor_t$ is computed as follows:

$$WSA_t = \frac{Stor_t}{Stor_{\max}} * WSA_{\max} \qquad \ldots(2.24)$$

where WSA_{max} is maximum water spread area corresponding to maximum live storage $Stor_{max}$.

iii) Evaporation and recharge losses ($ERCLOS_t$) for the reservoir are computed by multiplying the sum of evaporation depth (corresponding to thiessen polygon of ET stations in the basin) and recharge depth (optional parameter specified at the beginning of simulation) with the WSA_t.

iv) Net storage available ($NStor_t$) after meeting evaporation and recharge losses is computed by subtracting $ERCLOS_t$ from $Stor_t$.

v) Highest priority is given to domestic and industrial water supply. If $NStor_t$ is more than domestic water demand, then domestic demand is met in full. Otherwise, $NStor_t$ is supplied as domestic supply. $NStor_t$ is calculated again after subtracting domestic water supply from its previous value.

vi) Next priority is given to minimum flow requirements in the downstream reach. If $NStor_t$ is more than minimum flow demand, then it is met in full. Otherwise, $NStor_t$ is supplied as minimum flow possible. $NStor_t$ is calculated again after subtracting minimum flow supply from its previous value.

vii) Next priority is given to irrigation demand. If $NStor_t$ is more than irrigation demand, then it is met in full. Otherwise, $NStor_t$ is supplied as irrigation supply. $NStor_t$ is calculated again after subtracting irrigation release from its previous value.

viii) Next priority is given to the exports from reservoir. If $NStor_t$ is more than required export, then it is met in full. Otherwise, $NStor_t$ is supplied as possible exports from reservoir. $NStor_t$ is calculated again after subtracting export from its previous value.

ix) If the net storage ($NStor_t$) left after meeting all demands exceeds the $Stor_{max}$, then the storage in excess of $Stor_{max}$ is taken as spill from the reservoir. Final storage of the reservoir is then set to $Stor_{max}$.

x) Reservoir storage at the end of a day is saved in a separate file which is then read for the next day simulation.

All the variables at daily time step are saved and daily reservoir working table is presented as output for each hydraulic structure. The variables are also accumulated for the whole month and monthly working table for all reservoirs is also prepared.

g) Surface water/groundwater allocation module

Using this module, the use of surface water and groundwater in the river basin is ascertained. The allocation is made for domestic/industrial demands and irrigation demands. The allocation is performed after reservoir operation module is executed and actual surface water supplies for different demands are known.

Rural domestic supply is met from groundwater only. If an urban grid (city) is connected to a reservoir, then its demands are compared with the supply. If the reservoir supply is less than the demand, then rest of the demands are met through groundwater withdrawal, limited to groundwater potential at the grid.

For rainfed agriculture grid, irrigation water either from surface water or groundwater is not supplied. For the irrigated agriculture grid within the command area of a reservoir, the actual surface water supply from reservoir is computed as:

$$SWAlloc_t = \frac{TIrSup_t * GIrDem_t * PPA}{100 * TIrDem_t} \qquad \ldots(2.25)$$

where $SWAlloc_t$ is surface water allocation at the grid, $TIrSup_t$ is total supply for irrigation from reservoir, $TIrDem_t$ is total irrigation demand from the reservoir, $GIrDem_t$ is irrigation demand at the grid for tth day, and PPA is proposed profitable area of reservoir in %. If the irrigation demand at the grid exceeds $SWAlloc_t$, then groundwater allocation ($GWAlloc_t$) limited to the groundwater potential, is met from the groundwater. Since at-grid irrigation demands are increased enroute to the reservoir to compensate for surface water efficiency and water is accordingly released from the reservoir, the excess water is taken as recharge to groundwater at the grid where irrigation water is applied.

For irrigated agriculture grid outside the command area of a reservoir, the surface water is not supplied and its demands are met through groundwater use. For such grids, groundwater withdrawal limited to the groundwater potential, is computed and is supplied as irrigation input. The model keeps track of the surface water and groundwater supply in different areas and monthly cumulated values are presented in the output for each sub-basin.

h) Base flow computation module

Using this module, the groundwater contribution to baseflow at each gauging site is determined. Calculations proceed from the most upstream gauging site in the direction of flow.

For the gauging site (having no upstream station), the total depth of groundwater storage in the catchment above the river bed level at gauge site is determined. For each grid in the catchment, depth of groundwater above the gauging site bed level is estimated and it is multiplied by the soil porosity to give equivalent water depth. This depth is accumulated for all grids in the sub-basin to give total groundwater storage (GWS) above the gauging site bed level. A parameter, GWFAC is specified for each sub-basin for each month. GWS for a sub-basin is multiplied by the GWFAC for the month to give groundwater contribution to base flow at any upstream gauging site.

For a downstream gauging station having upstream gauging site also, the groundwater storage above the bed level in its free catchment area is computed. Next, for each upstream sub-basin, groundwater storage in-between bed levels of two gauge sites under consideration is also determined. All the groundwater storages of upstream individual sub-basins are added to give total groundwater storage (GWS) at the downstream site. This is then multiplied by the GWFAC of sub-basin for the month to get groundwater contribution to base flow.

Initial estimates of GWFAC parameter for various gauging stations for different months can be computed by knowing the observed flows and groundwater levels in those months that have no rainfall events.

2.4 Linkage with Groundwater Flow Model

In the model, prevailing groundwater surface in the basin is an important input for deciding the depth of vadose zone below root zone, groundwater contribution to meet evapo-transpiration demands, and to assess the groundwater potential in the basin at each grid. It can also help in formulating basin management plans for conjunctive use of surface and groundwater. To analyze groundwater behavior, a groundwater simulation model with GIS interface is already available (Visual MODFLOW), developed by the Waterloo Hydrogeologic Inc. (2002), and the same has been linked to the model to generate groundwater surfaces corresponding to monthly pumping and recharge patterns in the river basin. A brief description of Visual MODFLOW is presented here.

2.5 Various Interlinking Sub-models

Various sub-models have been developed to design the database for the model and to link input and output with GIS and VMOD. Five sub-models are developed for database generation (DIMENSION, IMAGE, TOPO_COD, CSRS_COD, and RCSL_COD), one sub-model (GWPOT) for estimation of grid-wise groundwater potential, and one sub-model (WELL) for linking grid-wise pumping and recharge to the VMOD. These sub-models are:

a) DIMENSION

The purpose of this sub-model is to reduce the dimensions of model program. A basin area is considered as being composed of a number of regular square grids. The modeling approach considers the basin in the form of rows and columns and the calculations proceed for each grid of all rows and columns. Generally, boundaries of a basin form an irregularly shaped area such that a number of grids in rectangular image representation lie outside of the basin. These grids do not contribute to analysis but unnecessarily increase the program dimensions.

The objective of DIMENSION is to find the number of grids in each row that lie within the boundaries of the basin area and their location in the row. Input to the sub-model is the rectangular raster image of the basin in ASCII format, which is generated using ILWIS. Output of the sub-model specifies for each row, the location of the starting grid which lies within the boundary of the basin and the total number of grids within the basin boundary in that row. Result file of DIMENSION is used by all sub-models to find the position of grids within a rectangular image for which analysis is to be carried out.

b) IMAGE

The purpose of IMAGE is to convert a rectangular image (generated in GIS) into data file for input to the simulation model or to convert the model output (in ASCII form) into the image form for display in ILWIS GIS.

The IMAGE sub-model uses the result file of DIMENSION to remove the redundant grids in the input image from the GIS system and the data of basin area grids are stored in a separate file. After the analysis is performed and spatial output is obtained from the basin simulation model (such as soil moisture content, pumping/recharge etc. at different grids in the basin), the same is required to be converted to the image form for display in GIS. To convert the simulation model results, the redundant grids are attached to the basin area grids so as to form a rectangular image, which is then imported in ILWIS GIS system and displayed as an image.

c) TOPO_COD/CSRS_COD/RCSL_COD

The purpose of *_COD sub-models is to reduce the dimensions of the model program. A number of spatially distributed data (crop, soil, rainfall, flow direction, surface elevation, groundwater depth etc.) are used by the basin simulation model. If all these data are input as separate thematic layers, then program dimensions exceed the working limit of compilation. Therefore, data of different spatial variables (crop, soil, thiessen polygon of rainfall and ET station, flow direction etc.), which do not vary within a particular month, are merged in the form of a single code.

*_COD sub-models develop a code depending on the value of different spatial variables at a grid. Inputs to the module include result file of DIMENSION, and image files of various spatial variables. Image files are generated in ASCII format by ILWIS GIS system.

TOPO_COD sub-model integrates the elevation, slope (in percent and up to one decimal digit), flow direction (1 – 8), and district information at each grid and generates a code (IELSL) which is read by the basin model and these variables are decoded at each grid.

CSRS_COD sub-model integrates the crop type, soil type, nearest rainfall station (as per thiessen polygon), nearest ET station (as per thiessen polygon), and sub-basin information at each grid and generates a code (ICSRED) which is read by the basin simulation model and these variables are decoded at each grid.

RCSL_COD sub-model integrates the land use, command areas of different reservoirs, water spread areas of different reservoirs, and drainage network layout information at each grid and generates a code (ISORIV) which is read by the basin simulation model and these variables are decoded at each grid. The city map and the groundwater depth maps are directly imported in the model.

d) GWPOT

The purpose of GWPOT sub-model is to estimate daily groundwater potential at each grid. In a region, groundwater potential depends on the groundwater development (number of pumping wells and pump capacity), the energy available for groundwater pumping and the groundwater depth. If these details are available, GW potential at a grid is estimated as:

$$GWP = \frac{36 * TEner * P_{eff}}{9.817 * GWD} \quad \ldots(2.27)$$

where GWP is groundwater potential in m^3 per day, TEner is the total energy available (number of pumps * pump capacity * daily hours of available electric supply) in kilowatt-hour for pumping groundwater, GWD is groundwater depth in m, and P_{eff} is pump efficiency.

At times, above mentioned information is difficult to obtain. Rather, information about groundwater utilisation in different districts is available from the statistical records. In that case, groundwater potential at each grid in a district is estimated by uniformly distributing the district groundwater utilisation (in a day) in all urban, irrigated agriculture, and barren land use grids of that district.

e) WELL

The purpose of WELL sub-model is to link the pumping and recharge data at each grid to the groundwater simulation model (VMOD). Each grid is represented by a well through which pumping/recharge interaction takes place with the groundwater aquifer. WELL prepares the data in a form which can be directly imported in VMOD. The format for data includes the identity of the well, its location coordinates, the identity of the screen, the elevation of the top and bottom surface of the screen, the stress period of recharge/pumping, and value of recharge/pumping during stress period. The sub-model generates a unique identity for each well. Top screen elevation is taken to coincide with the land surface elevation. A part of the output file prepared by the sub-model is given in Table – 2.1.

Table - 2.1

Pumping/recharge information for input to VMOD

Well Identity	Location (m)		Screen Identity	Screen Elevation (m)		Stress Period (days)	Pumping/ Recharge (m3)
	X	Y		Top	Bottom		
W0001	18360	108912	W0001	211.13	161.13	30	5083.11
W0002	19360	108912	W0002	210.49	160.49	30	-4906.31
W0003	20360	108912	W0003	210.49	160.49	30	293.5

2.6 Computational Steps of Model

To realize the working of basin simulation model, computational steps of the algorithm are presented below:

1. The spatial database is developed in the ILWIS GIS system and all the GIS layers are exported as ASCII files. Attribute data, dynamic data, and initial model parameters for the basin are specified in ASCII data files.
2. First, DIMENSION sub-model is run. Then, IMAGE sub-model is run for all the GIS layers. Next, TOPO_COD, CSRS_COD, RCSL_COD, and GWPOT sub-models are run. Outputs of these sub-models become the inputs for the basin simulation model (BASIN).
3. The model reads various simulation options such as month and year of simulation, grid size, rainfall factor (to simulate scenarios corresponding to different rainfall conditions), recharge rate from water bodies (~ 0 to 3 mm/day), and initial moisture conditions. Model performs the analysis for the whole month at daily time step. After reading options, model reads all the specified data and extracts the dynamic data for the month for which analysis is being carried out. Based on the option chosen, initial moisture is either computed or read from the given file.
4. For each grid, various spatial variables are decoded and number of rural and urban grids in each district is computed.
5. Base flow module is executed and base flow contribution at each gauging site is found.
6. For first day of the simulation month, initial soil moisture content in each grid is computed/read and initial storage in different hydraulic structures is read from data file.
7. For the day for which simulation analysis is carried out, corresponding week is identified and root depth and crop coefficients of different crops in week are determined.
8. Domestic and industrial (D & I) demand module is invoked and water supply demands at different grids are computed. Grid-wise groundwater pumping for meeting these demands, overland flow generated due to surface drainage of D & I use, and total water supply demands from different reservoirs are also computed.
9. Overland flow generation module is invoked and rainfall-excess overland flow is determined at each grid corresponding to the present and 5-day antecedent rainfall, soil class, land use, slope.

10. Soil water balance module is invoked and computations are executed stating from the highest elevation grid. First, the effective soil depth is estimated. For a crop grid, time to crop and its root depth are determined. For other land uses, effective soil depth is given a specified value. Minimum value is assumed to be 200 mm in all cases. Next, initial moisture content is read. If groundwater level lies within the root zone, then groundwater contribution is computed. Next, different equivalent water contents corresponding to root depth and soil type are estimated and potential evapo-transpiration demands (PET) from different land uses are determined. Next, water balance computations are carried out assuming PET and no irrigation input. If the final water content falls below the D_{min}, then stress conditions and corresponding reduced evapo-transpiration (AET) is determined recursively. Next, groundwater recharge (if any) and saturation-excess overland flow (if any) are estimated. Finally, irrigation demands at a crop grid are determined. For rice crop, special consideration is made for D_{min}, standing water requirement and seepage losses.

11. After completing the soil water balance at a grid and computing the actual evapo-transpiration, recharge, saturation-excess overland flow, and irrigation demands at the grid, overland flow movement module is invoked to route the total overland flow (from D & I drainage, rainfall-excess, and saturation-excess) to the next lower elevation depending on the flow direction at the grid. If lower elevation grid (to which flow is moved) is a river grid, overland flow is dumped as flow in the corresponding river segment. If lower elevation grid is water spread of a reservoir, overland flow is dumped as peripheral inflow to the reservoir. If lower elevation grid is a simple grid (no river and reservoir), overland flow is recorded as inflow from the upstream grid at the receiving grid. Then, next lower elevation grid is taken and the combination of Step 10 and Step 11 is executed. This analysis is completed for all the grids.

12. Any imports to a river segment are added to its total flows.

13. Knowing the irrigation demands at individual grids and command area boundaries of different hydraulic structures, irrigation demand estimation module is invoked to estimate total irrigation demands from different reservoirs.

14. Next, the reservoir operation module is invoked. Here, first the flows in individual river segments are accumulated according to the river network connectivity starting from the most upstream river segment. If a reservoir is located at any segment, then the flow accumulation for the downstream river segments is carried out after performing the reservoir operation for the encountered reservoir. Any release from the reservoir is considered as the flow to the downstream river segment. Any export from a river segment is now subtracted from its accumulated flows.

15. Various water balance components of a hydraulic structure such as river inflows, peripheral inflows, rainfall on the reservoir, imports, evaporation loss, supply for D&I demands, minimum flow demands, irrigation demands, spill, and exports etc. are saved at daily time step for presentation of daily working table. These variables are also accumulated for a month for presenting the monthly output.

16. Next, surface water and groundwater allocation module is invoked to estimate the surface water supply (for D & I and irrigation demands) and necessary groundwater withdrawal for meeting balance demands. At this stage, soil water balance module is invoked again for the irrigated agriculture grids for simulating their soil water balance considering irrigation inputs. Irrigation demands are not evaluated now.
17. After accumulating the river flows and simultaneously operating the reservoirs, the daily flows at different gauging sites are stored for presenting daily record. Flows are also accumulated for the whole month for presenting monthly values at each gauging site.
18. Final soil water content at each grid and storage content in different hydraulic structures are stored in temporary file which are recalled for the basin simulation for the next day.
19. Simulation is carried out for all the days in a month and the model outputs are stored in different files. Knowing the monthly grid-wise pumping and recharge of groundwater, WELL module is used to prepare the input pumping/recharge file for the VMOD. Monthly pumping/ recharge is imported in VMOD and revised groundwater levels for the next week are determined.
20. Calibration of the model requires adjustment of surface flow factor (CNFAC and SBFAC) and groundwater factor (GWFAC) for different sub-catchments of gauging sites so as to match the observed and simulated flows at different gauging sites and the observed and simulated groundwater levels at different observation wells in the basin.

2.7 Output of the Model

The model prepares the output through image and tabular presentation. Image maps prepared by the model include: i) final soil water content at the end of a month, ii) groundwater pumping and recharge in the month, and iii) monthly values of evapo-transpiration. These maps can be converted from ASCII file using IMAGE module and can be imported and displayed in the ILWIS GIS system.

Tabular output is prepared by the model at daily and weekly time step. Tables prepared at daily time step include: i) river flows at different gauging stations in the basin, and ii) working table of different hydraulic structures in the basin. Tables prepared at monthly time step include: i) river flows at different gauging stations in the basin, ii) working table of different hydraulic structures in the basin, and iii) hydrological details for different sub-basins which include the following:

- domestic and industrial demand and supply (total demand in urban and rural area, surface water use, groundwater withdrawal, groundwater recharge, and overland flow generated),
- hydrological details for different land uses (rainfall, groundwater contribution, irrigation application, evapo-transpiration losses, overland flow generated, soil moisture change, and groundwater recharge),

- irrigation demands and supply [irrigation demands within command areas, irrigation demands (from groundwater) outside command areas, surface water supply in command areas, groundwater withdrawal in command areas, and groundwater withdrawal outside command areas],
- runoff stagnated in the sub-basin or moved out of the basin/sub-basin,
- cumulative results of different reservoirs (total number of reservoirs; initial storage; peripheral inflows; rainfall contribution; imports; evaporation losses; D & I demands; minimum flow demands; irrigation demands; supply for D & I, minimum flow, and irrigation; spill; exports; and final storage)

By analyzing the model results, an overall picture of water availability and demands in the basin can be obtained. Also, by operating the model for longer time periods, sustainability of various water resources management plans can be examined. The model can be used to analyze the effect of various factors, such as: (i) change in land use (increase or decrease in forest area, cultivated area, barren land etc.); (ii) change in the cropping pattern in the area; (iii) change in water use and conveyance efficiencies; (iv) construction of new water resources projects or change in the design of existing projects; and, (v) change in population and corresponding D & I demands on the water resources of a basin. The model can predict future scenarios corresponding to any given climate change scenario (change in spatial or temporal rainfall pattern or change in reference evapo-transpiration due to temperature or humidity modifications).

2.8 Application of the Model for the Tapi Basin

To have a brief glimpse of the model inputs and outputs, its application for Tapi River basin is briefly presented here. The Tapi river is the second largest west flowing river of India with its catchment area lying in the States of M.P., Maharashtra and Gujarat States. The total catchment area of basin up to Ukai dam is 62,225 sq. km. Nearly 80% of the basin lies in State of Maharashtra. Fifteen spatial data layers have been generated in ILWIS GIS system using remote sensing analysis and GIS analysis. The basin DEM and other topographic attributes have been obtained from SRTM data. Maps related to basin boundary, slope, flow direction, drainage network, and sub-basin have been derived by using the "DEM Hydro-processing" module of ILWIS. Sub-basin map has been generated corresponding to 11 gauging stations in the basin. 55 rainfall stations and 8 ET stations have been considered for Thiessen polygon development. There are 11 districts and 192 cities in the basin which have been demarcated using toposheets and Landsat satellite image. Multi-temporal NOAA AVHRR data (1 km resolution) and ancillary crop acreage and CCA information in Tapi basin has been used to determine cropping pattern and delineating the irrigable command areas of different reservoirs. Landsat (TM sensor) data of the basin has been used for delineating different reservoirs and extent of cities in the basin. A total of 77 reservoirs/diversion structures have been considered which were located using Landsat TM image. Soil map has been obtained from NBSSLUP and soils have been grouped in 4 hydrological classes. Land use map for the basin has been downloaded from USGS land use/land cover map for Eurasia. Groundwater depth information for one season of a number of observation wells could be obtained from CGWB. A few maps of the Tapi basin are shown in Figure – 2.6 (a – c).

Attribute data of crops, soils, gauging sites, various hydraulic structures etc. have been obtained from a variety of sources. Dynamic data of rainfall of a few years of record (1992-96) was obtained from CWC. Average evapo-transpiration depths have been worked out through CROPWAT model by using the average meteorological parameters. The database preparation for model is quite exhaustive but has been described here in brief for Tapi basin. For details of model application, please refer to Goel et al. (2008).

The model has been run using the rainfall data of 55 stations for the period 1992 – 96 for the entire basin up to Ukai dam and the model parameters have been refined so that the

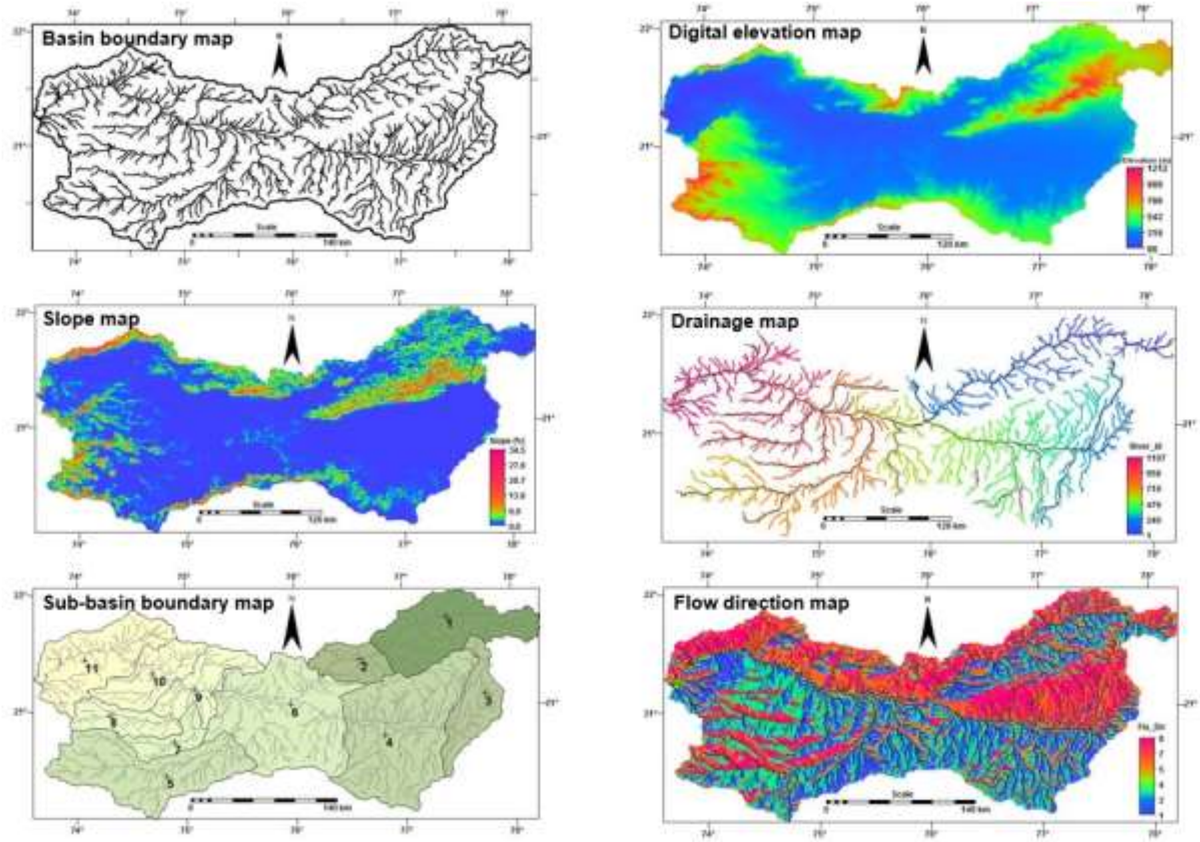
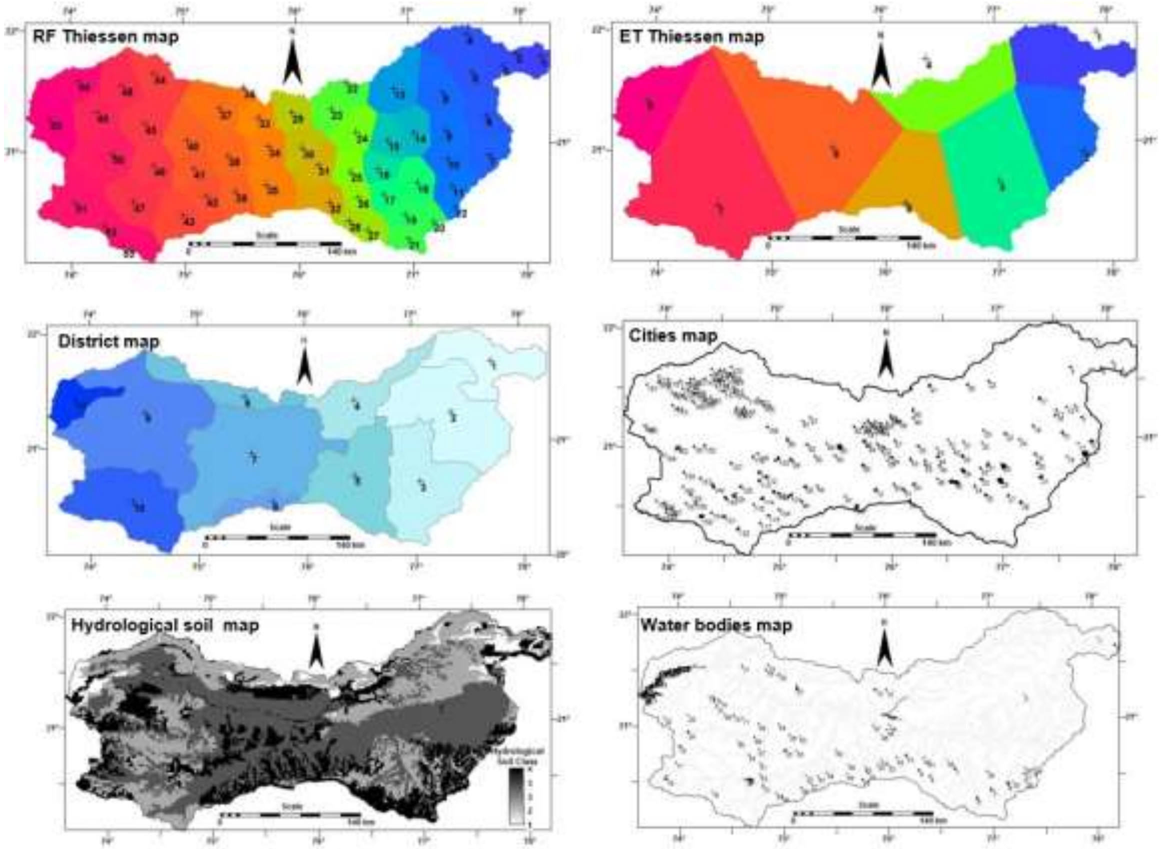


Figure – 2.6 (a): Spatial maps of the Tapi basin for input to the model



RF Thiessen map

ET Thiessen map

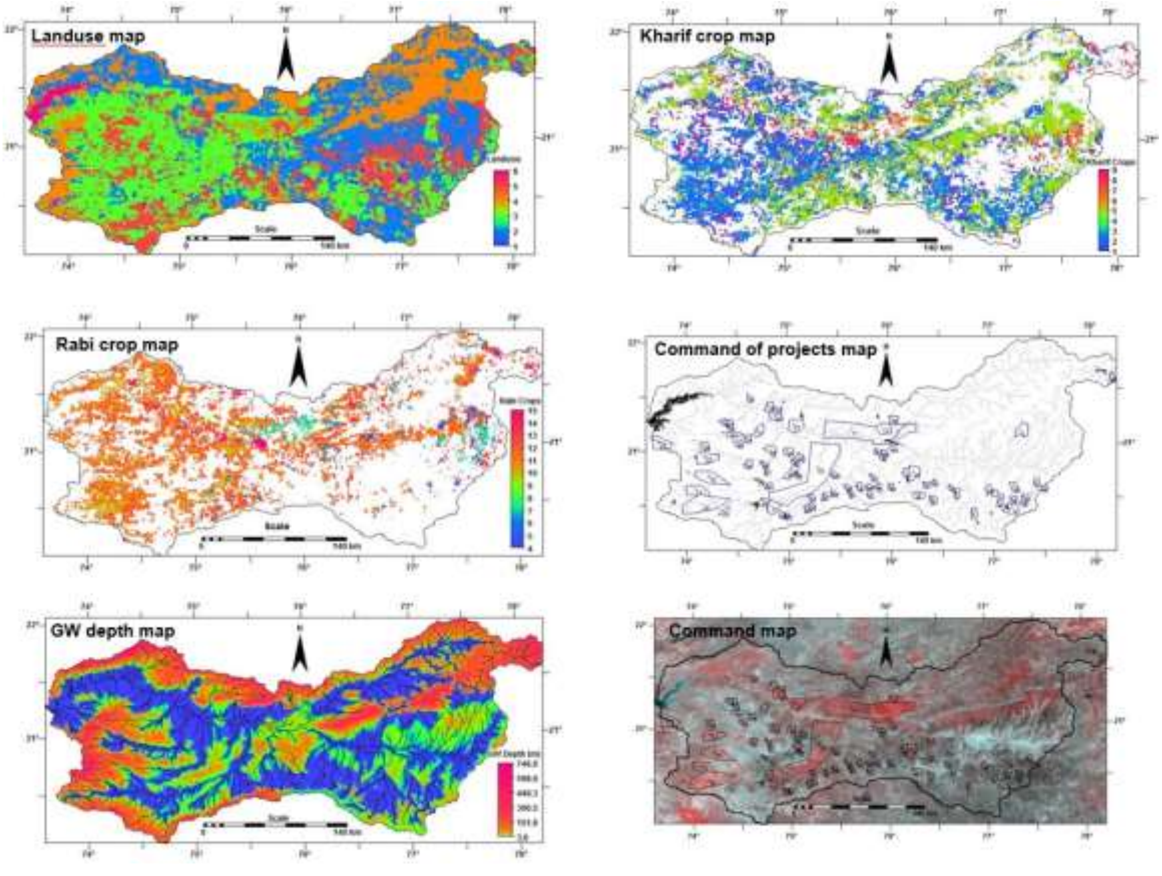
District map

Cities map

Hydrological soil map

Water bodies map

Figure – 2.6 (b): Spatial maps of the Tapi basin for input to the model



Landuse map

Kharif crop map

Rabi crop map

Command of projects map

GW depth map

Command map

Figure – 2.6 (c): Spatial maps of the Tapi basin for input to the model observed and simulated flows at various gauging sites match to a considerable extent. The observed and simulated flows at five major gauging sites for the year 1992-93 and 1995-96 are presented in Figure – 2.7 (a, b).

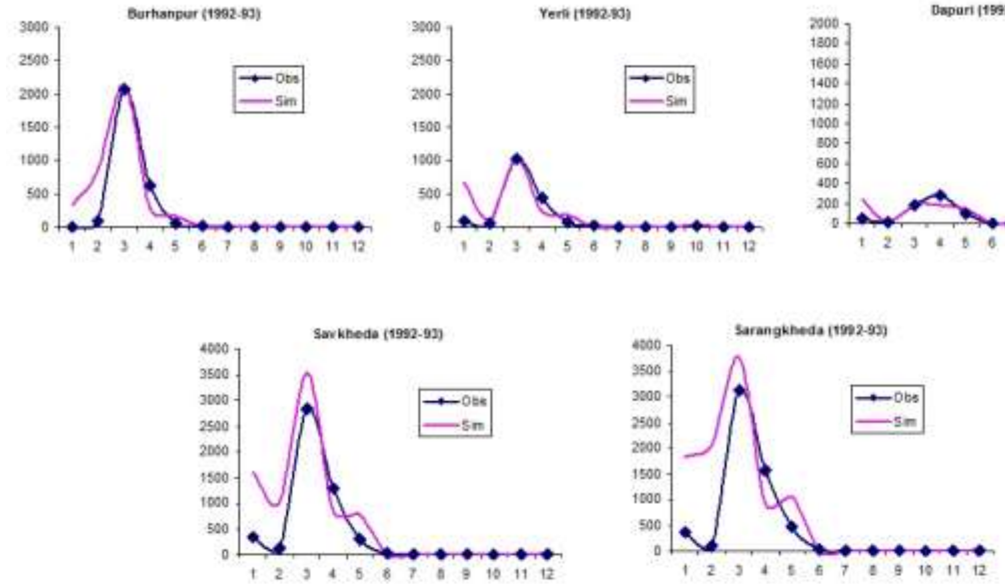


Figure – 2.7 (a): Observed/simulated flows (MCM) at different sites in Tapi basin in 1992-93

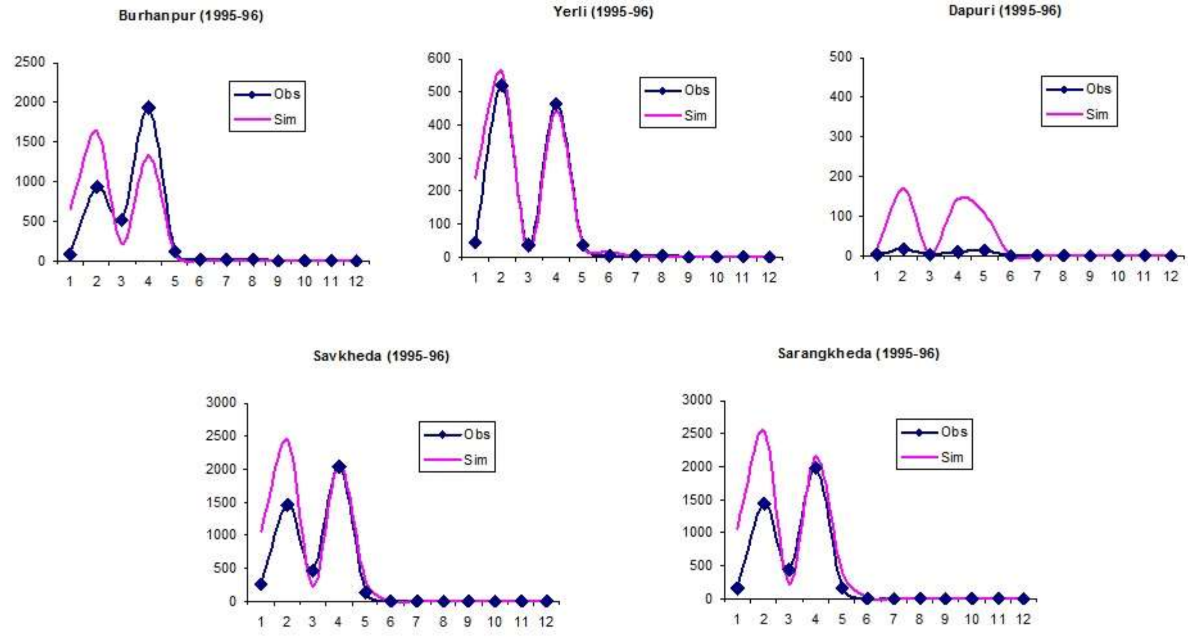


Figure –2.7 (b): Observed/simulated flows (MCM) at different sites in Tapi basin in 1995-96

Though a number of assumptions have been made in some sets of data (annual average ET, reservoir operation as per SLOP policy, derived project command boundaries, derived cropping pattern etc.), the match of the observed and simulated flows at different gauging sites was encouraging. In addition to the simulated flows at different gauging sites, a few spatial outputs are also generated which can be visualized using ILWIS GIS system. The sample spatial outputs corresponding to a particular period are shown in Figure – 2.8.

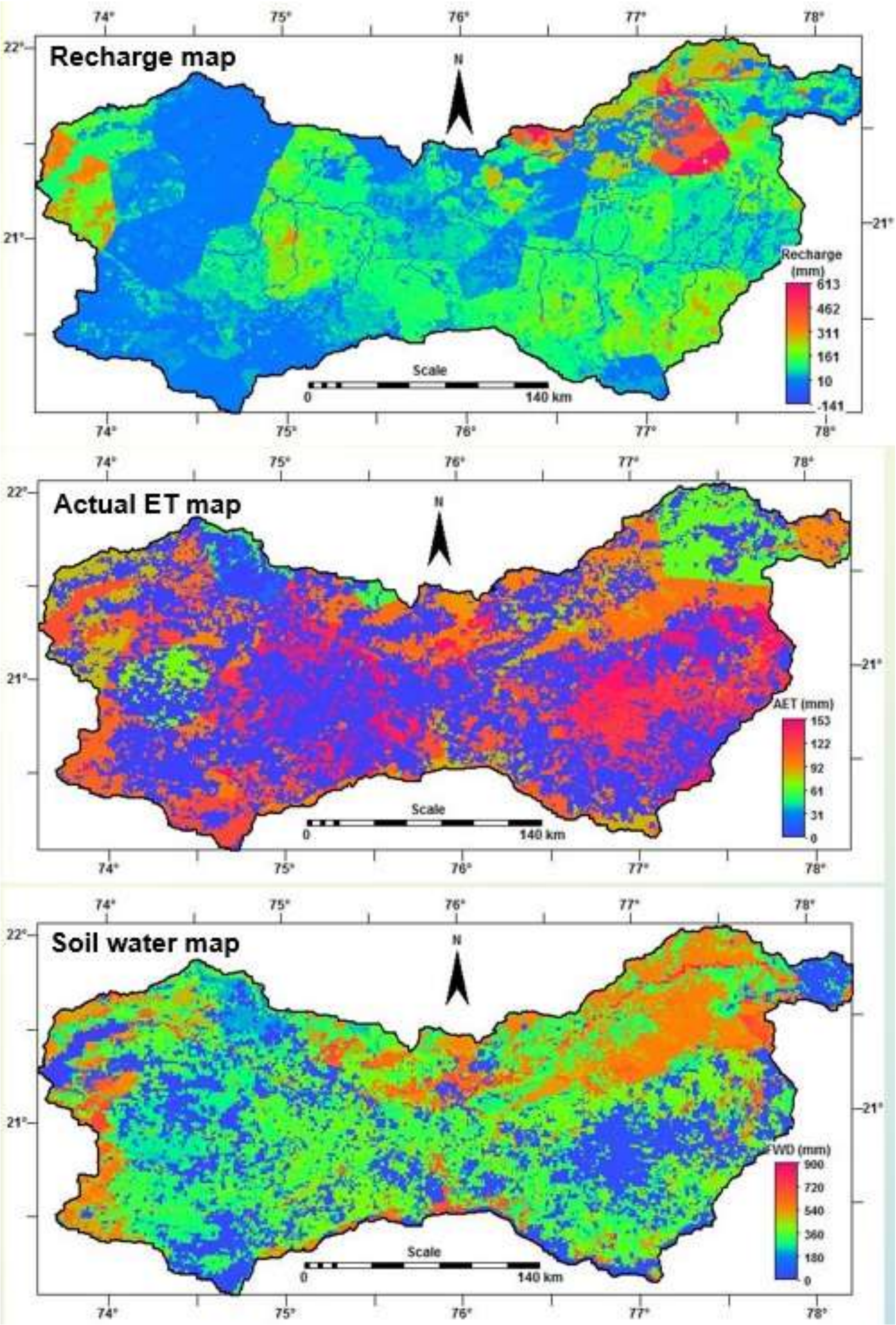
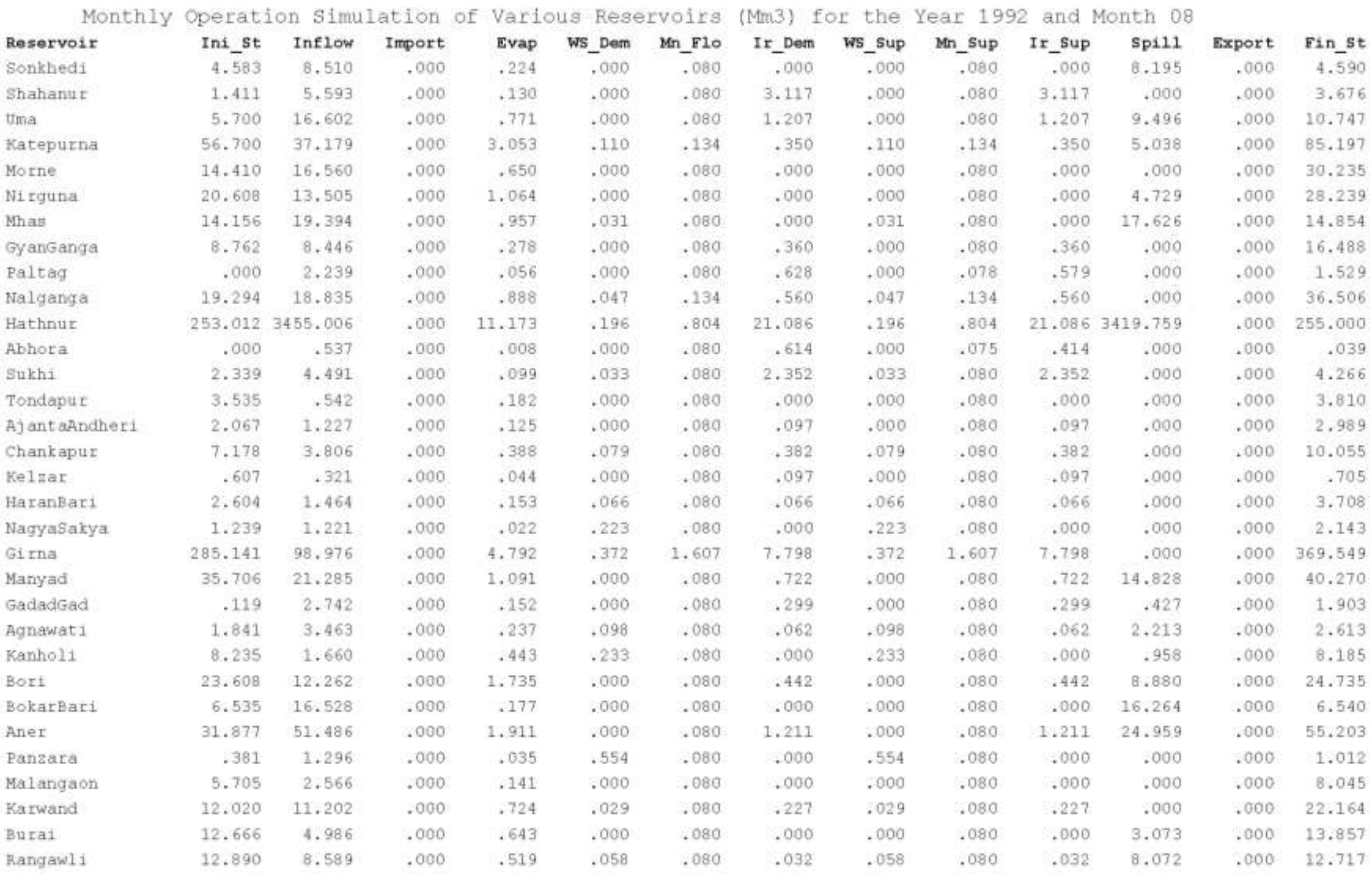


Figure –2.8: Spatial outputs of simulation model at the end of a month

Further, the water balance of different hydraulic structures can be visualized at daily and monthly time step. One such computation at monthly time step for a few structures is shown in Figure – 2.9. Finally, the detailed water balance of different sub-basins for different land uses is computed by the model at monthly time step and one such computation for a sub-basin is presented in Table – 2.2. From the monthly values, annual estimates of important hydrological components can be obtained as shown in Table – 2.3.



```
        Monthly Operation Simulation of Various Reservoirs (Mm3) for the Year 1992 and Month 08
Reservoir          Ini_St   Inflow   Import     Evap   WS_Dem   Mn_Flo   Ir_Dem   WS_Sup   Mn_Sup   Ir_Sup    Spill   Export   Fin_St
Sonkhedi            4.583    8.510     .000     .224     .000     .080     .000     .000     .080     .000    8.195     .000    4.590
Shahanur            1.411    5.593     .000     .130     .000     .080    3.117     .000     .080    3.117     .000     .000    3.676
Uma                 5.700   16.602     .000     .771     .000     .080    1.207     .000     .080    1.207    9.496     .000   10.747
Katepurna          56.700   37.179     .000    3.053     .110     .134     .350     .110     .134     .350    5.038     .000   85.197
Morne              14.410   16.560     .000     .650     .000     .080     .000     .000     .080     .000     .000     .000   30.235
Nirguna            20.608   13.505     .000    1.064     .000     .080     .000     .000     .080     .000    4.729     .000   28.239
Mhas               14.156   19.394     .000     .957     .031     .080     .000     .031     .080     .000   17.626     .000   14.854
GyanGanga           8.762    8.446     .000     .278     .000     .080     .360     .000     .080     .360     .000     .000   16.488
Paltag               .000    2.239     .000     .056     .000     .080     .628     .000     .078     .579     .000     .000    1.529
Nalganga           19.294   18.835     .000     .888     .047     .134     .560     .047     .134     .560     .000     .000   36.506
Hathnur           253.012 3455.006     .000   11.173     .196     .804   21.086     .196     .804   21.086 3419.759     .000  255.000
Abhora               .000     .537     .000     .008     .000     .080     .614     .000     .075     .414     .000     .000     .039
Sukhi               2.339    4.491     .000     .099     .033     .080    2.352     .033     .080    2.352     .000     .000    4.266
Tondapur            3.535     .542     .000     .182     .000     .080     .000     .000     .080     .000     .000     .000    3.810
AjantaAndheri       2.067    1.227     .000     .125     .000     .080     .097     .000     .080     .097     .000     .000    2.989
Chankapur           7.178    3.806     .000     .388     .079     .080     .382     .079     .080     .382     .000     .000   10.055
Kelzar               .607     .321     .000     .044     .000     .080     .097     .000     .080     .097     .000     .000     .705
HaranBari           2.604    1.464     .000     .153     .066     .080     .066     .066     .080     .066     .000     .000    3.708
NagyaSakya          1.239    1.221     .000     .022     .223     .080     .000     .223     .080     .000     .000     .000    2.143
Girna             285.141   98.976     .000    4.792     .372    1.607    7.798     .372    1.607    7.798     .000     .000  369.549
Manyad             35.706   21.285     .000    1.091     .000     .080     .722     .000     .080     .722   14.828     .000   40.270
GadadGad             .119    2.742     .000     .152     .000     .080     .299     .000     .080     .299     .427     .000    1.903
Agnawati            1.841    3.463     .000     .237     .098     .080     .062     .098     .080     .062    2.213     .000    2.613
Kanholi             8.235    1.660     .000     .443     .233     .080     .000     .233     .080     .000     .958     .000    8.185
Bori               23.608   12.262     .000    1.735     .000     .080     .442     .000     .080     .442    8.880     .000   24.735
BokarBari           6.535   16.528     .000     .177     .000     .080     .000     .000     .080     .000   16.264     .000    6.540
Aner               31.877   51.486     .000    1.911     .000     .080    1.211     .000     .080    1.211   24.959     .000   55.203
Panzara              .381    1.296     .000     .035     .554     .080     .000     .554     .080     .000     .000     .000    1.012
Malangaon           5.705    2.566     .000     .141     .000     .080     .000     .000     .080     .000     .000     .000    8.045
Karwand            12.020   11.202     .000     .724     .029     .080     .227     .029     .080     .227     .000     .000   22.164
Burai              12.666    4.986     .000     .643     .000     .080     .000     .000     .080     .000    3.073     .000   13.857
Rangawli           12.890    8.589     .000     .519     .058     .080     .032     .058     .080     .032    8.072     .000   12.717
```

Figure –2.9: Sample output of monthly operation simulation of reservoirs in Tapi basin

Table – 2.2

A sample table showing hydrological details of a sub-basin in Tapi basin

```
---------------------------------------------------------------------------
                 Monthly Results for the Year 1992 and Month 08

                       Sub-basin --- Dedtalai
                      -------------------------

            Domestic & Industrial Demands and Supply (Mm3)
           ------------------------------------------------
        Total WS Demand in Rural Area            =       .8177
        Total WS Demand in Urban Area            =       .2882
        Total GW Withdrawal for meeting WS Demand =     1.1059
        Total SW Supply for meeting WS Demand     =      .0000
        Total GW Recharge from WS Discharge       =      .0000
        Total Overland Flow from WS Discharge     =      .0231

             Hydrological Details Under Different Landuses (Mm3)
            -----------------------------------------------------
                           Urban   RFed_Agr   Irr_Agr     Forest    Barren     Water       Total
Area (Sq. km)                 18       2234       322       3945       317         4        6840
Rainfall                  7.7410  1109.1900  112.8460  2210.1130  108.5090    1.2850   3548.3990
Surface Inflow             .0000      .0000     .0000      .0000     .0000     .0000       .0000
GW Contribution            .0000      .5153     .1287     3.0619     .0000     .0000      3.7058
Irr. Application           .0000      .0000     .0056      .0000     .0000     .0000       .0056
Evapo-Transpiration       1.5222    38.8890   17.0613   309.3272   29.3457     .3704    396.1455
Runoff                    6.1115   701.8326   69.1441   852.2864   53.3807     .0000   1682.7550
Rt Zn Soil Mois. Inc.     -.0316   172.6715   12.2924   147.4874   -1.7926     .0000    330.6269
GW Recharge                .1619   196.1441   14.4961   904.1920   27.5775     .3720   1142.5720

               Irrigation Demands and Supply (Mm3)
              -------------------------------------
         Total Irr. Demand in SW_Irr Area  =       .0000
         Total Irr. Demand in GW_Irr Area  =       .0753
         Total SW Supply in SW_Irr Area    =       .0000
         Total GW Supply in SW_Irr Area    =       .0000
         Total GW Supply in GW_Irr Area    =       .0056

               Runoff Stagnated or Out of Sub-basin (Mm3)
              --------------------------------------------
         Runoff Out of the Basin            =       .7922
         Runoff Out of the Sub-basin        =       .0229
         Runoff Stagnated in the Sub-basin  =       .6355

      Cumulative Results of Different Reservoirs in the Subbasin (Mm3)
     -------------------------------------------------------------------
         Number of Reservoirs in the Subbasin        =       2
         Initial Storage in Reservoirs               =      5.8280
         Total Riverflows to the Reservoirs          =     18.7028
         Total RF Contribution to the Reservoirs     =      1.2850
         Total Peripheral Inflow to the Reservoirs   =       .0000
         Total Imports to the Reservoirs             =       .0000
         Total Evaporation losses from Reservoirs    =       .4641
         Total WS Demand from the Reservoirs         =       .0000
         Total Min_Flow Demand from the Reservoirs   =       .1607
         Total Irrigation Demand from the Reservoirs =       .0000
         Total Release for WS from the Reservoirs    =       .0000
         Total Release for Mn_Flo from Reservoirs    =       .1607
         Total Release for Irr. from the Reservoirs  =       .0000
         Total Spill from the Reservoirs             =      9.3001
         Total Exports from the Reservoirs           =       .0000
         Final Storage in the Reservoirs             =     15.8862
```

Table – 2.3

Annual values of hydrological variables for Dedtalai sub-basin in Tapi basin

Hydrological Variables	**Annual values (MCM) for year (June – May)**			
	1992-93	**1993-94**	**1994-95**	**1995-96**
Domestic & Industrial Demands and Supply				
Total WS Demand in Rural Area	9.6276	9.6276	9.6276	9.6540
Total WS Demand in Urban Area	3.3933	3.3933	3.3933	3.4026
Total GW Withdrawal for meeting WS Demand	13.0210	13.0210	13.0210	13.0566
Total SW Supply for meeting WS Demand	0.0000	0.0000	0.0000	0.0000
Total GW Recharge from WS Discharge	0.0000	0.0000	0.0000	0.0000
Total Overland Flow from WS Discharge	0.2717	0.2717	0.2717	0.2725
Hydrological Details for the Sub-basin				
Rainfall	7265.6580	9646.3090	11008.7940	7310.1280
Surface Flow Absorbed	192.1150	234.4640	226.5410	138.8800
GW Contribution to Root Zone	317.3329	260.1798	254.8576	265.3124
Irrigation Application	6.2471	6.4756	6.2814	6.0842
Evapo-Transpiration Losses	3246.8410	3302.7185	3295.4444	2813.1143
Runoff Generated	2938.7575	4365.9039	5265.3742	3100.0472
GW Recharge	1744.6058	2048.4342	2474.7186	1411.0792
Irrigation Demands & Supply				
Total Irrigation Demand in SW_Irr Area	10.7217	10.7479	10.5514	10.0817
Total Irrigation Demand in GW_Irr Area	46.3636	45.9385	46.3759	45.8519
Total SW Supply in SW_Irr Area	4.0712	4.2922	4.0778	3.9337
Total GW Supply in SW_Irr Area	0.3373	0.3220	0.3362	0.3124
Total GW Supply in GW_Irr Area	1.8387	1.8616	1.8674	1.8384
Cumulative Details of Reservoirs in the Sub-basin				
Total Number of Reservoirs in the Sub-basin	2			
Total River flows to the Reservoirs	28.8687	81.7354	105.8027	35.2488
Total RF Contribution to the Reservoirs	2.5740	5.3030	6.2690	3.2700
Total Peripheral Inflow to the Reservoirs	0.0000	0.0000	0.0000	0.0000
Total Imports to the Reservoirs	0.0000	0.0000	0.0000	0.0000
Total Evaporation losses from Reservoirs	4.6085	5.5767	5.4181	5.2936
Total WS Demand from the Reservoirs	0.0000	0.0000	0.0000	0.0000
Total Min_Flow Demand from the Reservoirs	0.7664	0.7664	0.7664	0.7673
Total Irrigation Demand from the Reservoirs	16.1468	16.2939	15.9118	15.3428
Total Release for WS from the Reservoirs	0.0000	0.0000	0.0000	0.0000
Total Release for Min_Flo from Reservoirs	0.7336	0.7349	0.7362	0.7366
Total Release for Irr. from the Reservoirs	10.1777	10.7304	10.1946	9.8340
Total Spill from the Reservoirs	14.6914	69.6042	96.1946	22.3419
Total Exports from the Reservoirs	0.0000	0.0000	0.0000	0.0000

* * *

Chapter - 3

Description of Modifications Made in Model Methodology

3.1 Incorporation of E-A-C Relationships in River Basin Model

The operation analysis of existing and proposed hydraulic structures (storage reservoirs and diversion structures) in a river basin forms an important part of the planning and management of water resources system. Elevation-Area-Capacity (EAC) curves of a storage reservoir are among the primary requirements for various kind of reservoir analysis such as reservoir flood routing, reservoir classification, reservoir sediment distribution, and operation analysis of a reservoir for conservation and flood control purposes. A river basin may contain a large number of hydraulic structures. Though some general details for a reservoir like river bed level, MDDL, FRL, storage capacity/reservoir area at FRL and MDDL may be readily available from various sources (say, web site of India WRIS), it may be difficult to gather EAC tables for all reservoirs in the river basin.

In such circumstances, generalized relationships approximating the elevation-area and elevation-capacity characteristics of reservoirs can be adopted. In a separate study of NIH [Goel et al. (2013)], generalized elevation – area and elevation – capacity relationships have been developed for Indian reservoirs which give approximate area and capacity values at intermediate elevations in-between MDDL and FRL. The relationships have been applied to around 78 reservoirs (of various types and sizes) in different regions of India. With available EAC data, dimensionless plots of relative elevation v/s relative area have been made (shown in Figure – 3.1) and average dimensionless curves have been obtained and their mathematical equations derived (Eq. – 3.1).

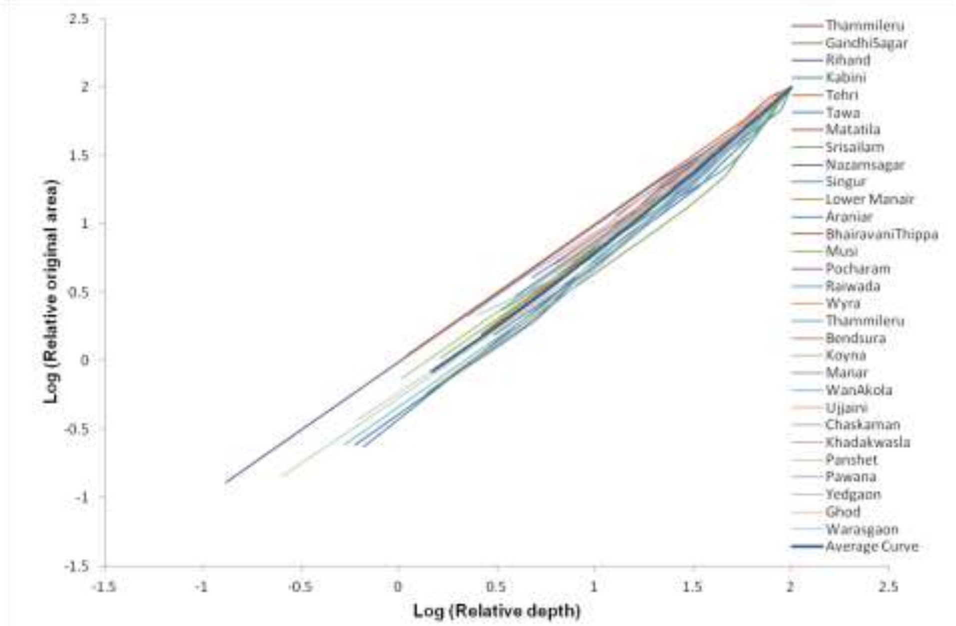


Figure – 3.1: Plot of relative original area curves for various Indian reservoirs

The mathematical relation for the dimensionless area curve is:

$$\text{Log}_{10}\,(\text{Relative area}) = 0.09 * X^2 + 0.94 * X - 0.24 \qquad \text{...(3.1)}$$

where X is the relative depth of reservoir within the live storage zone (MDDL to FRL) above the MDDL. Similarly, dimensionless plots of relative elevation v/s relative capacity have been made with available EAC data (shown in Figure – 3.2) and average dimensionless curves have been obtained and their mathematical equations derived (Eq. – 3.2).

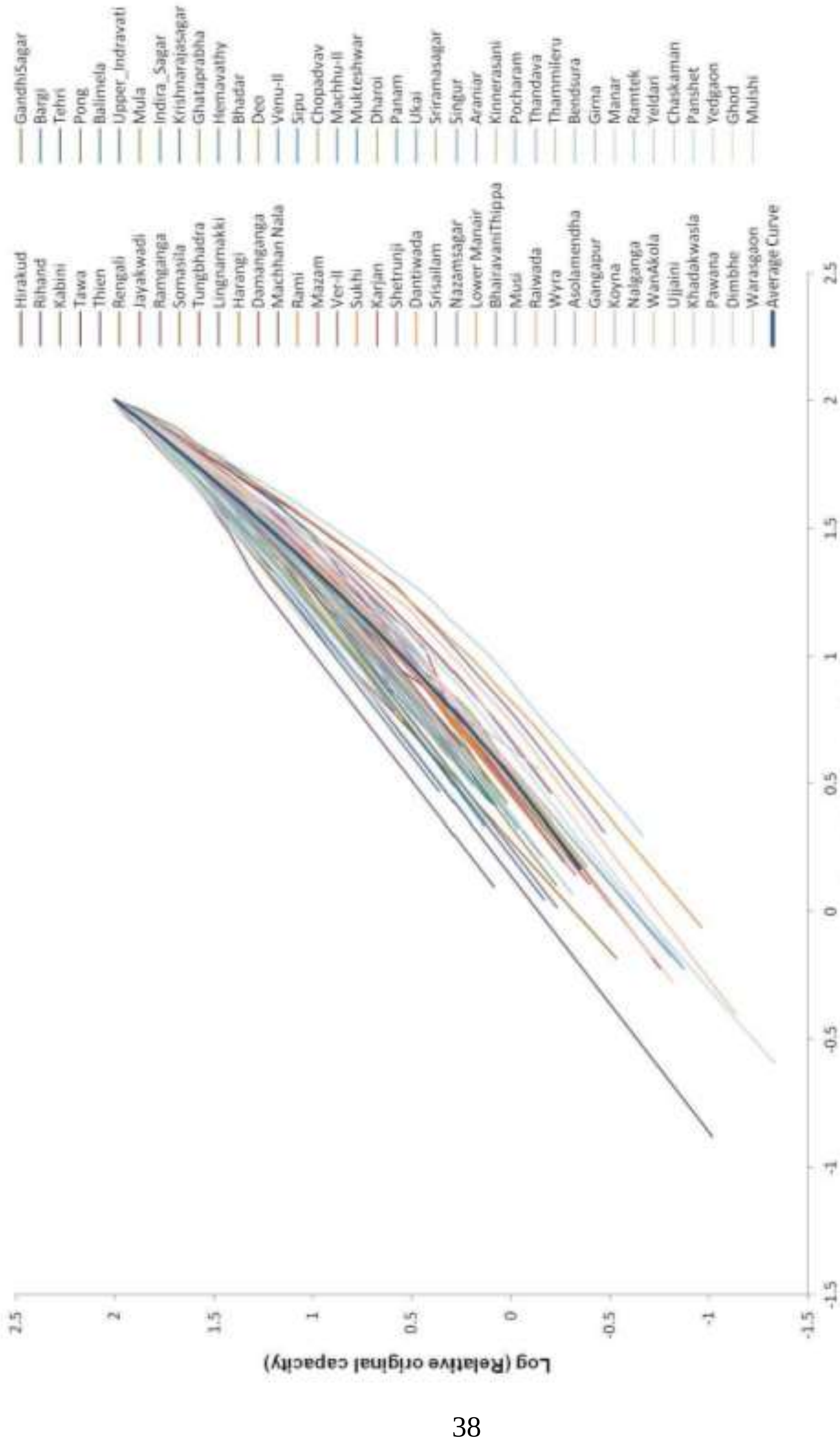


Figure – 3.2: Plot of relative original capacity for various Indian reservoirs

The mathematical relation for the dimensionless capacity curve is:

$$\text{Log}_{10}\ (\text{Relative capacity}) = 0.2 * X^2 + 0.85 * X - 0.5 \qquad ...(3.2)$$

where X is relative depth of the reservoir within the live storage zone (MDDL to FRL) above the MDDL. However, the limitation of this approach is that the relations are applicable within the live storage zone of a reservoir and do not take into account the type of reservoir under consideration. Since average relationships have been worked out from observed data, the mathematical relationships may over or under-estimate the intermediate area and capacity values for some reservoirs.

In addition to the development of dimensionless relationships using relative area and capacity at relative elevations above MDDL (NIH method), another approach developed by J. Mohammadzadeh-Habili et. al (2009) has been tested. The authors have developed area capacity relationships for reservoirs using similarity between the natural logarithmic function curve and the reservoir capacity curve. The obtained equations also consider a dimensionless parameter, named as the “reservoir coefficient”. This method approximates the Elevation-Area and Elevation-Capacity curves within full range of reservoir depth. Data requirement for the method includes river bed level (m) at the dam site, reservoir area (sq. km) and capacity (MCM) at FRL. Though the details of the method can be reviewed in the paper, brief steps of methodology are described below:

a) Total depth (m) of the reservoir from river bed level to FRL is determined and the relative depths at various elevations above river bed at which reservoir area and capacity are required are worked out.

b) Reservoir Coefficient ‘N’ is worked out by using the following equation:

$$N = 2 * \ln(2) * C_{FRL}/(A_{FRL} * D_{FRL}) \qquad ...(3.3)$$

C_{FRL}, A_{FRL}, and D_{FRL} are the reservoir capacity (MCM), area (sq. km), and total depth (in m from river bed level) at FRL.

c) Let ‘y’ be the intermediate depth above river bed at which capacity (C_y) and Area (A_y) are required. If y_m, C_m, and A_m represents the maximum depth, capacity, and area, and p (= y/y_m) represents the relative depth, then equations for C_y and A_y are:

$$C_y = C_m * [e^{(\ln(2)*p)} - 1]^{1/N} \qquad ...(3.4)$$

$$A_y = 0.5 * A_m * e^{(p*\ln(2))} * [e^{(p*\ln(2))} - 1]^{(1-N)/N} \qquad ...(3.5)$$

d) Using the equations 3.4 and 3.5, the reservoir capacity and area can be computed at any elevation above the river bed. The method is quite sensitive to the specification of river bed elevation as it affects reservoir coefficient and area capacity relationships.

A number of reservoirs with available data have been selected and comparative plots of areas and capacities from two methods (NIH and Habili method) have been prepared in conjunction with original curves. It is seen that the two methods approximate the intermediate areas and capacities quite close to the observed values. A few plots (Figure – 3.3 to 3.6) are presented for sake of illustration. In the previous river basin model, the method proposed by J. Mohammadzadeh-Habili et. al (2009) (referred to as ASCE method) has been adopted.

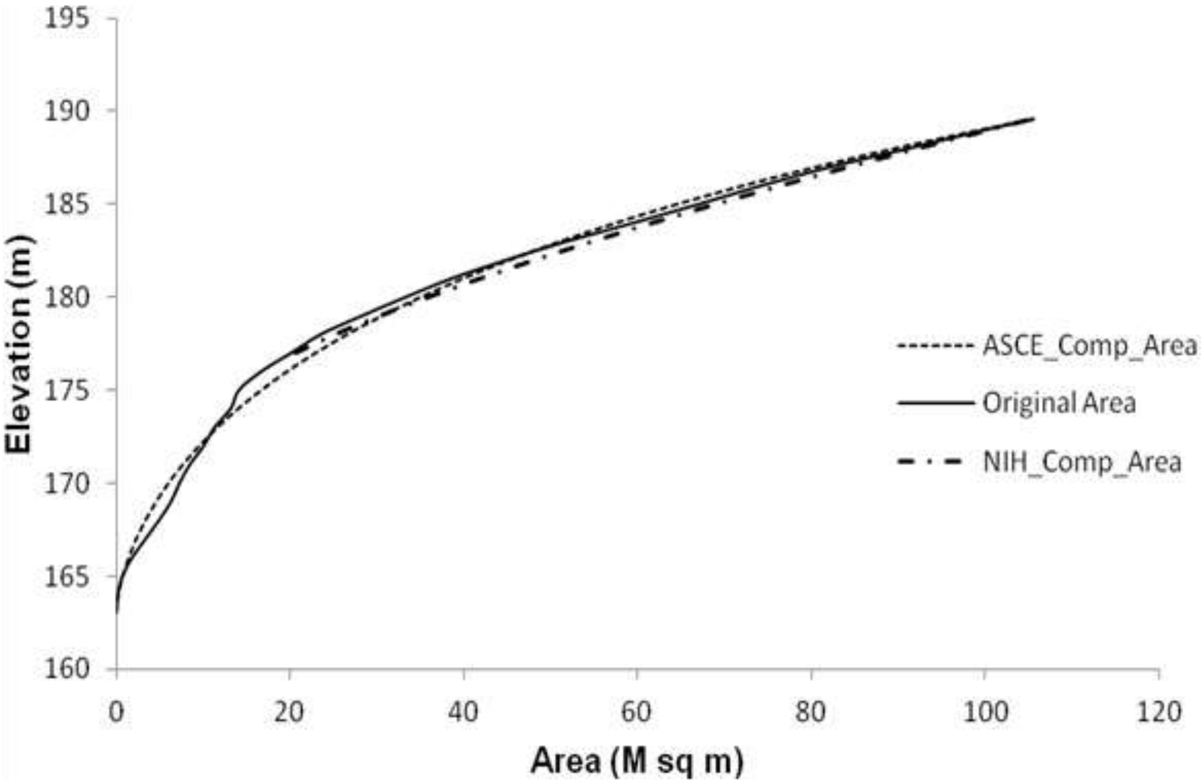


Figure – 3.3a: Plot of observed and computed elevation - area curves for Dharoi reservoir

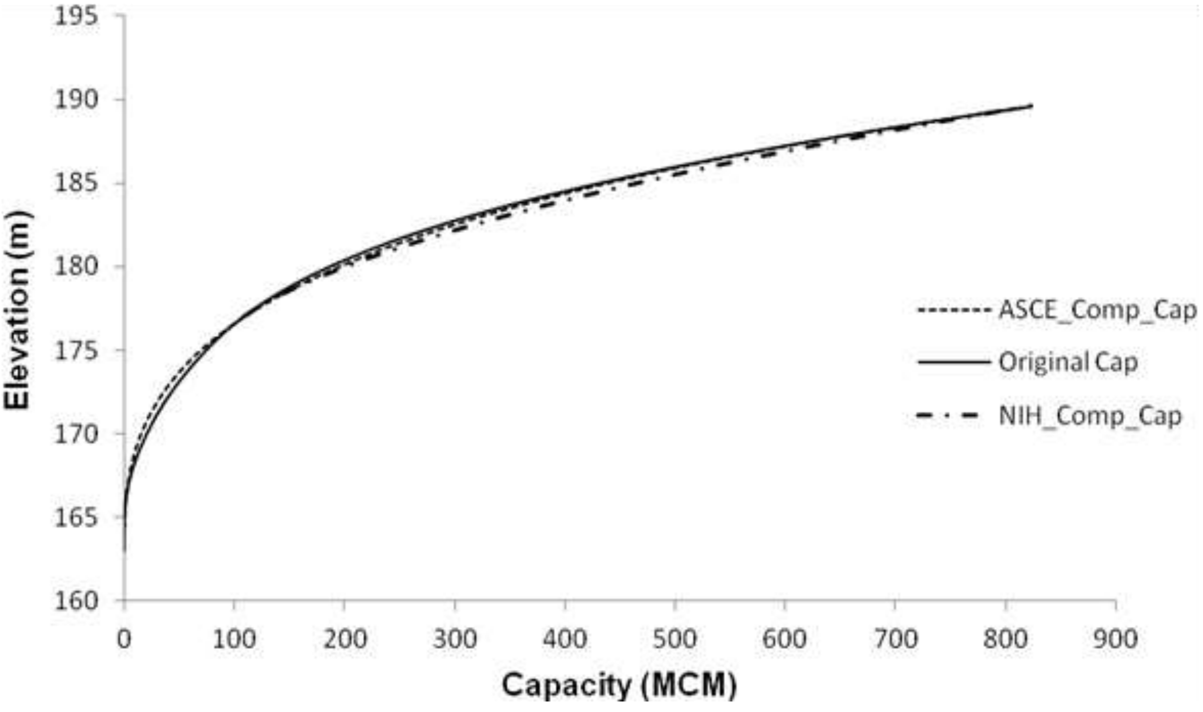


Figure – 3.3b: Plot of observed and computed elevation – capacity curves for Dharoi reservoir

In the previous approach, it was not possible to compute the reservoir elevation corresponding to some specified storage or water spread area which posed problems in the computation of head for generating hydropower. As a modification, the concept of elevation-area-capacity (EAC) relationships has been introduced in the river basin model. This concept will result in more realistic simulation analysis of reservoirs (knowing close approximations of water spread areas and capacities at different elevations), rule curve based operation, and analysis for hydropower demands and releases.

For approximating the EAC relationships for a reservoir, the approach developed by J. Mohammadzadeh-Habili et. al (2009) has been adopted. The main reason for its application is that the method approximates the elevation-area and elevation-capacity curves within full range of reservoir depth (from river bed to FRL). For the application of this method, additional data that needs to be specified for each reservoir includes: a) river bed level (m) at the dam site, b) MDDL (m) of the reservoir, and c) the FRL (m) of the reservoir. The reservoir area (sq. km) and storage capacity (MCM) at FRL are already specified for each reservoir. The method has been programmed in FORTRAN language and linked to the river basin model for computation of water spread areas and storage capacities of a reservoir at intermediate elevations between river bed level and FRL. Thus, this method avoids the necessity of obtaining EAC tables for various reservoirs in the river basin. In addition, it is also possible to specify the available EAC table for a reservoir. Depending on the available details, the operator can select the appropriate method of EAC specification of a reservoir.

3.2 Modifications for Rule-Curve Based Operation of Reservoirs in River Basin Model

The operation analysis of existing and proposed hydraulic structures (storage reservoirs and diversion structures) in a river basin forms an important part of the planning and management of water resources in a basin. One type of management frequently used for reservoir operation is based on rule curves. A rule curve or rule level specifies the water storage to be maintained in a reservoir during different times of the year. Here the implicit assumption is that a reservoir can best satisfy its purposes if the storage levels specified by the rule curve are maintained in the reservoir at different times. The rule curve, as such, does not give the amount of water to be released from the reservoir. This amount will depend upon the inflows to the reservoir, or sometimes it is specified in addition to rule curves.

The rule curves are generally derived by operation studies using historic or generated flows. Many times, due to various conditions like low inflows, minimum requirements for demands etc., it is not possible to stick to the rule with respect to storage levels. It is possible to return to the rule levels in several ways. One can be to return to the rule curve by curtailing the release beyond the minimum required if the deviation is negative or releasing an amount equal to safe carrying capacity if the deviation is positive. The rule curves implicitly reflect the established trade-off among various project objectives in the long run. For short-term operations, they serve only as a guide. The operation of a reservoir by strictly following rule curves becomes quite rigid. Many times, in order to provide flexibility in operation, different rule curves are followed in different circumstances.

3.2.1 Methodology of Rule-curve Based Reservoir Operation

Rule curves can be used to control the release for various demands from the reservoir depending on the available storage, level of demands and their priority, and likely inflows in the future. The various conservation purposes considered in the operation analysis of reservoirs in the river basin model include water supply for domestic and industrial purposes, irrigation, hydropower generation and minimum flow in the downstream river channel. For each storage reservoir, a set of rule curve levels are specified for different conservation demands. In addition, a rule curve is also specified for maintaining the highest water level in the reservoir, beyond which water can be spilled from the dam.

Each reservoir in the river basin is operated according to the prevailing reservoir level and the specified rule curve levels for different purposes during a particular month. Let us consider the example of a reservoir with three conservation demands (domestic supply including minimum d/s releases, irrigation, and hydropower in order of decreasing priority) and four rule curves as shown in Figure – 3.4: a) Upper rule curve (Curve-A), b) First middle rule curve (Curve-B), c) Second middle rule curve (Curve-C), and d) Lower rule curve (Curve-D). Curve-A represents such water levels in the reservoir in different months such that if these are maintained throughout the year, all the demands from the reservoir can be met in full. Though it is always desirable to fill a reservoir up to FRL, keeping the upper rule level below FRL (in monsoon months) can give extra room for flood absorption in the reservoir also. However, care should be taken that the conservation performance of reservoir is not affected.

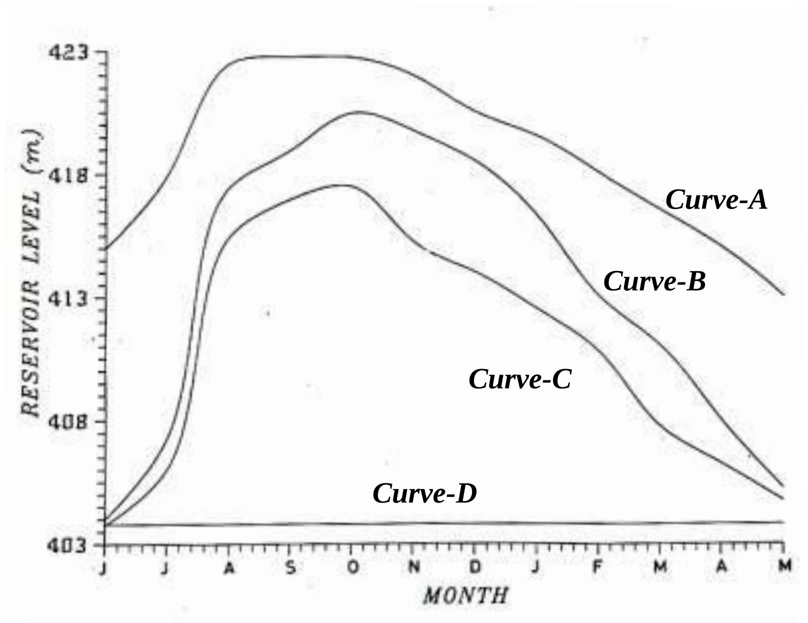


Figure – 3.4: Reservoir Rule Curves for Different Purposes

Position of rule curves for various demands depends on their relative priority. Starting upwards from the Minimum Draw Down Level (MDDL), first lies the rule curve (*Curve-D*) for the highest priority demand (domestic supply and minimum d/s requirement). This rule curve [also called Lower Rule Curve (LRC)] is specified for the case when there is very high scarcity of water and it is not possible to meet all the demands from the reservoir except for the full highest priority demands throughout the year. At/below this rule curve, only the highest priority demands are met. Next lays the rule curve (*Curve-C*) for second highest priority demand (irrigation or hydropower as specified by the user). This rule curve [also called Second Middle Rule Curve (SMRC)] is operated for the case when there is scarcity of water and it is not possible to meet all the demands except for the two highest priority demands throughout the year. If reservoir level in any month falls below this curve, then partial demands of the second highest priority demand and full demands of the highest priority demand are met. Above the SMRC lies the First Middle Rule Curve (FMRC) which represents the rule curve (*Curve-B*) for least priority demand. This rule curve is specified for the case when there is no scarcity of water and it is just possible to meet all the demands from the reservoir in full throughout the year. If the reservoir level falls in-between the FMRC and SMRC, then partial demands of the least priority demands and other demands in full are met. In all these rule curves, it is inherently assumed that the reservoir reaches the MDDL at the end of water year.

3.2.2 Modifications made in River Basin Model

In the previous river basin model, operation of a storage reservoir or diversion weir was simulated using standard linear operation policy (SLOP). Daily flows in the river network were accumulated to estimate the inflows to the hydraulic structures and then their operation was simulated using SLOP.

The model has been modified to include rule curve based operation for the storage reservoirs so that control on water resources utilization in the basin can be analyzed and basin water management issues can be addressed. The demands for irrigation and domestic supply are computed within the model while the minimum d/s flow requirements for different months are specified in the database. For rule curve based operation, in addition to the above data, the following data needs to be specified for the hydraulic structure for which rule curve based operation is invoked:

a) Specific reservoir levels, such as river bed level (m), MDDL (m), FRL (m).

b) Various demands being served by the reservoir in order of their decreasing priority, such as domestic supply, minimum d/s flow, irrigation demands, hydropower demands.

c) Monthly rule curve levels for various purposes such as rule curve levels for domestic supply and minimum flow demand (Curve-D), rule curve levels for irrigation (Curve-C), rule curve levels for hydropower (Curve-B), and upper rule curve levels for spilling the extra water and keeping some space in reservoir for flood moderation. In times of scarcity, release pattern for different demands in different reservoir zones is specified.

d) If hydropower plant is installed, then general details of power plant such as installed capacity of power plant (MW), minimum reservoir level (m) for power generation, efficiency of power plants, tail water elevation (m) or tail water rating curve, priority between irrigation and hydropower, and power demands (in MW).

e) Method of supply of releases for various demands through power plant (1 – no other release through power plant, 2 – only irrigation release pass through power plant, 3 – only domestic supply release pass through power plant, 4 – only minimum d/s flow release pass through power plant, 5 – irrigation and minimum d/s flow release pass through power plant, 6 – irrigation and domestic supply release pass through power plant, 7 – minimum d/s flow and domestic supply release pass through power plant, 8 – all release pass through power plant.

3.2.3 Computation Steps for Rule-Curve Based Operation in River Basin Model

As before, demands for irrigation and domestic supply are computed within the model and transferred to the connected reservoir for supplying the water. The demands for minimum d/s flow and power demands are specified for each storage project. The steps followed for computation of rule curve based operation of a reservoir is summarized below:

a) The river basin model is run at daily time step. If the reservoir is operated for hydropower demands, then, first the reservoir level is worked out (depending on the total storage available in the reservoir).

b) Evaporation losses are worked out based on water spread area at prevailing reservoir level.

c) Next, the prevailing reservoir elevation is compared with the rule curve levels for different purposes, and if permitted for hydropower release, then demands for meeting power demands (which depends on the head of water) is worked out. It needs to be mentioned here that two options are specified for fixing tail water elevation: i) fixed, and ii) tail water elevation is governed by the release rate from the power plants.

d) Next, water is released as per the specified criteria for meeting different demands in various zones (as per rule curves) and the reservoir storage at the end of time step is saved for specifying initial conditions at next time step.

e) The model computes the release for different purposes and the hydropower produced for each day which is written in the output file. A detailed operation table for each structure is optionally prepared. Using the operation table, the rule curves and the release pattern for different demands from the reservoir can be optimized. It is also possible to analyze different scenarios of transfer of water from different structures or inter-basin transfer.

3.3 Estimation of Average Groundwater Depth in a Sub-basin

In the previous model, prevailing groundwater surface in the basin was an important input for deciding the depth of vadose zone below root zone, groundwater contribution to meet evapo-transpiration demands, and for assessment of groundwater potential in the basin at each grid. It could also help in formulating basin management plans for conjunctive use of surface and groundwater. To analyze groundwater behavior, a groundwater simulation model with GIS interface (Visual MODFLOW) was linked to the model to generate groundwater surfaces corresponding to monthly pumping and recharge patterns in the river basin.

The previous model kept track of the daily recharge and withdrawal at each grid in the river basin. The recharge at a grid could occur from the rainfall (obtained from soil water balance module), water spread areas of reservoirs (depending on specified rate), or from irrigation areas in the command which receive water from the reservoirs. The water withdrawal at a grid was caused by the supply deficit for urban domestic demands and irrigation demands in the irrigated command areas. Rural domestic supply was met from groundwater withdrawal only. For irrigated agriculture grid outside the command area of a reservoir, the surface water was not supplied and its demands were met through groundwater withdrawal only. For such grids, groundwater withdrawal limited to the groundwater potential, was computed and was supplied as irrigation input. Groundwater potential at a grid was based on the groundwater development (number of pumping wells and pump capacity), the energy available for groundwater pumping and the groundwater depth and was estimated in a separate module in the model. The recharge and withdrawal of water at each grid from groundwater were accumulated for the whole month and net recharge or withdrawal was computed.

Next, a sub-model (WELL) was developed which was used to link the computed pumping and recharge at each grid to the groundwater simulation model (VMOD). Each grid was represented by a well through which interaction (pumping/recharge) took place with the groundwater aquifer. WELL prepared the data in a form which can be directly imported in VMOD. However, in addition to the spatially distributed pumping and recharge, various other data files were also required for the application of VMOD which include initial groundwater conditions; boundary conditions; characteristics of aquifer such as transmissibility, specific storage, and effective porosity.

The application of the groundwater simulation model at the scale of river basin required aquifer characteristics and other details for the whole basin. Further, such a model application was required to be executed at each month end for generating revised groundwater conditions which had become a tedious exercise if a long term simulation run is to be taken. Since the river basin model is used to analyze the consequences of different water management scenarios at basin scale, therefore it was envisaged to make a simplified representation of groundwater conditions in the river basin model.

3.3.1 Concept of Simplified Approach to Groundwater Modeling in River Basin Model

In the simplified approach to groundwater modeling at river basin scale, the computations for groundwater conditions are performed at the sub-basin scale. For each sub-basin, average groundwater depth is computed from the data of a large number of observation wells. A procedure, defined by DHI, Denmark in DSS under (HP-II) has been adopted for converting the irregular groundwater depth observations in different wells in a sub-basin. Further, value of specific yield (S_y) of the aquifer in each sub-basin is obtained either from the pumping test data or as specified by Groundwater Departments.

The grid-wise pumping and recharge estimations, as made earlier in the modules of river basin model, are accumulated over entire sub-basin and then divided by S_y to convert the water withdrawal/recharge to corresponding change in groundwater level. This change can be applied to the initial groundwater level to find the revised groundwater level in the sub-basin. The procedure for estimation of average groundwater level in a sub-basin is described below.

3.3.2 Estimation of Average Groundwater Level in a Sub-basin

DHI, Denmark has specified a procedure to compute the average groundwater level in a sub-basin from the data of a large number of observation wells. The procedure utilizes the long-term average groundwater levels in the sub-basin and tries to minimize the effect of any missing observation from the large number of well observations. The procedure is illustrated through a small example. Let us consider three wells with nos. W1, W2, and W3 and their monthly water depth observations are available as shown in Table – 5.1 (Col-1 to Col-3). Their averages have been worked out in Col-4 as shown in Figure – 3.5. DHI procedure suggests another way of computing the average value which utilizes the average value of the entire group of observations and the average value of observations of all individual wells. The steps of computation are as follows:

a) Compute the average value of the whole set of observations (average of Col-4) which comes out to be 7.304 in present case.

b) Compute the average value of observations of all individual wells which comes out to be 3.363, 6.125, and 12.425 for Well W1, W2, and W3 respectively.

c) Find deviation of each observation of a well from its average value as shown in Col-5.

d) Find the sum of deviations of all wells and add it to the average value of whole set of observations (Col-6).

e) The average values for all months, obtained from both the methods match.

f) If the individual observations for any month are not available (missing or not observed), still the DHI method estimates the basin average within a close range as compared to the average worked out by using the individual observations, the reason being that the DHI method uses the average of the whole group and average of individual observations also in addition to the individual values.

Table – 3.1

Example computations of average values by DHI method

Month	**Values in individual wells**			**Average of Col-2 to Col-4**	**Deviation of individual values from their average**			**Average by DHI method**
	W1	**W2**	**W3**		**W1**	**W2**	**W3**	
Mon-1	3.0	5.0	10.0	6.000	-0.363	-1.125	-2.425	6.000
Mon-2	3.5	6.0	13.0	7.500	0.138	-0.125	0.575	7.500
Mon-3	3.0	5.2	10.4	6.200	-0.363	-0.925	-2.025	6.200
Mon-4	3.6	7.1	14.0	8.233	0.238	0.975	1.575	8.233
Mon-5	3.1	4.9	10.0	6.000	-0.263	-1.225	-2.425	6.000
Mon-6	3.8	7.8	15.0	8.867	0.438	1.675	2.575	8.867
Mon-7	3.0	5.0	11.0	6.333	-0.363	-1.125	-1.425	6.333
Mon-8	3.9	8.0	16.0	9.300	0.538	1.875	3.575	9.300
Average	**3.363**	**6.125**	**12.425**	**7.304**				

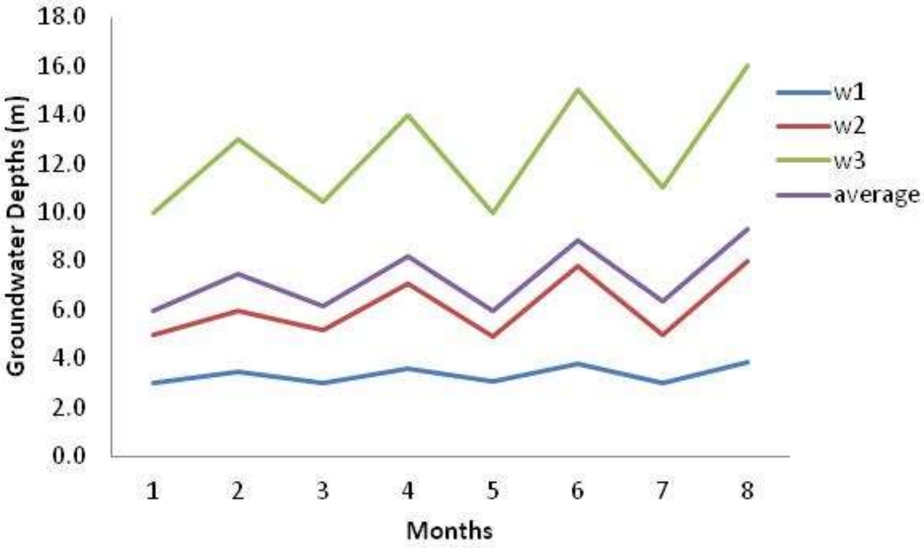
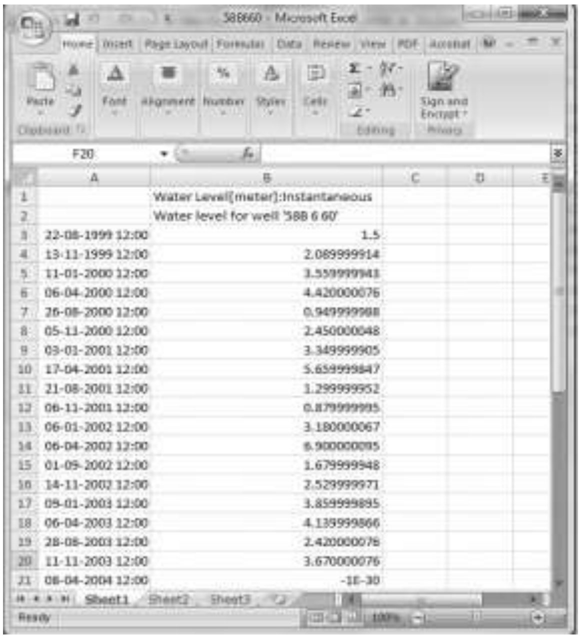


Figure – 3.5: Groundwater depth values in different wells

3.2.3 Computer Programs for Estimation of Average Groundwater Depth in a Sub-basin

Based on the experience of DSS (P) application to Indian States under HP (II), it is observed that the GW level data are taken in different months which do not follow a uniform observation pattern (sample shown in Figure – 3.6). It is a difficult and time-consuming task to apply the DHI technique manually to compute the average groundwater conditions in a sub-basin. For this reason, two computer programs have been developed to automate the procedure to a considerable extent. First program (GWDATA) receives the irregular data (at irregular time steps) of GW depths in a well and then creates a sequence of groundwater levels at uniform monthly time step. Second program (AGD) computes the time series of average GW level in a sub-basin from the created regular series of GW levels in a sub-basin by DHI procedure.



	A	B
1		Water Level(meter):Instantaneous
2		Water level for well '588 6 60'
3	22-08-1999 12:00	1.5
4	13-11-1999 12:00	2.089999914
5	11-01-2000 12:00	3.559999943
6	06-04-2000 12:00	4.420000076
7	26-08-2000 12:00	0.949999988
8	05-11-2000 12:00	2.450000048
9	03-01-2001 12:00	3.349999905
10	17-04-2001 12:00	5.659999847
11	21-08-2001 12:00	1.299999952
12	06-11-2001 12:00	0.879999995
13	06-01-2002 12:00	3.180000067
14	06-04-2002 12:00	6.900000095
15	01-09-2002 12:00	1.679999948
16	14-11-2002 12:00	2.529999971
17	09-01-2003 12:00	3.859999895
18	06-04-2003 12:00	4.139999866
19	28-08-2003 12:00	2.420000076
20	11-11-2003 12:00	3.670000076
21	08-04-2004 12:00	-1E-30

Figure – 3.6: GW level data in an observation well at irregular intervals

The developed programs have been linked with the river basin model so that average groundwater levels in various sub-basins can be computed from the irregular groundwater depth observations in various observation wells in the basin.

3.4 Incorporation of 3-Seasonal Cropping Pattern with/without projects

Contrary to the previous practice, where cropping pattern in the Kharif and Rabi season only were considered, modifications have been made for specifying spatial cropping patterns in Kharif, Rabi, and Hot-weather seasons under two conditions – with and without the water resources projects. Before the commissioning of a project, the cropping pattern (without project) in the command of the project is picked up while after the commissioning of project, the revised cropping pattern in the command of a project (after the project commissioning) in 3 seasons is used by the model. A computer program (CRSB_COD.for) is used to merge the 3-season spatial cropping pattern (without the projects) with the sub-basin information while another computer program (CRPR_COD.for) is used to merge the 3-season spatial cropping pattern (with the projects) with the sub-basin information. A maximum of 99 crops in each season and 1000 sub-basins can be specified. Impact of a water resources project is considered from the year and month of its commissioning which is specified in its attribute file.

3.5 Increasing the Dimensional Range of Cities, Soils, RF & ET Stations

A computer program (CSRE_COD.for) has been developed to integrate the spatial information of cities in the river basin, various soil types, and thiessen polygons of rainfall and ET stations. Modifications have been made to increase the dimensional range of these variables. Now, a maximum of 1000 cities in a river basin, 100 soil types, 1000 rainfall stations, and 100 ET stations can be specified.

3.6 Increasing the Dimensional Range of WR Projects, Water Bodies, River Network, and Land use

A computer program (RWSL_COD.for) has been developed to integrate the spatial information of man-made water resources projects in the river basin, various segments defining the river network, land use pattern, and natural water bodies. Modifications have been made to increase the dimensional range of these variables. Now, a maximum of 1000 man-made water resources projects in the river basin, 100000 river network segments, 60 land uses, and 1000 natural water bodies can be specified.

3.7 Increasing the Dimensional Range of Elevation, Slope, Flow Direction, and Districts

A computer program (TOPO_COD.for) has been developed to integrate the spatial information of elevations, slope, flow direction, and districts in a river basin. Modifications have been made to increase the dimensional range of number of districts. Now, a maximum of 1000 districts can be considered in a river basin.

3.8 Specification of GW Potential and Initial Depth

In the previous version of the model, GW potential and the initial groundwater depth was a spatial input and the GW potential which did not vary with time. In the revised version, the GW potential is computed for each sub-basin separately at the beginning of each day. The GW potential is based on the present GW level in the sub-basin, minimum level up to which GW can be extracted in the sub-basin, specific yield of the sub-basin aquifer, and the pumping capacity in the sub-basin which is obtained from the district-wise statistical records. For each day and for each sub-basin, the total water demands from the GW system (for urban and rural water supply and for irrigation) are worked out and compared with the GW potential. If the GW potential is limited in comparison to the sub-basin demands from groundwater, then highest priority is given to the domestic supply demands followed by irrigation. In case of deficit for a particular demand, the same is distributed among the demand grids in proportion of their magnitude. The revised GW level is computed in each sub-basin for each day depending on the overall pumping/recharge in the sub-basin.

3.9 Specification of Industrial Demands

In the previous version, the industrial demand was assumed to be equal to the domestic supply demand (which was computed from the population data in different districts for human and cattle population). As a modification, industrial demand has now been linked with the city attributes and a demand pattern is specified. The industrial growth rate is also considered as an attribute of district data which is used to compute revised industrial demands at the beginning of each year. Input also includes the year of establishment of industry so that its effect can be considered from that time onwards. In addition, industrial growth rate is also accounted for.

3.10 Computation of Base Flow

In the previous version, the base flow was computed for different months depending on the observations of GW storage above the gauging site. In the present case, the base flow is computed as a function of the GW storage in the independent sub-basin above the gauging site. Everyday, the GW pumping/recharge are estimated and revised GW level (and GW storage above gauging site bed elevation) in each sub-basin is computed and base flow is worked out.

3.11 Miscellaneous Modifications

In addition to the modifications mentioned above, a number of modifications have been made in the modeling methodology as briefly described below:

a) Since the concept of continuous simulation has been added, the calendar day, week, month, and year are worked out for each daily time step. Different variables utilize these time steps, say population projection is computed at annual time step while crop coefficients are used at weekly time step. An extra day in a leap year (Feb 29) is merged with Week 9 while extra day at the end of a year (Dec 31) is clubbed with week 52.

b) It is now possible to specify the population for different cities. This allows more realistic representation of city population as compared to the earlier scenario when the urban population in a district was uniformly distributed among different cities in the district. Now, the balance urban population (after accounting for specified urban population in selected cities) is distributed uniformly among the remaining cities in a district.

c) As earlier, rural population is assumed to reside uniformly in rural grids (with land use attributes of agricultural and barren lands). However, considering that this may not be the case in hilly/mountainous area, an elevation needs to be specified above which the assumed rural grid criterion is not applied.

d) Population growth is considered and revised human and cattle population in each grid is computed at the beginning of each year as per the growth rate criteria. In addition, percentage urban population change is also observed and applied to find relative urban population in the cities.

* * *

Chapter - 4

WINDOWS Interface for *NIH_Basin*

4.1 WINDOWS Interface of the Model

One of the envisaged objectives of study is to develop a WINDOWS interface of the model for easy application by the user groups. The WINDOWS interface has been developed in Visual Basic platform. In WINDOWS interface of the model, various data input forms have been developed. The layout plan of software for various activities is shown in Figure – 4.1.

Figure – 4.1: Layout plan of *NIH_Basin* main screen

Four important modules of the software are:

a) Database Preparation
b) GIS Analysis
c) Model Execution
d) Results

4.2 Description of "Select Project" Module

The various forms under these modules will be described in the following sections. In addition, there is *"Select Project"* module at the beginning of screen. This module is used to specify the location of various files related to databases (attribute, GIS, and temporal) and results of a particular basin for which analysis is currently being carried out. A sample screen for this module is shown in Figure – 4.2. A WINDOWS interface guides the user to select/ create the basin directory (say, D:\NIH_Basin\Tapi). If it is a new directory, then different sub-directories are automatically created to store the relevant files. An example is shown below:

D:\NIH_Basin\Tapi
- Database
    - Attribute
    - GIS
    - TimeSeries
- Results

Figure – 4.2: Sample screen for specifying the location of basin files under analysis

However, if it is an existing directory, then only the location of the directory is specified and the model is able to retrieve/save the relevant files without overwriting. The reason for such an arrangement is that the model has more than 30 input files and various output files which are linked to different software programs. The filenames of different files have been standardized, say attributes of cities in a basin are stored in *"city.atr"* file, rainfall data of different stations in the basin are stored in *"rf.tms"* file etc. In order to avoid confusion to the user in the selection of different files for different purposes, the filenames have been standardized and such standardized data filenames have been linked in various software files. However, this arrangement requires that analysis for one basin may be made at any given time in a computer.

After invoking the software, *"Select Project"* is the first module that is selected for specifying the location of basin files. The other modules can be worked with only after the specification of location of basin files. The standardized filenames adopted for various data files are shown in Table – 4.1.

Table – 4.1
Standardized filenames of different data files

Type of data	Standardized filename
Attribute Data	
Cities in the basin	City.atr
Crops in the basin	Crop.atr
District information in the basin	Dist.atr
Gauging station details in basin	Gage.atr
Hydraulic structure details in basin	Hstr.atr
River network details in basin	Rivr.atr
Soil properties in basin	Soil.atr

Type of data	Standardized filename
Time Series Data	
GW observation well data at single station	Gwell.tms
Monthly GW elevation time series at single station	Agwe.tms
Average GW elevation time series (monthly) in all sub-basins	Agweall.tms
Daily release time series from different dams in basin	Damrel.tms
Daily reference crop ET at all stations in basin	Et.tms
Daily rainfall data at all stations in basin	Rf.tms
Daily weather data for reference ET computation at single station	Etsingle.tms
Daily import data at different locations in the basin	Import.tms
Daily export data from different locations in the basin	Export.tms
Daily observed flow at different gauging station in the basin	Obsq.tms
GIS Data Layers	
Basin map showing location of grids with basin	Basin.dat
Crop map of Kharif season	Crp1.dat
Crop map of Rabi season	Crp2.dat
Crop map of Hot-weather season	Crp3.dat
Soil map of the basin	Soil.dat
LULC map of the basin	Lulc.dat
DEM of the basin	Dem.dat
Slope map of the basin	Slop.dat
Flow-direction map of the basin	Fdir.dat
River network map of the basin	Rnet.dat
Sub-basin map of the basin	Sbas.dat
District map of the basin	Dist.dat
City map of the basin	City.dat
Water bodies map of the basin	Wbod.dat
Irrigation command map of the basin	Icmd.dat
Thiessen polygon map of Rainfall stations	Rf.dat
Thiessen polygon map of ET stations	Et.dat
Miscellaneous General Information	
Options of the simulation analysis	Simopt.gen
Information for the GIS maps	Gisinfo.gen
Model parameters	Param.gen

4.3 Description of "Select Project" Module

All the data for a basin, except GIS layer development, is prepared in this module. Under this module, separate sections are prepared for entry of attribute data, temporal data, and miscellaneous information. Under various icons (say, *"Attribute Data"* icon), various related data types are specified. A sample screen of this module is presented in Figure – 4.3 which shows various data types under the *"Attribute Data"*. Forms are developed for each type of data depending on the model requirement. Once all the database is created for a basin, then this data is transferred to the modeling location (the location by default is *"C:\NIH_Basin"* directory) where all the programs are kept for execution. Using the *"Transfer database"* button, all the created data files are transferred to the directory *"C:\NIH_Basin"* in one go.

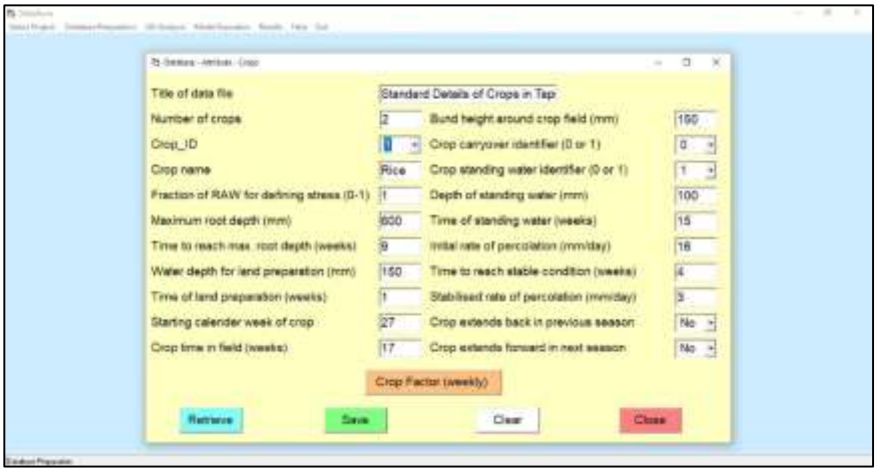
Figure – 4.3: Sample screen showing various menu items under “Database Preparation”

4.3.1 Database Preparation – Attribute Data

Various kind of attribute data prepared for the model include the attributes for the cities, districts, crops, soils, gauging stations, hydraulic structures, and river network in a river basin. The related forms of these attributes are described below.

4.3.1.1 Crop attributes

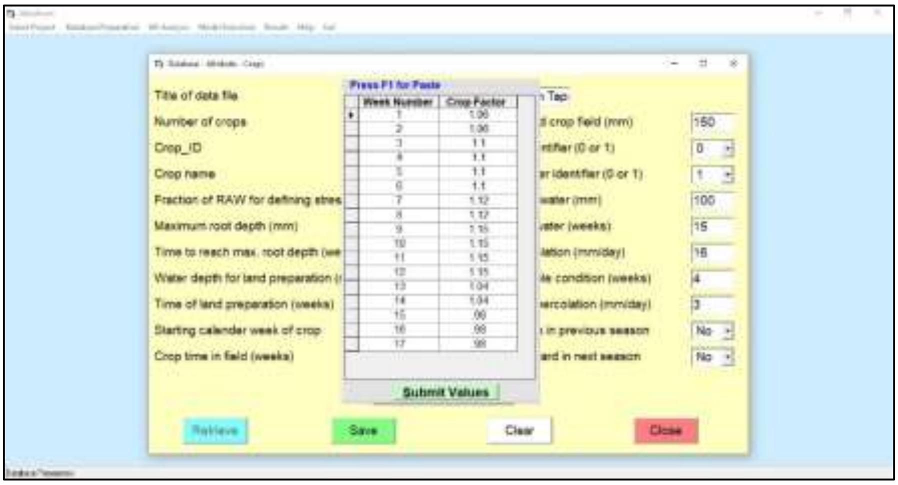
The crop attribute screen is shown in Figure – 4.4. Properties of a maximum of 100 crops can be specified using this form. As the number of crops is changed, the combo-box corresponding to the *“Crop ID”* shows the same number of numeric values. Each Crop ID corresponds to a particular type of crop with related attribute data. After specifying the Crop ID, all related information including the tabular *“Crop Factor”* is entered in relevant boxes. As soon as the Crop ID is changed, the information entered previously for a particular Crop ID, including crop factor, gets stored. The number of rows in the “Crop Factor” table corresponds to the “Crop time in field (weeks)” for the particular Crop ID.



Title of data file	Standard Details of Crops in Tap		
Number of crops	2	Bund height around crop field (mm)	150
Crop_ID	1	Crop carryover identifier (0 or 1)	0
Crop name	Rice	Crop standing water identifier (0 or 1)	1
Fraction of RAW for defining stress (0-1)	1	Depth of standing water (mm)	100
Maximum root depth (mm)	600	Time of standing water (weeks)	15
Time to reach max. root depth (weeks)	9	Initial rate of percolation (mm/day)	16
Water depth for land preparation (mm)	150	Time to reach stable condition (weeks)	4
Time of land preparation (weeks)	1	Stabilised rate of percolation (mm/day)	3
Starting calender week of crop	27	Crop extends back in previous season	No
Crop time in field (weeks)	17	Crop extends forward in next season	No

Figure – 4.4: Sample screen for specifying crop attributes for “Rice” crop

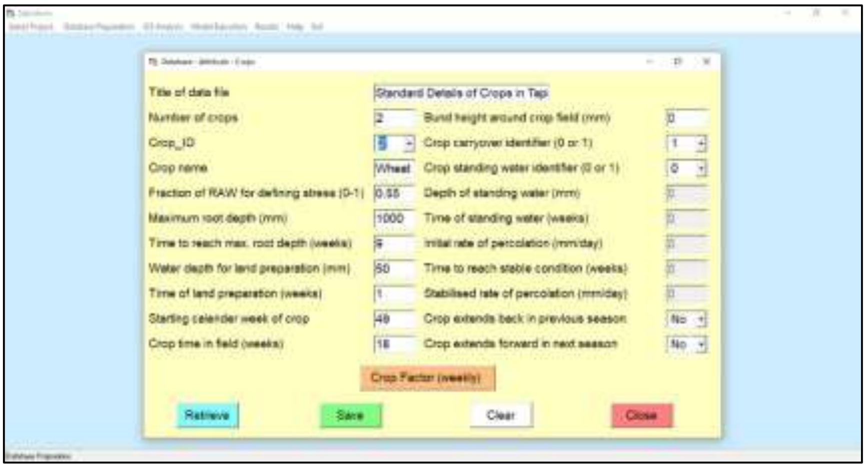
If a crop is carried over from one calendar year to the next, *"Crop carryover identifier"* is taken as 1 otherwise 0. Further, if the crop requires standing water, then the *"Crop standing water identifier"* is selected as 1 otherwise, 0. If the crop requires standing water, then the five subsequent cells are enabled for entry of related data, otherwise they are disabled. If a crop extends back/forth in previous/next season (e.g. if the Rabi crop is grown early and it extends back in the pre-defined duration of Kharif season for some time or if a Kharif season crop is extended forth in Rabi season (say, Cotton)), then this option is selected as Yes otherwise no. An example of rice and wheat crop is shown here as example in Figure – 4.4 to Figure – 4.6.


Press F1 for Paste

Week Number	Crop Factor
1	1.06
2	1.06
3	1.1
4	1.1
5	1.1
6	1.1
7	1.12
8	1.12
9	1.15
10	1.15
11	1.15
12	1.15
13	1.04
14	1.04
15	.99
16	.99
17	.99

d crop field (mm)	150
ntifier (0 or 1)	0
er identifier (0 or 1)	1
water (mm)	100
vater (weeks)	15
lation (mm/day)	16
le condition (weeks)	4
ercolation (mm/day)	3
in previous season	No
ard in next season	No

Figure – 4.5: Sample screen for specifying crop factor data for "Rice" crop


Title of data file: Standard Details of Crops in Tapi

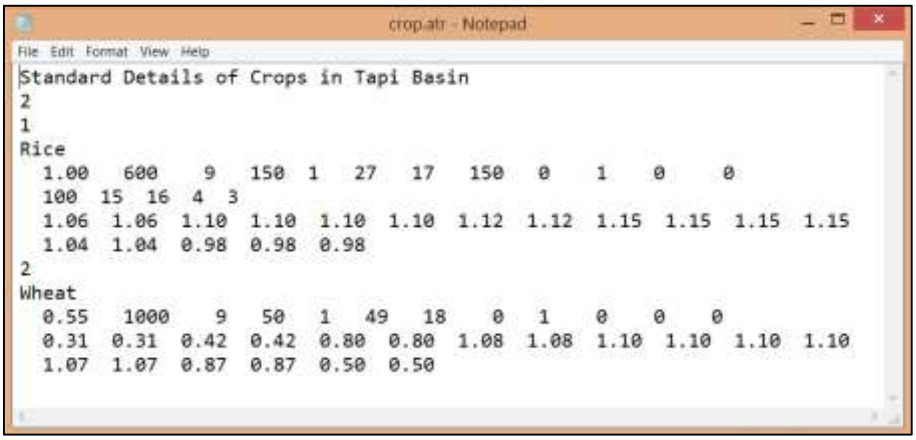
Number of crops	2	Bund height around crop field (mm)	0
Crop_ID	5	Crop carryover identifier (0 or 1)	1
Crop name	Wheat	Crop standing water identifier (0 or 1)	0
Fraction of RAW for defining stress (0-1)	0.55	Depth of standing water (mm)	0
Maximum root depth (mm)	1000	Time of standing water (weeks)	0
Time to reach max. root depth (weeks)	6	Initial rate of percolation (mm/day)	0
Water depth for land preparation (mm)	50	Time to reach stable condition (weeks)	0
Time of land preparation (weeks)	1	Stabilised rate of percolation (mm/day)	0
Starting calender week of crop	48	Crop extends back in previous season	No
Crop time in field (weeks)	18	Crop extends forward in next season	No

Figure – 4.6: Sample screen for specifying crop attributes for "Wheat" crop

It is to mention that these forms store/retrieve the data as/from text files on which different software program are executed to get the results. The sample crop file for 2 crops that is generated from the form (crop.atr) is shown in Figure – 4.7.

4.3.1.2 Soil attributes

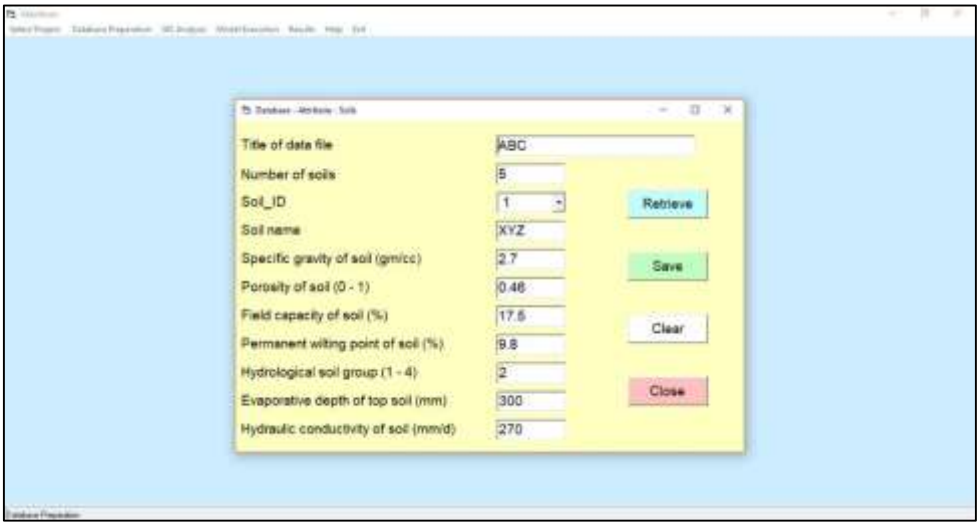
The soil attribute sheet is shown in Figure – 4.8. Soil properties of a maximum of 100 soils can be specified using this form. Same as for crops, as the number of soils is changed, the



```
Standard Details of Crops in Tapi Basin
2
1
Rice
  1.00   600    9   150  1   27    17   150   0    1    0     0
  100  15  16  4  3
  1.06  1.06  1.10  1.10  1.10  1.10  1.12  1.12  1.15  1.15  1.15  1.15
  1.04  1.04  0.98  0.98  0.98
2
Wheat
  0.55   1000    9   50   1   49    18    0   1    0    0    0
  0.31  0.31  0.42  0.42  0.80  0.80  1.08  1.08  1.10  1.10  1.10  1.10
  1.07  1.07  0.87  0.87  0.50  0.50
```

Figure – 4.7: Sample screen for specifying soil attributes

combo-box corresponding to the *"Soil ID"* shows the same number of numeric values. Each Soil ID corresponds to a particular type of soil with related attribute data. There is no tabular data associated with this form. After specifying the Soil ID, all related information is entered in relevant boxes. As soon as the Soil ID is changed, the information entered previously for a particular Soil ID gets stored. Here, the *"Evaporative depth of top soil"* represents the top depth of soil layer from which loss of moisture due to evaporation can be considered. Below this depth, soil moisture is not considered to be depleted due to direct evaporation and can only be extracted by the plants.



Title of data file	ABC
Number of soils	5
Soil_ID	1
Soil name	XYZ
Specific gravity of soil (gm/cc)	2.7
Porosity of soil (0 - 1)	0.46
Field capacity of soil (%)	17.6
Permanent wilting point of soil (%)	9.8
Hydrological soil group (1 - 4)	2
Evaporative depth of top soil (mm)	300
Hydraulic conductivity of soil (mm/d)	270

Figure – 4.8: Sample screen for specifying soil attributes

4.3.1.3 City attributes

The city attribute sheet is shown in Figure – 4.9. Properties of a maximum of 1000 cities in a river basin can be specified using this form. *"Number of grids covered by city"* represents the extent of city coverage and is used to divide the city population in different grids and find the grid-wise domestic urban water demand. "Adjacent river segment ID" is used to pin-point the river segment for diversion of river water to the city. "Water supply source" varies between 1 and 2 (1 means that GW is fully used while 2 means that SW is fully used) and represents the relative contribution of GW and SW in meeting city demands. A value of 1.35 means that 65% of GW and 35% of SW is utilized to meet city water demands.

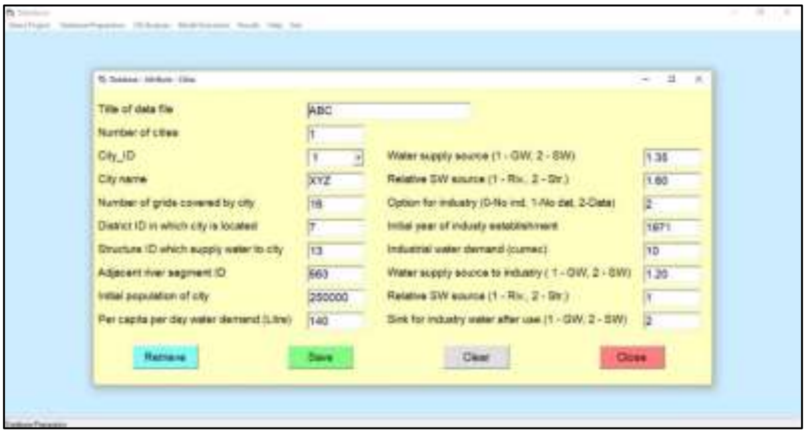

Title of data file: ABC
Number of cities: 1
City_ID: 1
City name: XYZ
Number of grids covered by city: 16
District ID in which city is located: 7
Structure ID which supply water to city: 13
Adjacent river segment ID: 563
Initial population of city: 250000
Per capita per day water demand (Litre): 140
Water supply source (1 - GW, 2 - SW): 1.35
Relative SW source (1 - Riv., 2 - Str.): 1.60
Option for industry (0-No ind, 1-No dat, 2-Data): 2
Initial year of industry establishment: 1971
Industrial water demand (cumec): 10
Water supply source to industry (1 - GW, 2 - SW): 1.20
Relative SW source (1 - Riv., 2 - Str.): 1
Sink for industry water after use (1 - GW, 2 - SW): 2

Figure – 4.9: Sample screen for entry of city attributes

Similarly, "Relative SW source" shows the relative contribution of diverted river water and stored reservoir water. Similarly, sink for industry water represents the relative drainage of used industrial water to SW or GW.

4.3.1.4 District attributes

The district attribute sheet is shown in Figure – 4.10. Here, first the data of grey cells is filled and then the attribute data of each district is filled. Most of these data can be obtained from the district statistical records. Per capita per day (PCPD) demands for different purpose can be adopted from standard or prevailing estimates. Properties of a maximum of 1000 districts in a river basin can be specified using this form. *"Consumptive use fraction"* represents the return flow from domestic water use and industrial use. Further, "% of used water drained in SW" is used to specify the sink where used water is drained. "Min. GW elevation for GW use" specifies the minimum GW level in the district below which GW is not pumped for utilization. Since negligible population is generally found in higher elevation ranges, "Highest elevation for population" represents the highest surface elevation above which uniform distribution of rural population in various grids is not to be considered.

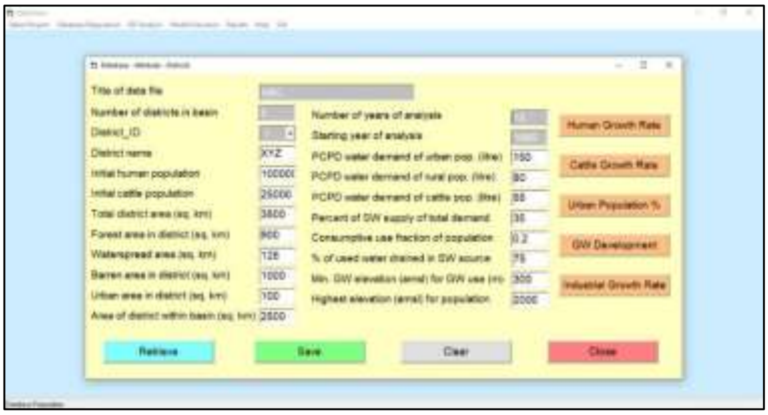

Title of data file:
Number of districts in basin:
District_ID:
District name: XYZ
Initial human population: 10000(
Initial cattle population: 25000
Total district area (sq. km): 3800
Forest area in district (sq. km): 900
Waterspread area (sq. km): 128
Barren area in district (sq. km): 1000
Urban area in district (sq. km): 100
Area of district within basin (sq. km): 2500
Number of years of analysis:
Starting year of analysis:
PCPD water demand of urban pop. (litre): 150
PCPD water demand of rural pop. (litre): 80
PCPD water demand of cattle pop. (litre): 55
Percent of GW supply of total demand: 35
Consumptive use fraction of population: 0.2
% of used water drained in SW source: 75
Min. GW elevation (amsl) for GW use (m: 300
Highest elevation (amsl) for population: 2000

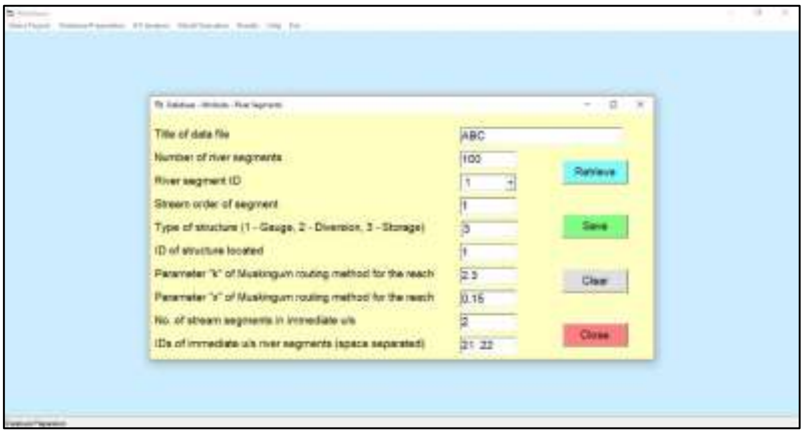
Figure – 4.10: Sample screen for entry of district attributes

There are five tabular attributes associated with district information. *“Human growth rate”* represents the growth rate in different districts and different years to be considered to find the revised population in each district in different years. Similarly, cattle and industrial growth rates are specified in different districts for different years to estimate their revised water demands at different time periods. To account for the migration of rural population to urban cities, *“Urban population %”* is specified for different districts for different years. Thus, the total revised population at any time is divided into urban and rural population and these are then distributed among different cities and rural grids. Finally, *“GW development”* represents the temporal GW pumping potential of different districts. All these temporal information is independent of District IDs and is used to simulate the basin as close to reality as possible. However, some of the required info (not readily available) can be suitably assumed. Figure – 4.11 shows the sample layout for tabular data.

Figure – 4.11: Sample screen for entry of tabular data in district attributes

4.3.1.5 River network attributes

The river network attribute sheet is shown in Figure – 4.12. The river network is obtained in the GIS by hydro-processing of the DEM. To each river segment, a numeric identity is specified starting from the upstream segment with number 1. This river network information is used to define the connectivity of river links in the network. It is also used to define the location of reservoir, barrages, or gauging stations at different locations.



Title of data file	ABC
Number of river segments	100
River segment ID	1
Stream order of segment	1
Type of structure (1 - Gauge, 2 - Diversion, 3 - Storage)	3
ID of structure located	1
Parameter "k" of Muskingum routing method for the reach	2.3
Parameter "x" of Muskingum routing method for the reach	0.15
No. of stream segments in immediate u/s	2
IDs of immediate u/s river segments (space separated)	21 22

Figure – 4.12: Sample screen for entry of river network attributes

Stream order defines the level of streams in a network and all lower order streams are processed first before taking-up analysis for higher order streams. This ensures analysis movement from upstream to the downstream. For some higher order streams, parameters “K and x” of Muskingum routing method are specified to account for the channel routing in those stretches. For smaller order streams, these can be taken as 0. Finally, “IDs of immediately u/s river segments” is not a numeric cell and values in this cell are entered as space-separated as shown in Figure – 4.12.

4.3.1.6 Gauging station attributes

The gauging station attribute sheet is shown in Figure – 4.13. Each gauging station is given a numeric identity starting with 1 from the most upstream station. *“IDs of immediately u/s gauging stations”* is used to define the connectivity of different sub-basins in the whole river basin. Finally, *“IDs of immediately u/s gauging stations”* is not a numeric cell and values in this cell are entered as space-separated as shown in Figure – 4.13.

Title of data file: ABC
Number of river gauging stations: 7
Gauging station ID: 1
Gauging station name: XYZ
ID of river segment on which gauging station is located: 682
Bed level of river at the gauging station (m): 153.20
No. of gauging stations in immediate u/s: 2
IDs of immediate u/s gauging stations (space separated): 5 6

Figure – 4.13: Sample screen for entry of gauging station attributes

4.3.1.7 Hydraulic structure attributes

The hydraulic structure attribute sheet is shown in Figure – 4.14. Each hydraulic structure is given a numeric identity starting with 1 from the most upstream structure. The tabular information in various tables (EAC, monthly demands, rule curve levels, and crop-pattern change) is dependent on the Structure ID. Thus for each Structure ID, the attribute information in different cells and the tabular information in each table are entered together before shifting to the next Structure ID. The existence of a hydraulic structure in software is invoked from the June month of its year of commissioning and revised cropping pattern in its command is considered for evaluation of irrigation demands since that time. Number of rows in EAC table depends on the “Number of level in EAC table” while the number of rows in “Crop-pattern Change” table depends on the “Number of crop changes in command”. The software facilitates inter-link transfer of water from one structure/river segment to another structure/river segment. “Diversion capacity” info is used at a barrage for defining maximum

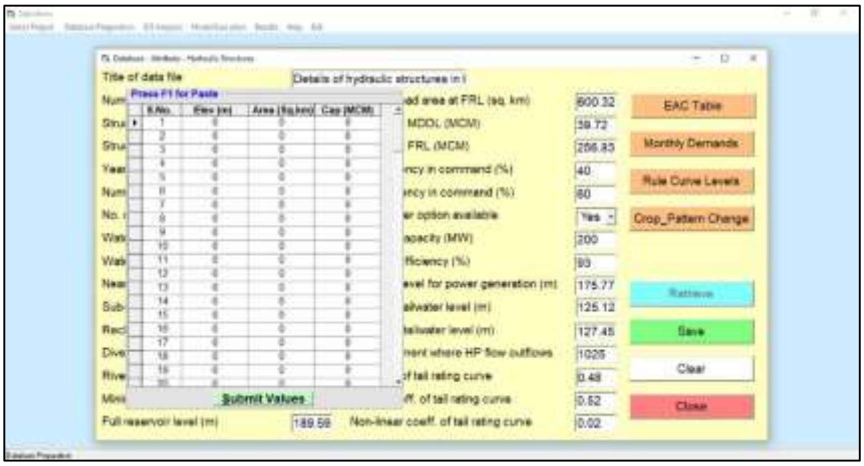
Title of data file: Details of hydraulic structures in l
Number of structures in basin: 5
Structure ID: 8
Structure Name: ABC
Year of commissioning: 1975
Number of levels in EAC table: 10
No. of crop changes in command: 5
Water is received from structure: 3
Water is sent to structure: 8
Nearby ET station ID: 8
Sub-basin_ID of structure location: 9
Recharge rate from str (mm/day): 2
Diversion capacity (cubic m/day): 900000
River bed level (m): 140.32
Minimum draw down level (m): 176.77
Full reservoir level (m): 189.59
Waterspread area at FRL (sq. km): 600.32
Storage at MDDL (MCM): 38.72
Storage at FRL (MCM): 256.83
SW efficiency in command (%): 40
GW efficiency in command (%): 60
Hydropower option available: Yes
HP plant capacity (MW): 200
HP plant efficiency (%): 93
Minimum level for power generation (m): 175.77
Minimum tailwater level (m): 125.12
Maximum tailwater level (m): 127.45
River segment where HP flow outflows: 1025
Constant of tail rating curve: 0.48
Linear coeff. of tail rating curve: 0.52
Non-linear coeff. of tail rating curve: 0.02

Figure – 4.14: Sample screen for entry of hydraulic structure attributes

diversion capacity of water to another location. The water in excess is spilled in the downstream river. “River bed level” info is used to compute the EAC table with the procedure specified in Section - 3.1. “SW and GW efficiency” terms are used to compute the gross irrigation requirement at hydraulic structure from the grid-wise irrigation demands computed in its command area. As the option of hydropower simulation has been added, various related details are also required if a hydraulic structure has hydropower plant. To account for the tail rating curve, the option of specifying the relationship for the tail rating curve has been added. The equation used to define the relationship is:

$$\text{Tail level} = a + b * (\text{daily HP release}) + c * (\text{daily HP release})^2 \qquad \ldots(4.1)$$

where a, b, and c are constant, linear coefficient, and non-linear coefficient of rating equation which need to be specified in the form. The outflow from the hydropower plant may either join the downstream segment or some other stream segment or may send water to outside of the basin. “River segment where HP flow outflows” is used to represent these conditions. If it is “0”, then water is sent to out of basin, otherwise the river segment ID is specified where outflow from HP plant joins. If HP option is not available, all related cells are disabled. For specifying the EAC table or a hydraulic structure, “EAC table” icon is clicked. EAC table form appears (shown in Figure – 4.15) with row numbers equal to the “Number of level in EAC table”.



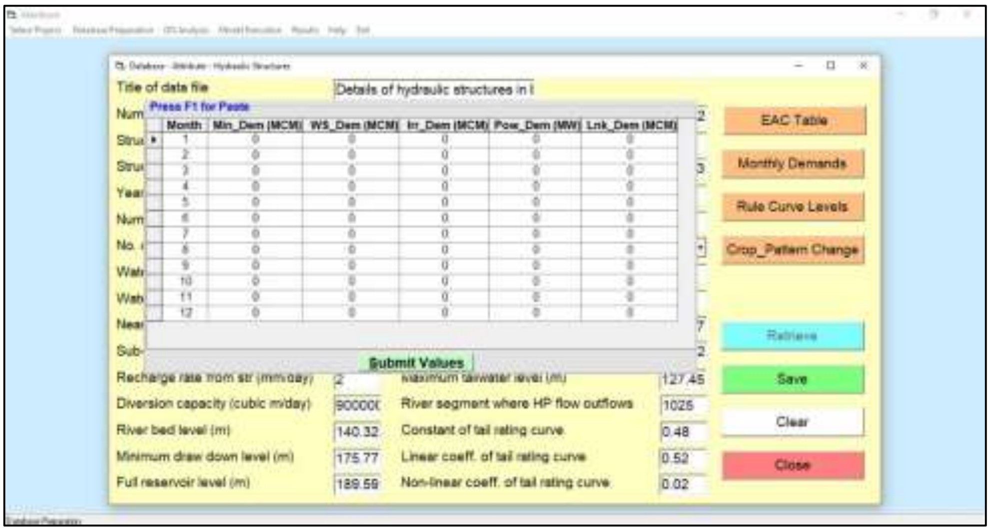
Press F1 for Paste

S.No.	Elev (m)	Area (Sq.km)	Cap (MCM)
1	0	0	0
2	0	0	0
3	0	0	0
4	0	0	0
5	0	0	0
6	0	0	0
7	0	0	0
8	0	0	0
9	0	0	0
10	0	0	0
11	0	0	0
12	0	0	0
13	0	0	0
14	0	0	0
15	0	0	0
16	0	0	0
17	0	0	0
18	0	0	0
19	0	0	0
20	0	0	0

Title of data file: Details of hydraulic structures in l
Full reservoir level (m): 189.59

Figure – 4.15: Sample screen for entry of tabular EAC table for a reservoir

In addition to manual entry of data, the same can be copied from MS-Excel and pasted in table (using F1 key). It is important to note that the units of variables are specified in the table header and the user need to conform to these units. Similarly, the monthly demands table (shown in Figure – 4.16), rule curve levels table (shown in Figure - 4.17), and crop pattern change table (shown in Figure - 4.18) are entered.

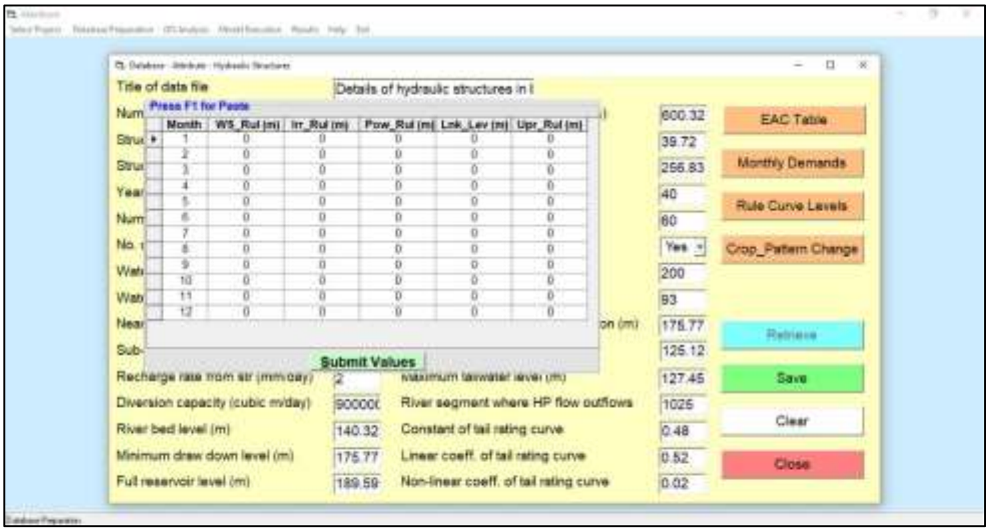


Title of data file: Details of hydraulic structures in I

Month	Min_Dem (MCM)	WS_Dem (MCM)	Irr_Dem (MCM)	Pow_Dem (MW)	Lnk_Dem (MCM)
1	0	0	0	0	0
2	0	0	0	0	0
3	0	0	0	0	0
4	0	0	0	0	0
5	0	0	0	0	0
6	0	0	0	0	0
7	0	0	0	0	0
8	0	0	0	0	0
9	0	0	0	0	0
10	0	0	0	0	0
11	0	0	0	0	0
12	0	0	0	0	0

Recharge rate from str (mm/day): 2
Diversion capacity (cubic m/day): 90000(
River bed level (m): 140.32
Minimum draw down level (m): 175.77
Full reservoir level (m): 189.59
Maximum tailwater level (m): 127.45
River segment where HP flow outflows: 1025
Constant of tail rating curve: 0.48
Linear coeff. of tail rating curve: 0.52
Non-linear coeff. of tail rating curve: 0.02

Figure – 4.16: Sample screen for entry of tabular monthly demands table for a reservoir



Title of data file: Details of hydraulic structures in I

Month	WS_Rul (m)	Irr_Rul (m)	Pow_Rul (m)	Lnk_Lev (m)	Upr_Rul (m)
1	0	0	0	0	0
2	0	0	0	0	0
3	0	0	0	0	0
4	0	0	0	0	0
5	0	0	0	0	0
6	0	0	0	0	0
7	0	0	0	0	0
8	0	0	0	0	0
9	0	0	0	0	0
10	0	0	0	0	0
11	0	0	0	0	0
12	0	0	0	0	0

Recharge rate from str (mm/day): 2
Diversion capacity (cubic m/day): 90000(
River bed level (m): 140.32
Minimum draw down level (m): 175.77
Full reservoir level (m): 189.59
Maximum tailwater level (m): 127.45
River segment where HP flow outflows: 1025
Constant of tail rating curve: 0.48
Linear coeff. of tail rating curve: 0.52
Non-linear coeff. of tail rating curve: 0.02

Figure – 4.17: Sample screen for entry of tabular rule curve levels table for a reservoir

Various demands considered by the software include minimum flow demands, domestic supply demands, irrigation demands, power demands, and link diversion demands. Out of these, domestic supply and irrigation demands are also worked out for each day within the model. However, if the domestic supply and irrigation demands are specified in this data file, then the demands computed within the model are not used and reservoir is operated as per the specified tabular demands. Otherwise, if these demands are mentioned as “0” in the tabular data, then the daily demands computed within the model are used. Similarly, if the power demands are specified in the tabular data, then reservoir is operated to meet the target power demand. Otherwise, if it is specified as “0”, then the incidental power that can be generated within the limits of installed capacity is worked out. Various modes of supply of water through the power plant is specified in cell corresponding to “Hydropower option available”. If this cell value is “0”, then there is no power plant at the reservoir. However, if it is more than “0”, then different methods of releases for various demands through power plant are as specified here: 1 – no other release through power plant, 2 – only irrigation release pass through power plant, 3 – only domestic supply release pass through power plant, 4 – only min. d/s flow release pass through power plant, 5 – irrigation and min. d/s flow release pass through power plant, 6 – irrigation and domestic supply release pass through power plant, 7 – min. d/s flow and domestic supply release pass through power plant, 8 – all release pass through power plant.

Rule curve levels can be specified for domestic supply, irrigation, hydropower, link diversion, and for spilling. Rule curve levels should generally lie in-between MDDL and FRL. If the reservoir is above the upper rule level at any time, extra water is spilled from the reservoir and it is brought back to upper rule level. If the reservoir is below the upper rule level but above the power, irrigation and domestic supply rule level, then all demands are met in full. If the reservoir is below the power/irrigation rule level but above the irrigation/power and domestic supply rule level, then power/irrigation demand is curtailed in the proportion of release reduction factor given as:

Release reduction factor = (reservoir level – domestic supply level)/(power/irrigation level – domestic supply level) ...(4.2)

At/below the domestic supply rule level, release for power/irrigation is completely curtailed and domestic supply is curtailed by domestic reduction factor given as:

Domestic reduction factor = (reservoir level – MDDL)/(domestic rule level – MDDL) ...(4.3)

Below the link levels, water is not transferred to the link. The concept of rule curve levels is also applied to the diversion links such that if the reservoir is above the power, irrigation, and domestic supply rule level and diversion level, then water is diverted to the link. However, if the reservoir level falls below the power/irrigation rule level or diversion level, then supply for link transfer is completely curtailed.

Title of data file: Details of hydraulic structures in I

S.No.	Old-Crop_ID	New-Crop_ID
1	0	0
2	0	0
3	0	0
4	0	0
5	0	0

Water is received from structure: 3
Water is sent to structure: 8
Nearby ET station ID: 6
Sub-basin_ID of structure location: 9
Recharge rate from str (mm/day): 2
Diversion capacity (cubic m/day): 90000
River bed level (m): 140.32
Minimum draw down level (m): 175.77
Full reservoir level (m): 189.59
Waterspread area at FRL (sq. km): 800.32
Storage at MDDL (MCM): 36.72
Storage at FRL (MCM): 256.83
SW efficiency in command (%): 40
GW efficiency in command (%): 60
Hydropower option available: Yes
HP plant capacity (MW): 200
HP plant efficiency (%): 93
Minimum level for power generation (m): 176.77
Minimum tailwater level (m): 125.12
Maximum tailwater level (m): 127.46
River segment where HP flow outflows: 1025
Constant of tail rating curve: 0.48
Linear coeff. of tail rating curve: 0.52
Non-linear coeff. of tail rating curve: 0.02

Figure – 4.18: Sample screen for entry of tabular crop pattern change table for a reservoir

The crop pattern change table avoids the necessity of incorporating revised crop map of the basin. Rather, the table specifies as to which old crops in the command of the reservoir are to be replaced with new crops after the commissioning of reservoir. However, the properties of all such crops should be specified in the crop attributes.

4.3.2 Database Preparation – Temporal Data

Various kind of temporal data prepared for the model include the time series of rainfall, reference crop evapo-transpiration, observed GW level, release from dams, observed flows at gauging sites/hydraulic structures, and import/export to/from multiple locations within the basin. The related forms of these time series are described below.

4.3.2.1 Rainfall time series

The rainfall time series screen is shown in Figure – 4.19. The cell values corresponding to *"Number of days of analysis"* and the *"Number of rainfall stations"* define the size of tabular data in *"Rainfall modification factor*" and *"Daily rainfall"* tables. The rainfall modification factor is used to modify the historical rainfall data by a specified fixed percent so as to account for any climate change impact on the rainfall at different stations in the basin. Historical rainfall data is entered in the Daily rainfall table where each column represents the data of one station for the specified length of analysis. MS-Excel can be used to copy/paste the data directly. The daily rainfall entry form is shown in Figure – 4.20.

Title of data file: ABC

Number of days of analysis: 500

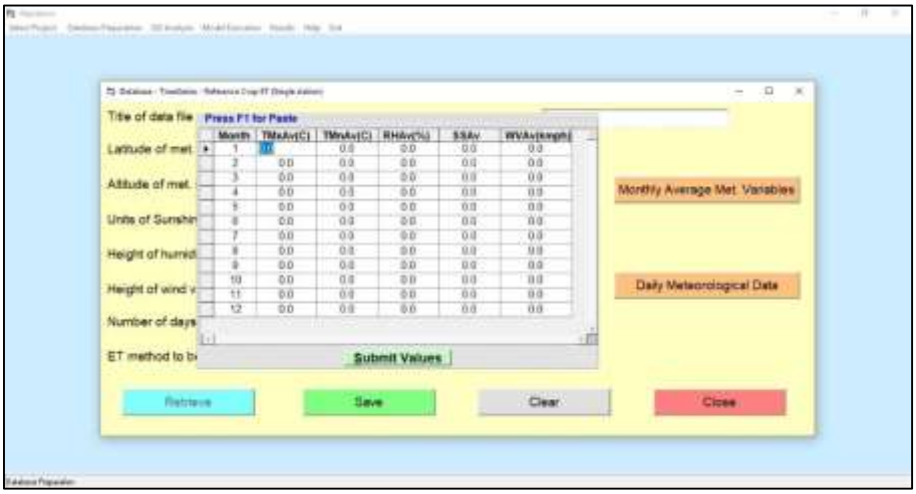
Number of rainfall stations: 20

Figure – 4.19: Sample screen for entry of rainfall data at different stations in a basin

Figure – 4.20: Sample screen for entry of tabular daily rainfall data at different stations

4.3.2.2 Reference crop ET (single station)

The reference crop ET estimation screen at a single station is shown in Figure – 4.21. This feature has been build-in the software so as to help the users to compute the values from the known meteorological observations. Three methods have been programmed: Penman Monteith method, Penman method and Hargreaves method. Since the Hargreaves method requires long-term monthly average meteorological estimates, a tabular icon has been provided to specify these values. Sample forms for providing the average meteorological estimates and daily meteorological data at a station are shown in Figure – 4.21 and Figure 4.22 respectively.



Month	TMxAv(C)	TMnAv(C)	RHAv(%)	SSAv	WVAv(kmph)
1	0	0.0	0.0	0.0	0.0
2	0.0	0.0	0.0	0.0	0.0
3	0.0	0.0	0.0	0.0	0.0
4	0.0	0.0	0.0	0.0	0.0
5	0.0	0.0	0.0	0.0	0.0
6	0.0	0.0	0.0	0.0	0.0
7	0.0	0.0	0.0	0.0	0.0
8	0.0	0.0	0.0	0.0	0.0
9	0.0	0.0	0.0	0.0	0.0
10	0.0	0.0	0.0	0.0	0.0
11	0.0	0.0	0.0	0.0	0.0
12	0.0	0.0	0.0	0.0	0.0

Figure – 4.21: Sample screen for entry of average monthly met. Estimates at a station

Day_S.No.	TAv(C)	RHAv(%)	SSAv	WVAv(kmph)
1	0	0	0	0
2	0	0	0	0
3	0	0	0	0
4	0	0	0	0
5	0	0	0	0
6	0	0	0	0
7	0	0	0	0
8	0	0	0	0
9	0	0	0	0
10	0	0	0	0
11	0	0	0	0
12	0	0	0	0
13	0	0	0	0

Figure – 4.22: Sample screen for entry of tabular daily met. data at a station

4.3.2.3 Reference crop ET (multiple stations)

After the estimation of reference crop ET at all the stations in a river basin, the same are arranged in a separate file that is used by the *NIH_Basin* model. The form for such file creation is shown in Figure – 4.23. It is quite similar to the rainfall form mentioned in Section

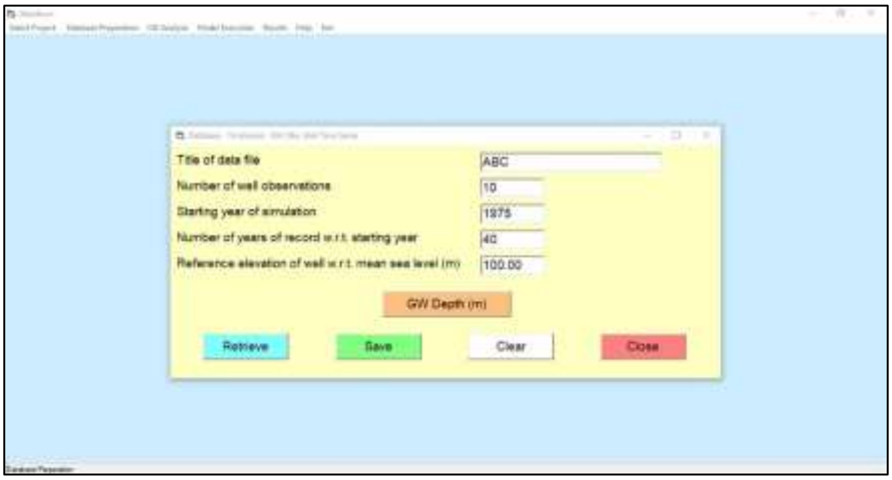
4.3.2.1. Here, ET modification factor has been introduced in the same way to account for the climate change impact on the reference ET values at different stations in the basin.

Title of data file: ABC
Number of days of analysis: 600
Number of ET stations: 20

Figure – 4.23: Sample screen for entry of reference crop ET of various stations in the basin

4.3.2.4 GW observation well time series

A form has been developed to arrange the irregular data of GW level in an observation well to equidistant time series. This form is shown in Figure – 4.24. Here, the reference elevation of the GW station is used to transform the GW depth data to GW elevation terms w.r.t the mean sea water level.



Title of data file: ABC
Number of well observations: 10
Starting year of simulation: 1975
Number of years of record w.r.t. starting year: 40
Reference elevation of well w.r.t. mean sea level (m): 100.00

Figure – 4.24: Sample screen for entry of GW observation well info at a single station

Since the observations may or may not be at regular time interval, it is also necessary to mention the year and month of observation. Thus, the GW depth form requires the input of year, month, and data of GW depth. The sample form is shown in Figure – 4.25. Using this form, the irregular GW depth observations at various observation wells in a basin is transformed to regular GW elevation time series for the period of analysis.

Title of data file

Number of well observations

Starting year of simulation

Number of years of record w.r.t.

Reference elevation of well w.r.

Press F1 for Paste

	Obs.No.	Year	Month	GW Depth (m)
▸	1	0	0	0
	2	0	0	0
	3	0	0	0
	4	0	0	0
	5	0	0	0
	6	0	0	0
	7	0	0	0
	8	0	0	0
	9	0	0	0
	10	0	0	0

Figure – 4.25: Sample screen for entry of GW depth data at a single station

4.3.2.5 GW elevations of observation wells in a sub-basin

This form is developed to arrange the regular GW elevations (obtained from previous module in Section 4.3.2.4) in various observation wells in a sub-basin for the estimation of average GW elevation time series. This form is shown in Figure – 4.26. Based on the number of observation wells in a sub-basin and the period of analysis, a table is generated for the entry/copy-paste of GW elevations of various stations. Sample form is shown in Figure – 4.27.

Title of data file: ABC

Number of observation wells in the sub-basin: 10

Starting year of analysis: 1975

Number of years of analysis: 40

Figure – 4.26: Sample screen for entry of GW elevations info in obs. wells in a sub-basin

Figure – 4.27: Sample screen for entry of GW elevations in observation wells in a sub-basin

4.3.2.6 Average GW elevations in all sub-basins

This form is developed to arrange the average GW elevation time series (obtained from previous module in Section 4.3.2.5) in all sub-basins in a river basin for use in the *NIH_Basin* software. This form is shown in Figure – 4.28. Based on the number of sub-basins and the period of analysis, a table is generated for the entry/copy-paste of average GW elevation time series of various sub-basins. Sample form is shown in Figure – 4.29.

Title of data file: ABC
Number of sub-basins in the basin: 10
Starting year of analysis: 1975
Number of years of analysis: 40

Figure – 4.28: Sample screen for entry of average GW elevation info in sub-basins

Press F1 for Paste

S. No.	Year	Month	SubBas_1	SubBas_2	SubBas_3	SubBas_4	SubBas_5
1	0	0	0	0	0	0	0
2	0	0	0	0	0	0	0
3	0	0	0	0	0	0	0
4	0	0	0	0	0	0	0
5	0	0	0	0	0	0	0
6	0	0	0	0	0	0	0
7	0	0	0	0	0	0	0
8	0	0	0	0	0	0	0
9	0	0	0	0	0	0	0

Figure – 4.29: Sample screen for entry of average GW elevations in various sub-basins

4.3.2.7 Dam release time series

In a large basin with a number of reservoirs, it is quite probable that some dams have the data related to the spills from the reservoir. This data can be crucial in matching the observed and simulated flows at downstream gauging sites. Otherwise, these computations are made inside the model as per reservoir operation criteria. To better utilize the available spill data from reservoirs, this form has been developed. This form is shown in Figure – 4.30. Since only a selected few reservoirs in a basin may have this data, the table corresponding to “Node_IDs with release data” is used to define the node numbers of such reservoirs (shown in Figure – 4.31) and their release data is specified in table corresponding to “Daily release” icon (shown in Figure – 4.32).


Title of data file: ABC
Number of days of analysis: 365
Number of nodes with release data: 10

Figure – 4.30: Sample screen for entry of info related to dams with release data


Press F1 for Paste

S. No.	Node_ID
1	
2	0
3	0
4	0
5	0
6	0
7	0
8	0
9	0

Figure – 4.31: Sample screen for entry of Node_IDs of dams with release data


Press F1 for Paste

Day_S.No.	RelNod_1	RelNod_2	RelNod_3	RelNod_4	RelN
1	0	0	0	0	
2	0	0	0	0	
3	0	0	0	0	
4	0	0	0	0	
5	0	0	0	0	
6	0	0	0	0	
7	0	0	0	0	
8	0	0	0	0	
9	0	0	0	0	

Figure – 4.32: Sample screen for entry of dam release data

4.3.2.8 Observed flow time series

This form is developed to enter the historical observed inflows at different gauging sites or reservoirs at the outlet of each sub-basin in the river basin. This data is used for calibration and validation of model parameters. This form is self-explanatory as shown in Figure – 4.33.

Title of data file: ABC

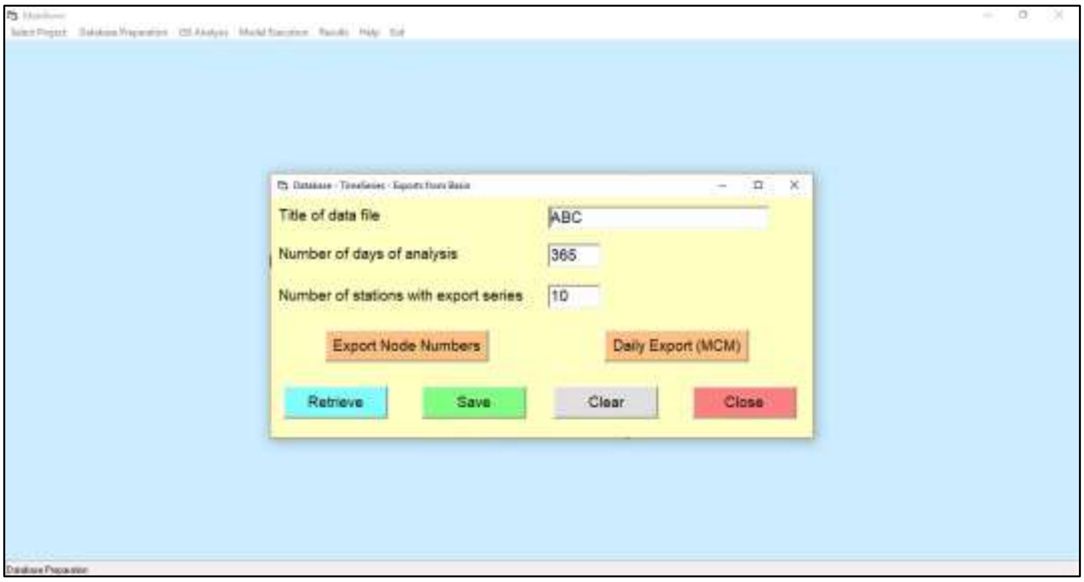
Number of days of analysis: 365

Number of flow observation stations: 10

Figure – 4.33: Sample screen for entry of observed flows at the outlet of various sub-basins

4.3.2.9 Export time series

Export from a river basin affect the water resources in the downstream reach and need to be properly accounted for while simulating the flows in a river basin. With this need in view, this form, as shown in Figure – 4.34, is developed. As the export can take place from a number of locations in a basin, one needs to specify the node numbers of hydraulic structures/gauging stations from which export time series is specified.



Title of data file: ABC

Number of days of analysis: 365

Number of stations with export series: 10

Figure – 4.34: Sample screen for entry of export info from various nodes out of basin

4.3.2.10 Import time series

Like export, import in a river basin also affect the water resources in the downstream reach and need to be properly accounted for while simulating the water resources in a river basin. With this need in view, this form, as shown in Figure – 4.35, is developed. As the import can take place to a number of locations in the basin, one needs to specify the node numbers of hydraulic structures/gauging stations at which import time series is specified.

Title of data file: ABC
Number of days of analysis: 365
Number of stations with import series: 10

Figure – 4.35: Sample screen for entry of import info at various nodes in the basin

4.3.3 Database Preparation – Miscellaneous Information

In addition to the attribute and temporal information, various other details for the simulation at the basin scale are required. These are specified in following sections:

4.3.3.1 Simulation options

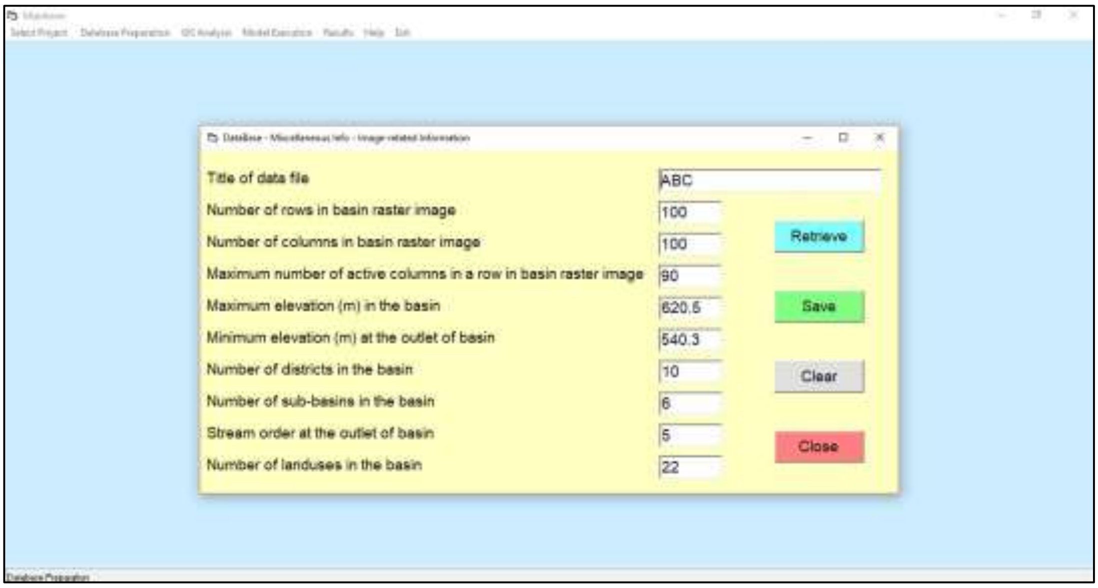
Various simulation options are defined before taking the simulation run for a river basin. The screen showing various options is presented in Figure – 4.36. First option is regarding the continuous or monthly run of the model. In continuous, simpler GW representation is considered and model is run for entire period of record while in monthly simulation, the grid-wise pumping and recharge are computed for each month for input into a calibrated groundwater modeling system (say, Visual MODFLOW). The GW model simulates the GW flows and find the revised GW surface which is taken as input to the *NIH_Basin* model for the next month simulation. Next, the starting day, month, and year and the number of days are specified defining the period of simulation. Size of the grid is also given as an option. However, the grids of all spatial layers should conform to this size. Next, the initial moisture at each grid is specified. It is either taken as some fixed value or a map of initial moisture content can be specified. Finally, the start and end days and months of 3 crop seasons (Kharif, Rabi, and Hot-weather) needs to be specified. The days are specified as calendar days starting from January 1 as 1 for the non-leap years.

Title of data file	ABC		
Simulation option	Continuous		
Starting year of simulation	1975	End month of 1st crop season (say, Kharif)	10
Starting month of simulation	6	Starting day of 2nd crop season (say, Rabi)	305
Starting day of simulation	25	Starting month of 2nd crop season (say, Rabi)	11
Number of days of simulation	3650	End day of 2nd crop season (say, Rabi)	90
Grid size (m)	1000	End month of 2nd crop season (say, Rabi)	3
Initial moisture at each grid	Map	Starting day of 3rd crop season (say, Hot Weather)	91
Starting day of 1st crop season (say, Kharif)	152	Starting month of 3rd crop season (say, Hot Weather)	4
Starting month of 1st crop season (say, Kharif)	6	End day of 3rd crop season (say, Hot Weather)	151
End day of 1st crop season (say, Kharif)	304	End month of 3rd crop season (say, Hot Weather)	5

Figure – 4.36: Sample screen for entry of simulation options under misc. information

4.3.3.2 Image-related information

In addition, some information is required by a number of modules for conversion of raster image into active cell info or vice versa. Further, some results of the model are converted into the image form for display in GIS system. All such information is specified in this form as shown in Figure – 4.37. A basin raster is actually a rectangular image with specified rows and columns in accordance with the grid size and size and shape of the basin. Generally, the rectangular image is selected such that there is at least one active cell (of the basin) in all the outer rows and columns. The number of rows and columns and maximum number of active columns in a row can be obtained from GIS info of the rectangular image. Similarly, the maximum and minimum elevation in the basin can also be obtained from GIS info. Other details that are specified are shown in the form.



Title of data file	ABC
Number of rows in basin raster image	100
Number of columns in basin raster image	100
Maximum number of active columns in a row in basin raster image	90
Maximum elevation (m) in the basin	620.5
Minimum elevation (m) at the outlet of basin	540.3
Number of districts in the basin	10
Number of sub-basins in the basin	6
Stream order at the outlet of basin	5
Number of landuses in the basin	22

Figure – 4.37: Sample screen for entry of image-related info under misc. information

4.3.3.3 Model parameters

Various parameters of the model include the curve numbers for different sub-basins for different land uses; the minimum GW elevations in different sub-basins for generation of base flow and for GW utilization; the relationship defining the GW storage above the bed level elevation of the sub-basin outlet and the base flow; and the parameters defining the movement of GW from one sub-basin to its adjacent sub-basin depending on the difference of GW elevation difference in the two sub-basins.

4.3.3.4 Transfer database

Using this module, all the data files in various sub-directories (Attribute, GIS, and TimeSeries) are transferred to a fixed location (C:\NIH_Basin) which contains all the computer programs of the software. Before transferring the database, it is important to generate various GIS layers in the GIS sub-directory of Database directory and export them as *.asc (ILWIS ASCII) files. Clicking on the *"Transfer Database"* icon copies (or overwrites) all the relevant data files of the study basin in one go. Therefore, it is most important that before transferring the database to modeling location, all the data files for the study basin with standardized file names must be available in their respective sub-directories. This needs to be thoroughly checked. The standardized names of various GIS layers after they are exported as ASCII files are given in Table – 4.2.

Table – 4.2

Standardized filenames of different GIS layers (after export as ASCII files)

Type of GIS Layers	Standardized filename
Crop map of Kharif season	Crp1.asc
Crop map of Rabi season	Crp2.asc
Crop map of Hot-weather season	Crp3.asc
Soil map of the basin	Soil.asc
LULC map of the basin	Lulc.asc
DEM map of the basin	Dem.asc
Slope map of the basin	Slop.asc
Flow direction map of the basin	Fdir.asc
River network map of the basin	Rnet.asc
Sub-basin map of the basin	Sbas.asc
District map of the basin	Dist.asc
City map of the basin	City.asc
Water bodies map of the basin	Wbod.asc
Irrigation command map of the basin	Icmd.asc
Thiessen polygon map of rainfall stations in the basin	Tprf.asc
Thiessen polygon map of reference ET stations in the basin	Tpet.asc

4.4 Description of "GIS Analysis" Module

As mentioned earlier, a number of GIS layers have been linked with the modeling methodology. This requires development of spatial layers through a GIS system. In the present case, ILWIS 3.6 software has been linked with the modeling scheme such that GIS layers can be input to the NIH_Basin model and some results of analysis can be displayed as GIS layers in this GIS system. The screen of *"GIS Analysis"* module is shown in Figure – 4.38. The modules generated under the GIS analysis system are briefly described below.

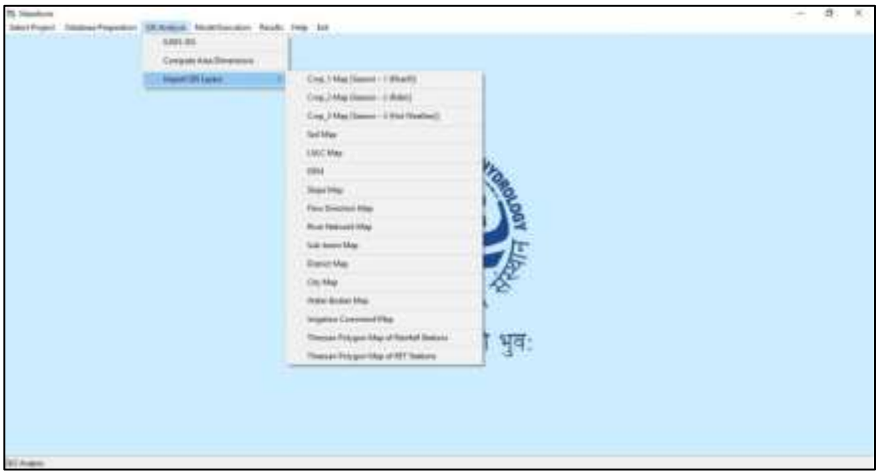


Figure – 4.38: Screen showing various sub-modules under *"GIS Analysis"*

4.4.1 ILWIS - GIS

ILWIS GIS is an open source GIS system developed by the ITC, The Netherlands. This is a simple and easy to use system for geo-spatial analysis and can be freely downloaded from 52N site (https://52north.org/software/software-projects/ilwis/). The ILWIS GIS software is linked to the NIH_Basin and 3.6.01 version of this GIS system gets installed along with the NIH_Basin software. The software is invoked as soon as ILWIS-GIS key is pressed. Initial screen of the software is shown in Figure – 4.39. Though a number of GIS analysis is carried out to generate various GIS layers of the study basin, detailed description of GIS analysis is beyond the scope of present study and will be taken up in the User Manual of the software.

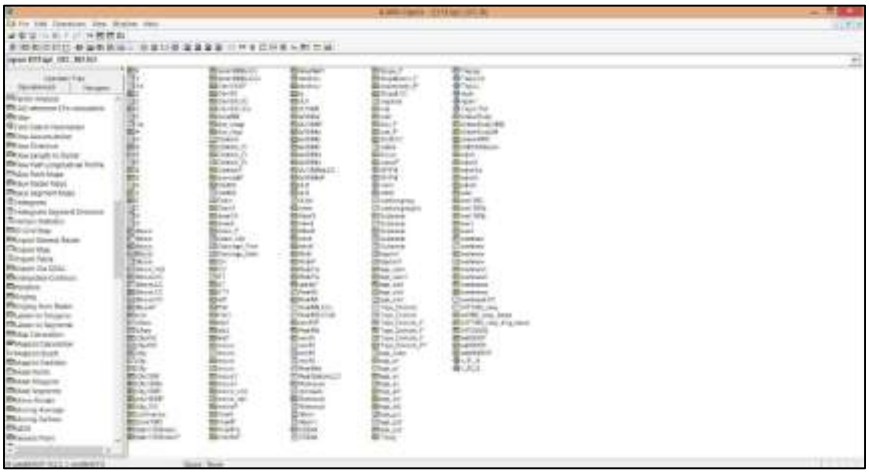


Figure – 4.39: Screen showing ILWIS-GIS system

4.4.2 Compute area dimensions

This module is used to compute the number and location of active cells (within the river basin) in each row of the raster image. As an example, an image of Tapi basin is shown in Figure – 4.40.

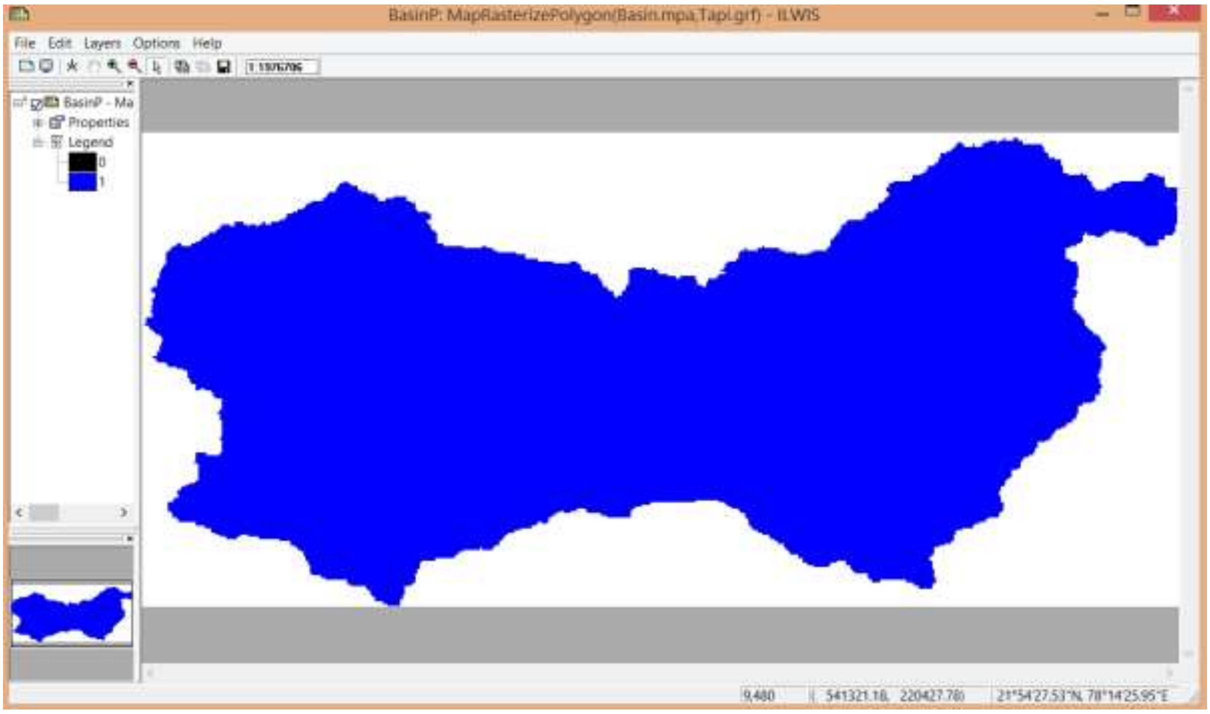


Figure – 4.40: Screen showing ILWIS-GIS system

Clicking on the *"Compute area dimensions"* execute a program on the raster basin image and identifies the location of active cells that are located within the study basin in each row of the raster image. The standard output file after export of raster basin image in ASCII format is *"Basin.asc"* while the file formed after the execution of this computer program is *"Basin.dat"*. This information is used to carry out the *NIH_Basin* analysis for only the active cells in the rectangular raster image. This information is also used to transform the results of analysis to rectangular raster image form for display in GIS system.

4.4.3 Import GIS layers

Using the information about the location of active cells (within the study basin) in the rectangular raster image as obtained in the previous module (Section 4.4.2), this module is used to extract the values of active cells in respective GIS layers. Various GIS layers used in the analysis include 3 crop maps corresponding to Kharif, Rabi, and Hot-weather seasons, soil map, LULC map, DEM, slope map, flow direction map, river network map, sub-basin map, district map, city extent map, water bodies map, irrigation command map, and Thiessen polygon maps of rainfall and reference ET stations. The layout screen for this module is already shown in Figure – 4.39.

Just clicking on a map icon executes a software program on the related map and an output file with standardized filename is generated. It needs to be mentioned that all the GIS analysis is carried out in the GIS folder of the Database sub-directory under the specified basin directory. All GIS layers generated in the ILWIS GIS system must be in the same geo-reference and coordinate system. The generated GIS layers are exported as ASCII files with extension *.asc. For example, the LULC layer generated in ILWIS GIS system is exported as LULC.asc file in the GIS sub-directory under the Database directory. As soon as the Import GIS Layers > LULC map icon is clicked, the LULC in each active cell of the rectangular raster image is read and this information is written in an output file "LULC.dat". This file is used in various *NIH_Basin* programs for analysis and computations.

4.5 Description of "Model Execution" Module

Under this module, various computer programs are run on the data files for the detailed analysis of water resources in a river basin. A screen of the module is shown in Figure – 4.41. The description of various sub-modules is explained below.

Figure – 4.41: Screen showing sub-modules under *"Model Execution"* module

4.5.1 Compute Reference Crop ET

This computer program is used to compute the reference crop evapo-transpiration time series from the meteorological observations at a station in the river basin. For each ET station in the river basin, the reference crop ET time series needs to be calculated which is used as an input for the *NIH_Basin* software. For each station, the meteorological data is entered using *"Reference Crop ET Compute for Single Station"* in the Temporal Data sub-module under Database Preparation module and this program is run and the results are saved in a separate file (say, an MS-Excel file) with each column showing the reference crop ET for a particular station. Finally, the reference crop ET of all meteorological stations in the river basin are computed and the composite results of all stations are saved in the data form corresponding to *"RET Time Series for Multiple Stations in Basin"* in the Temporal Data sub-module under Database preparation module.

4.5.2 Arrange well depth data

This computer program is used to arrange the irregular GW level data in an observation well to regular time series at monthly time step. Further, using the reference level of the observation well, the GW level data is converted to the GW elevation data with reference to the mean sea level. The output of this program is used to compute the average GW elevation time series in each sub-basin of a river basin. Like the reference ET program defined above (Section 4.5.1), this program is also run for all the individual GW observation stations in each sub-basin of the river basin.

The data for this program for each GW observation well is entered using the form corresponding to *"GW Obs. Well Time Series Arrange for Single Station"* in the Temporal Data sub-module under Database Preparation module. The results of the program for each observation station in a sub-basin are saved in a separate file (say, an MS-Excel file) such that a column represents the GW elevation time series for a particular station. Finally, the GW elevation time series of all GW wells in a sub-basin are computed and the composite results of all stations within a sub-basin are saved in the data form corresponding to *"Average GW Elevation Compute for a Sub-basin"* in the Temporal Data sub-module under Database preparation module.

4.5.3 Compute Average GW Elevation in Sub-basin

After the regular time series data of GW elevations at various stations in a sub-basin is entered in the data form corresponding to *"Average GW Elevation Compute for a Sub-basin"* in the Temporal Data sub-module under Database preparation module, the average GW elevation time series in the sub-basin is computed using this module. A click on this sub-module generates the average GW elevation time series for a sub-basin which can be stored in a separate file (say, an MS-Excel file) such that a column represents the average GW elevation time series for a particular sub-basin. Finally, the average GW elevation time series of all sub-basins in a river basin are computed and the composite results of all sub-basins within a river basin are saved in the data form corresponding to *"Average GW Elevation Time Series for All Sub-basins"* in the Temporal Data sub-module under Database preparation module.

4.5.4 Codify Crop Maps + Sub-basin Map

This program is used to merge the spatial information of 3 crop maps (corresponding to Kharif, Rabi, and Hot-weather seasons) and the sub-basin map of the river basin and prepare a single code for each active grid which can be used to get the information of these four data types in the NIH_Basin model. The main purpose behind this codification is to reduce the program dimensions and the number of input files (spatial images) in the NIH_Basin model. Clicking on this sub-menu executes the program and prepares an output file with standardized file names which are used in other software programs.

4.5.5 Codify City + Soil + Rainfall Station + ET Station Maps

This program is used to merge the spatial information of city map, soil map, and Thiessen polygon maps of rainfall and ET stations in the study basin. Clicking on this sub-menu executes the program and prepares an output file with standardized file names which are used in other software programs.

4.5.6 Codify District + DEM + Slope + Flow Direction Maps

This program is used to merge the spatial information of district map, DEM, slope map, and flow direction map in the study basin. Clicking on this sub-menu executes the program and prepares an output file with standardized file names which are used in other software programs.

4.5.7 Codify Irrigation Command + River Network + LULC + Water Bodies Maps

This program is used to merge the spatial information of irrigation command map, river network map, LULC map, and the water bodies map in the study basin. Clicking on this sub-menu executes the program and prepares an output file with standardized file names which are used in other software programs.

4.5.8 Simulate Basin Hydrology

After all the database is prepared and all codification of various spatial layers is completed, the *NIH_Basin* model is run to simulate the basin hydrology at daily time step and compute various components of the hydrological cycle at the level of each grid and each sub-basin in the study basin. If there is any change in any of the spatial layers at any time, the corresponding codification program is run before executing the *NIH_Basin* model so as to consider revised conditions.

The model results are compared with respect to the observed surface water flows (volume of water passed through the sub-basin outlet in a month) at various sub-basin outlets and the computed average GW elevations in different sub-basins at monthly time step. A good match of the two hydrological variables in the long-run can assure proper calibration of the model for the study basin which can then be used to analyze/visualize various scenarios such as:

a) impact of land use or cropping pattern change on basin water resources,

b) impact of climate change (in terms of rainfall, temperature, humidity etc.) on basin water resources,

c) impact of population and industrial growth on the basin water resources,

d) analysis of various management options like inter-basin transfer of water, development of new water resources projects, development of GW infrastructure, increasing the water use efficiency etc. and their impact on the basin water resources.

4.6 Description of “Results” Module

After the *NIH_Basin* model is calibrated and validated for the study basin, various types of results of the model can be analyzed. A screen showing various options under the *“Results”* module is shown in Figure – 4.42.

Figure – 4.42: Screen showing sub-modules under *“Results”* module

First, all the result files of the model are transferred from the modeling location (C:\NIH_Basin) to the *“Results”* directory under the specified location of the study basin. Results are written separately for the simulated flows at different sub-basin outlets; detailed hydrological components for each river basin; simulated GW elevations in different sub-basins; working tables of each hydraulic structure; and spatial maps related to soil moisture status in root zone, actual evapo-transpiration, and recharge/withdrawal of GW in the basin. Though the analysis is carried out at the daily time step and various computations in different result files are available at daily time step, it is desirable to accumulate the results at monthly/yearly time step so as to compute average monthly and yearly estimates and derive useful hydrological information for the study basin. For this purpose, it is desirable to prepare suitable files in MS-Excel so that once the results are imported in such file, then automated worksheets can be generated for drawing miscellaneous charts and for accumulation of results to larger time step and make useful interpretation of the results.

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Chapter - 5

Concluding Remarks

A detailed spatially distributed model has been developed at NIH to assess various components of the hydrological cycle in a river basin. The model incorporates spatial variation of land-use, soil type, rainfall, evapo-transpiration, physiographic characteristics, cropping pattern, irrigation development, groundwater conditions, river network and hydraulic structures in a river basin. GIS is employed to link the spatial data with the simulation model and to project the model results in map form. The basin is divided into grids of uniform size (~ 1 km) and model computes various components of hydrologic cycle such as actual evapo-transpiration, overland flow, groundwater recharge, and residual soil water content at monthly time step for each grid. The model brings out total water availability in the basin; water consumed by different uses; and water storage in different hydraulic structures, in soil water zone, and in groundwater aquifer in a river basin. By taking repeated runs of the model for longer time periods, sustainability of various water resources management plans can be examined.

The model is under continuous stages of development. In the present report, an effort has been made to make some modifications in the model methodology and develop a WINDOWS interface (named as ***NIH_Basin*** – **NIH_Basin-Simulation**) of the model for easy application by the user groups. Some of the previous limitations of the model which have been addressed include: i) specification of EAC tables or corresponding relationships for various storage structures, ii) rule-curve based operation of reservoirs so that different management options of the system can be simulated, iii) option of hydropower simulation of hydraulic structures in the basin, iv) simplified representation of groundwater system at the basin scale.

For approximating the EAC relationships for a reservoir, the approach developed by J. Mohammadzadeh-Habili et. al (2009) has been programmed within the FORTRAN code of the model. In addition, it is also possible to specify available EAC table for a project. Rule-curve based approach has been added in the FORTRAN code for simulating the reservoir operation as per specified operation policy. The option of hydropower simulation of a reservoir has also been added and eight different methods of supply of water through the power plants have been considered. Tail water elevation is also considered as a function of release through the power plants. Model has been updated to work in two modes: a) monthly mode (in which the simulation is carried out at daily time step for a month and then the spatial recharge and discharge pattern are externally used to find the revised water table in the basin with groundwater simulation model, say Visual MODFLOW, and the revised groundwater table is used for the subsequent month), and b) continuous mode (in which the simulation is carried out at daily time step for the complete period, say for 30 years of record, for which hydro-meteorological data are available). In the second mode, grid-wise pumping and recharge estimations are accumulated over each sub-basin and then divided by the Specific yield "S_y" of the sub-basin aquifer to convert water withdrawal/recharge to corresponding change in groundwater level which can be applied to initial groundwater surface to find the revised surface in the sub-basin, thus avoiding the necessity of detailed groundwater simulation. For each sub-basin, average groundwater elevation is computed from data of a large number of observation wells (a procedure, defined by DHI, Denmark has been adopted for converting irregular observations in different wells in a sub-basin) has been programmed and added as a module in the software. In addition to the envisaged modifications, a number of minor modifications have been made so that the model can simulate a river basin quite close to the reality. Some of these modifications are:

a) Number of landuse classes has been increased from 6 to 60 for more detailed representation. Similarly, dimensions of model have been increased so that it may be applicable to larger basins with large number of rainfall and ET stations, large number of districts and cities, and large number of crops, soils, and hydraulic structures.
b) Option has been included to consider industrial demands separately (earlier, it was merged with domestic demands) and the same has been linked to city attributes.
c) Date of commissioning of hydraulic structures has been included such that in the command area of hydraulic structures, the revised cropping pattern is considered since the period of commissioning of projects for computing irrigation demands.
d) Now, variable GW development is considered (which was taken constant previously) by specifying the growth rate of GW development in a district. The groundwater potential in each sub-basin is now linked to the average GW elevation in a sub-basin and the groundwater development at a particular time.
e) Base flow computation is now made dependent on the GW elevation in the aquifer storage in a sub-basin which contributes to the base flow at its outlet. The reversal of base flow (flow from river to GW) is also possible depending on the GW elevation in the associated sub-basin.
f) Rather than considering constant population for human and cattle population, population growth is considered as per defined rate in a district and for long-term simulation, revised population is estimated at the beginning of each year.

In the WINDOWS interface of the model, four important modules of the software include: a) Database preparation, b) GIS analysis, c) Model execution, and d) Results. Various data input forms have been prepared and extensively tested for the correct preparation of data files in user-friendly environment. The report gives a detailed presentation of these forms and details of some distinctive options of the forms have been included for sake of clarification.

Finally, it is to emphasize that the model links the intricate variables and parameters of water resources processes at the scale of a river basin. These can be best understood with the applications of the system for some large river basins and development of a User’s Manual. The progress is on for the application of the model for a large river basin (possibly Subarnarekha basin) as most of the basin data has been collected. After thorough testing of model and with acceptable results, the User’s Manual would be prepared and courses would be planned for transfer of the developed technology.

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