Application of a Distributed Hydrological Model for River Basin Planning and Management

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PREFACE

Effective management of water and related environment in a river basin requires an integrated and co-ordinated planning within the basin. A conceptual spatially distributed water balance model, earlier developed at NIH, has been applied to the Upper Bhima basin up to Ujjani dam. Model computes various components of hydrologic cycle such as rainfall, AET, runoff, groundwater recharge, soil moisture change etc. for various land uses and soil conditions in different sub-basins of a river basin. 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.

The model has been applied to the Upper Bhima basin up to Ujjani dam. Extensive database has been generated for the basin and model runs have been taken from June 1992 to May 2001. Various outputs of the model for the Upper Bhima basin have been discussed in detail. The model results have been have been found to be satisfactory within the assumptions and limitations of the study. The application has suggested a number of modifications in the model some of which include: i) specification of EAC tables for various storage structures, ii) rule-curve based operation of reservoirs so that different management operations can be simulated, iii) option of hydropower simulation of reservoirs, iv) option of spill release to different river segment/sub-basin, v) simpler groundwater representation for river basin planning, vi) development of WINDOWS interface etc.

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ABSTRACT

Any plan related to inter-basin transfer of water from a water-surplus basin to a water-deficit basin has to take into account the water availability and demands under the present and future scenarios of water use. Any water-related activity that takes place in one part of a river basin may have consequences in the other part. Therefore, effective management of water and related environment in a river basin requires an integrated and co-ordinated planning within the basin.

A conceptual spatially distributed water balance model, earlier developed at NIH, has been applied to the Upper Bhima basin up to Ujjani dam. Various types of spatial, attribute, and dynamic data are integrated by the model to perform the water balance analysis to simulate various components of the hydrologic cycle at the scale of a river basin. Model computes various components of hydrologic cycle such as rainfall, actual evapo-transpiration, runoff, groundwater recharge, soil moisture change etc. for various land uses in different sub-basins of a river basin. 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. Using this model, various scenarios of water availability in a river basin can be generated and analyzed. By taking repeated runs of the model for longer time periods, sustainability of various water resources management plans can be examined.

The model has been applied to the Upper Bhima basin up to Ujjani dam. Extensive database has been generated for the basin and model runs have been taken from June 1992 to May 2001. Basin data has been used to check the model linkages. Various outputs of the model for the Upper Bhima basin have been discussed in detail. The model results have been checked by matching the river flows at different gauging sites and they have been found to be satisfactory. However, the application has suggested a number of modification requirement in the model some of which include: i) specification of EAC tables for various storage structures, ii) rule-curve based operation of reservoirs so that different management operations can be simulated, iii) option of hydropower simulation of reservoirs, iv) option of spill release to different river segment/sub-basin, v) simpler groundwater representation for river basin planning, vi) option of lift irrigation etc.

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Chapter – 1
INTRODUCTION

1.1 General

At a place, water descends in the form of rainfall or precipitation. In the course of time, it gets partitioned into surface water or groundwater resource. A river basin (or catchment) is the area drained by a river and its tributaries i.e., the area from which a river catches or collects its water. A catchment area can be very small, just a few hectares, or it may cover an enormous area, as for example, the Ganga or the Brahmaputra River basins. Apart from the loss by evapo-transpiration, all the water that falls as rain within a catchment area will either run off on the surface or sink into the ground to become groundwater, eventually reaching the river which drains the basin. Since ancient times, both surface water and groundwater have been used for agricultural, industrial and domestic purposes. Surface water and groundwater, though two distinguished resources, tend to be inter-related in the sense that groundwater may feed surface water bodies and vice-versa.

With time, we are becoming more increasingly aware of the fact that our water supplies are limited both in quantity and quality. Because water has multiple and often competing uses, water resources systems are inter-related with other physical and socio-economic systems. The fact that every living being depends on water to live and its limited availability in terms of both quantity and quality makes it a resource that living beings compete for. This precious resource has competitors that need it in one way or another as a result of which it often becomes challenging in space and time to fully satisfy the needs of these competitors for water. The viable solution under such conditions is "balancing out". A key function of river basin planning is to strike a balance between environmental, social and economic interests.

Any water-related activity that takes place in one part of a river basin may have consequences in the other part. Therefore, effective management of water and related environment in a river basin requires an integrated and co-ordinated planning within the basin. Thus, river basin planning is an ongoing process that promotes sustainable water use while protecting and improving the water environment.

Environment is in dynamic balance with its elements. If changes are introduced in some of the elements, a new order develops which, in course of time, stabilizes in an altered environment. Planning of water resources projects should be accomplished in a manner such that the changed environment is healthy and there are no adverse impacts. Introduction of water resources projects (reservoirs, diversion structures etc.) in a river basin sets in new hydrological regime in the basin with revised conditions of surface water and groundwater availability and use. In addition, a number of interacting water-related variables are involved in a river basin such as rainfall, evapo-transpiration, land use and land cover, landscape and flow direction, soil types and their water holding and transmission characteristics, prevailing cropping pattern and their water demands, irrigated/rainfed area, groundwater potential/development and its temporal availability, urban/rural area and their human and cattle population water demands, industrial development and water demands, water resources structures and their demands/supply, drainage network and water movement, hydro-meteorological and river gauge network and spatial and temporal data availability etc. For preparing any integrated river basin plan, it is imperative to gather the details about these interacting variables and to establish their linkages for evaluation of their impact on the basin water resources.

Some of the water-related variables are susceptible to change with time, say land use/land cover, irrigated/rainfed area, cropping pattern, spatial and temporal rainfall amount/pattern and potential evapo-transpiration due to varying climate, development of new water resources projects, spatial and temporal availability of groundwater, population and industrialization etc. For developing any future scenarios corresponding to modified water-related variables, a modeling system is required that can evaluate the impact of revised variables and can establish the water availability in the modified situation.

1.2 Need of a Distributed Basin-scale Model

Generally, the methodology used for water availability assessment in a river basin depends on the long-term rainfall and discharge data series in the basin. Based on the development of water resources projects in the basin with time, virgin flows are estimated and regression analysis is performed between the available virgin discharge and rainfall series. Using the developed relationship, virgin discharge data in missing years of record are obtained. Next, discharge corresponding to a specified reliability (say, 75%) is taken to be the water availability for the basin after duly taking into account the influence of present and proposed hydraulic structures in the basin. River discharge is considered as the basic information for water availability assessment and groundwater development and utilization in space and time is not given enough consideration.

However, in the approach mentioned above, it is difficult to account for the effect of various temporal changes in the water-related variables (specified above) that might have occurred in the basin for present scenario or might change in future. For example, change in meteorological variables like temperature, wind, and humidity may influence the evapo-transpiration losses from the basin. So a basin-scale model is required that can incorporate detailed representation of various factors influencing the water availability in a river basin. The model needs to address various components of the hydrologic cycle to establish linkages among water-related variables to simulate situation corresponding to any past, present or future conditions.

1.2.1 Use of remote sensing data with GIS platform

Vastness of the river basins, time and manpower constraints in data collection and annual/decadal changes in the information require fast inventory of river basins. In all these circumstances, remote sensing can be looked upon as an aid in planning and decision-making. The usefulness of remote sensing techniques in inventory of land use/land cover such as built-up area, water bodies, agricultural area, irrigated area, forest land, barren land etc. have been well-established [Bastiaanssen (1998, 2000)]. Advances in remote sensing technology have led to considerable saving in time and money spent in data collection and data input.

Further, information is vital in reducing uncertainty, evaluating alternative courses of action and revealing new avenues. Availability of right information at the right time to the right person and at the right cost is a crucial factor in decision-making. All hydrologic processes relate to space making it plausible to associate geo-information with hydrologic processes. Survey of some of the recent literature shows several attempts that have been made to incorporate a Geographic Information System (GIS) into hydrologic analyses. A GIS is a computer-based system designed to store, process and analyze geo-referenced spatial data and their attributes. Greene and Cruise (1995) classify these attempts into four groups: 1) calculation of input parameters for existing hydrologic models; 2) mapping and display of hydrologic variables; 3) watershed surface representation; and 4) identification of hydrologic response units. Since several GIS database layers can be overlain, GIS can be a very useful tool to integrate the analyses of hydrologic processes of river basins.

1.3 Objectives and Scope of the Study

A conceptual spatially distributed water balance model was earlier developed at NIH. Various types of spatial, attribute, and dynamic data are integrated by the model to perform the water balance analysis and to simulate various components of hydrologic cycle at the scale of a river basin. Various components of hydrologic cycle include rainfall, actual evapo-transpiration, runoff, groundwater recharge, soil moisture change etc. for various land uses in different sub-basins of a river basin. 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. Using this model, various scenarios of water availability in a river basin can be generated and analyzed. By taking repeated runs of the model for longer time periods, sustainability of various water resources management plans can be examined.

The objective of the present study is the application of the developed distributed model to the Upper Bhima basin up to Ujjani dam. This basin has also been selected as a pilot basin for DSS applications under HP-II project. The aim of the application is to check and compare the results of the semi-distributed model (NAM model) with the present application.

It is aim of the application to get insight into the development of the distributed model and its application in different river basins so that it can act as a decision support tool for river basin authorities in evaluating the water resources of a river basin. Through this experience, different modification requirements in the developed model can be identified to make it more robust and useful. The model is also envisaged to evaluate the impact of changing a particular variable (say forest area, or cropping pattern, or developing a new hydraulic structure, or changing the population and industrial demands etc.) on the water resources of the basin.

* * *

Chapter – 2
MODEL DESCRIPTION

2.1 Description of the Developed Model

Efforts made in the past to develop simulation models for river basin planning and management has been tremendous. The aim of developing the present model is 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 the reservoirs, and artificial water transfer from any reservoir/stream outside the basin.
- 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 soil moisture for satisfying evapo-transpiration demands.
- 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.

2.1.2 Input Data Requirement

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 the 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 as follows:

<u>*Crop attributes:*</u> 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.

2.1.3 Various Modules

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 present 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.

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:

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

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

d) The slope adjusted curve number is then modified for the 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 the curve number derived in step 'c' is not modified as it represents normal AMC. 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 per the following equations:

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

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

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:

$$Runoff = \frac{(Rain - 0.3 * S)^2}{Rain + 0.7 * S} \quad \text{...(2.8)}$$

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.

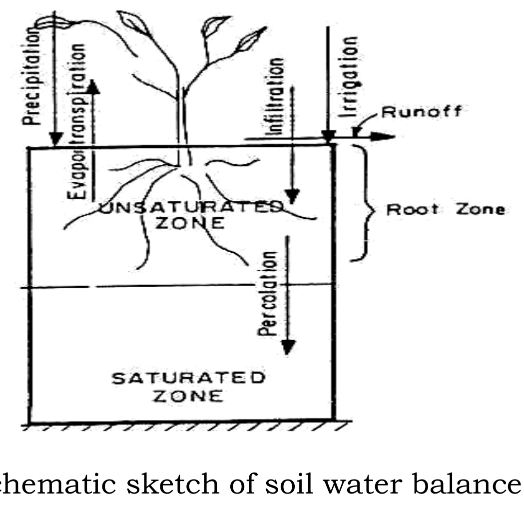


Figure – 2.1: Schematic sketch of soil water balance components

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.

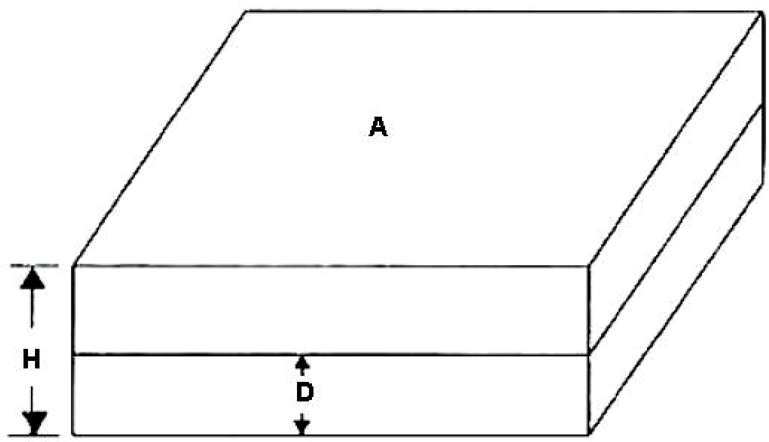


Figure – 2.2: A grid representing soil reservoir

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 $D = 10.w.G_a.H$ ...(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:

$$WDS = 10 \, . \, w_s . \, G_a \, . \, H$$

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

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

$$= 10. \, \eta. \, H \quad \text{...(2.12)}$$

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

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

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

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:

$$UL = WDS + D_{max} \quad \text{...(2.15)}$$

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.

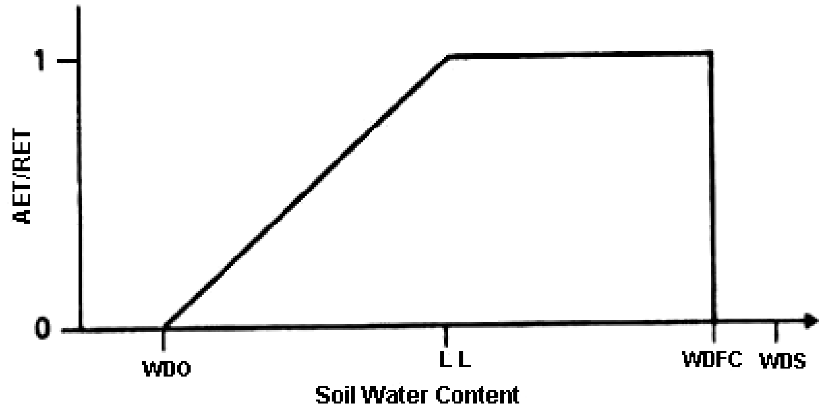


Figure – 2.3: Variation of actual crop evapo-transpiration with soil water content

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.

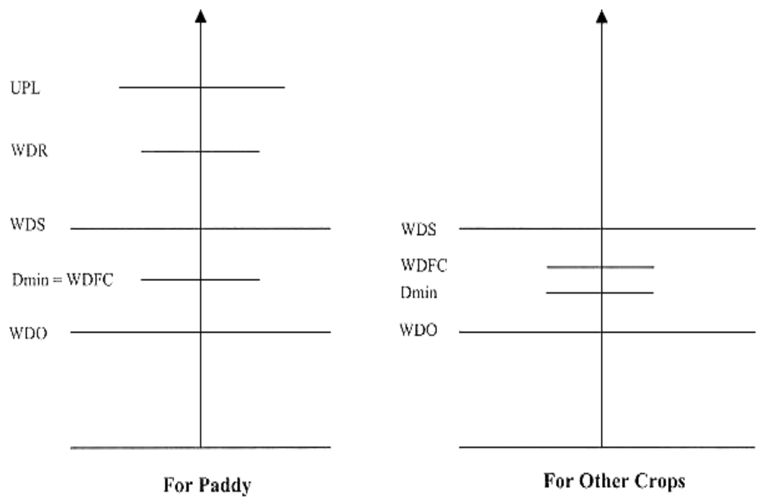


Figure-2.4: Definition sketch of specific equivalent water depths

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:

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

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 the WD_t lies below the D_{min}, then AET_t is determined as per the following:

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

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:

$$DPER_t = \text{min. of (hydraulic conductivity, } WD_t - WDFC) \quad ...(2.20)$$

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:

$$SWR_t = ETC_t - ERF_t - GWC_t - OLFI_t \quad \text{...(2.21)}$$

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

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

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:

$$Pop_U = \frac{TPOP_{Dist} * NGRD_{Bas} * PERUR_{Dist}}{100 * NARE_{Dist} * NGRD_U} \quad \text{...(2.23)}$$

$$Pop_C = \frac{TCPOP_{Dist}}{(NARE_{Dist} - TURB_{Dist})} \quad \text{...(2.24)}$$

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 the overland flow (converted from depth to volume units) is added as flow to the 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.

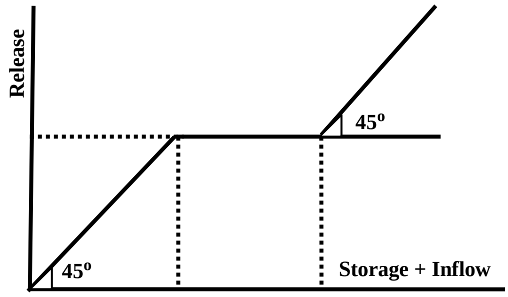


Figure-2.5: Standard linear operating policy

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 as follows:

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

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

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:

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

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 release 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:

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

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 t^{th} 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 the bed levels of the two gauging 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 the 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.

2.1.4 Linkage with Groundwater Flow Model

In the present 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 present 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.

Description of Visual MODFLO

A groundwater model is a computer-based representation of the groundwater system that provides a predictive scientific tool to quantify the impact of specified hydrological stresses on the system. In the process of groundwater modeling, the continuous aquifer system parameters are replaced by an equivalent set of discrete elements. Equations governing the flow of ground water in the discretized model are written in finite-difference (or finite element) form which are solved numerically. VMOD provides modeling environment for three-dimensional groundwater flow and contaminant transport simulations. The menu-based structure and graphical tools of VMOD help to easily dimension the model domain, assign model properties and boundary conditions, run model simulations, and visualize the results. Of the various capabilities of VMOD, groundwater simulation model (MODFLOW) is used in this study.

MODFLOW is a MODular 3-dimensional finite difference groundwater FLOW model developed by McDonald and Harbough (1988). It simulates steady and unsteady flow in three dimensions for an irregularly shaped flow system in which aquifer layer can be confined, unconfined, or a combination of these. Flow from external sources, such as flow to wells, recharge, flow to drains, and flow through river, can be simulated. MODFLOW uses a modular structure wherein similar program functions are grouped together. The modular structure consists of a main program and a large number of independent subroutines called "modules" which are grouped into "packages". Each package deals with a specific aspect of the hydrological system to be simulated.

The three dimensional unsteady movement of groundwater of constant density through porous earth material in a heterogenous anisotropic medium can be described by the following partial differential equation:

$$\frac{\partial}{\partial x}\left(K_{xx}\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(K_{yy}\frac{\partial h}{\partial y}\right)+\frac{\partial}{\partial z}\left(K_{zz}\frac{\partial h}{\partial z}\right)-W=S_s\frac{\partial h}{\partial t} \quad \text{...(2.26)}$$

where,

K_{xx}, K_{yy}, K_{zz}	:	hydraulic conductivity along major axes [LT^{-1}],
h	:	potentiometric head [L],
W	:	volumetric flux per unit volume. It represents sources and/or sinks of water [T^{-1}],
S_s	:	specific storage of the porous material [L^{-1}] and,
t	:	time [T].

In general, S_s, K_{xx}, K_{yy} and K_{zz} are functions of space whereas W and h are functions of space and time. Equation (2.26) together with specification of flow conditions at the boundaries of an aquifer system and specification of initial head conditions constitutes a mathematical model of ground water flow. Possible inflow/outflow terms in a groundwater system include recharge from rainfall, artificial recharge through wells, pumping through wells, evapo-transpiration, recharge through river/canal cells, outflow into a river/canal cell, inflow/outflow across a boundary cell, outflow through drains, spring flow etc. Input to the groundwater model include initial groundwater conditions; boundary conditions; characteristics of aquifer such as transmissibility, specific storage, effective porosity; recharge data, evapo-transpiration data, pumping to/from the wells, artificial recharge etc.

Major outputs from the model are in form of water levels, drawdowns, water balance of the model domain, and inflow/outflow across model boundaries.

MODFLOW discretizes the model domain with a mesh of blocks called 'cells' in which medium properties are assumed to be uniform. The varying thickness of vertical layers of aquifer systems are transformed into a set of parallel 'layers'. The location of each cell is described in terms of rows, columns, and layers. Within each cell there is a point called a 'node' at which groundwater head is calculated. The model distinguishes a cell into: i) variable-head cell (the head varies with time), ii) constant head cell (the head is constant), or iii) no flow or inactive cell (no flow takes place within the cell). The period of simulation is divided into a series of 'stress period' within which stress parameters are constant. Each stress period, in turn, is divided into a series of time steps. The user specifies the length of stress period, the number of time steps at each stress period, and the time step multiplier. Using these terms, the program calculates the length of each time step in the stress period. With these discretization in space and time, Equation (2.26) leads to a system of simultaneous linear algebraic equation which are solved iteratively.

Various modules that are provided in MODFLOW to deal with different field situations include Basic package (BAS), Block-centered flow package (BCF), River package (RIV), Recharge package (RCH), Well package (WEL), Drain package (DRAIN), Evapotranspiration package (ET), General-head boundary package (GHB) and the simulation technique packages. BAS package handles a number of administrative tasks for the model. It reads data for: a) the discretization of the model domain, b) initial and boundary conditions after distinguishing a cell into variable-head, constant-head or inactive cell, c) the discretization of simulation time into stress period, time step and the time step multiplier, and d) units for the input variables. BCF package computes the conductance components of the finite-difference equation, which determine flow between adjacent cells and computes the terms to find rate of movement of water to and from storage. Rivers and streams contribute water to the groundwater system or drain water from it depending on the head gradient between the river and the groundwater. The purpose of RIV package is to simulate the effect of flow between surface water features and groundwater systems. RCH package simulates the aerially distributed recharge to the groundwater flow system. WEL package simulates the inflow or outflow through recharging or pumping wells. Wells are handled by specifying the location of each individual well and its flow rate (Q). Negative values of Q are used to indicate well discharge, while positive values of Q indicate a recharging well. DRAIN package simulates the effect of open and closed drains and it works in much the same way as the RIV package except that the leakage from the drain to the aquifer is not considered. ET package simulates the effects of plant transpiration and the direct evaporation in removing water from the saturated groundwater. GHB package simulates flow into or out of a cell from an external source. The flow into a cell is assumed proportional to the difference between the head in the cell and the head assigned to the external source. Detailed description of various packages is available in Visual MODFLOW 3.0 - User's Manual (2002).

In addition to the three main models as stated above, nine other modules have been developed for generation of database for the scheme and for linking the input and output of various component models with GIS. Description of these modules is given in this chapter. After the development of different modules, the sequencing of operation of different modules for database generation is presented. Finally, a flow chart of the integrated geo-simulation scheme is given.

2.1.5 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 briefly described in the following:

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 the analysis but unnecessarily increase the dimensions of the computer program.

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 the 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 simulation 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 basin simulation 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, groundwater 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 the 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

2.1.5 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. The 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 determined.
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 the data file.
7. For the day for which simulation analysis is carried out, corresponding week is identified and the root depth and crop coefficients of different crops in that 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, the irrigation demands (if it is 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.

2.1.5 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).

* * *

Chapter – 3
DATABASE DEVELOPMENT FOR UPPER BHIMA RIVER BASIN

3.1 General

The river basin simulation model, developed at NIH, has been applied to the Upper Bhima basin to check for its computational algorithm, performance analysis, and any modification required for its application to various river basins of India. Spatial, attribute, and dynamic data has been collected for the Upper Bhima basin. Various 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. Information has also been obtained from the Irrigation Department of Maharashtra State. Attribute data of crops, soils, gauging sites, various hydraulic structures etc. have been obtained from a variety of sources. Dynamic data of rainfall and flow of a few years of record from 1992 – 2001 was also obtained from a variety of sources.

It needs to be mentioned that database requirement of the model is quite extensive. This study was mainly concerned with the model application for a river basin and individual efforts have been made by the study team to gather the information for the study basin as accurately as possible. In some cases, when the actual field details could not be obtained, the same have been generated by using different ancillary means. However, since the model involves multi-dimensional data that is covered by number of departments/ agencies (Central Water Commission, Central Ground Water Board, Indian Meteorological Department, Agriculture Department, Statistical Directorate, Project authorities in the river basin etc.), there is a strong need for close collaboration of these departments/ agencies for the successful execution of the model for a river basin.

This chapter describes the database development for the Upper Bhima basin. After a brief introduction of the Upper Bhima basin, various methods and resources employed to generate various data layers and obtain various attribute data are presented.

3.2 The Upper Bhima River Basin

The Upper Bhima River is a part of the Krishna river system in the State of Maharashtra. The Bhima river rises in the Western Ghats at Bhimashanker in Pune District of Maharashtra at an altitude of about 944.88 m. The river flows for a total length of 860.99 km through Maharashtra, Karnataka and Andhra Pradesh and falls into the Krishna.

The Bhima river receives the waters of the Mula-mutha on the right bank near Pune about 136.79 km from its source, at an elevation of 518.16 m. In 136.79 km, the bed fall is 3.11 m per km. Lower down, the Bhima is joined by the Ghod of which the Mina, the Kukadi and the Hanga are tributaries, at about 165.76 km on the left bank at an elevation of about 513.59 m. The fall between 136.79 and 165.76 km is 0.16 m per km. The Bhima passes the Ujjani dam site at 321.87 km at an elevation of 458.11 m. Subsequently, the river is joined at 358.88 km on the right bank by the Nira and then by the Man on the right bank. For a stretch of 74.02 km (between 487.63 to 561.66 km), the Bhima river forms the boundary between Maharashtra and Karnataka before entering to Karnataka. An Index map of Upper Bhima basin is presented in Figure – 3.1. The map also shows the location of major water resources projects in the upper Bhima basin up to Ujjani dam.

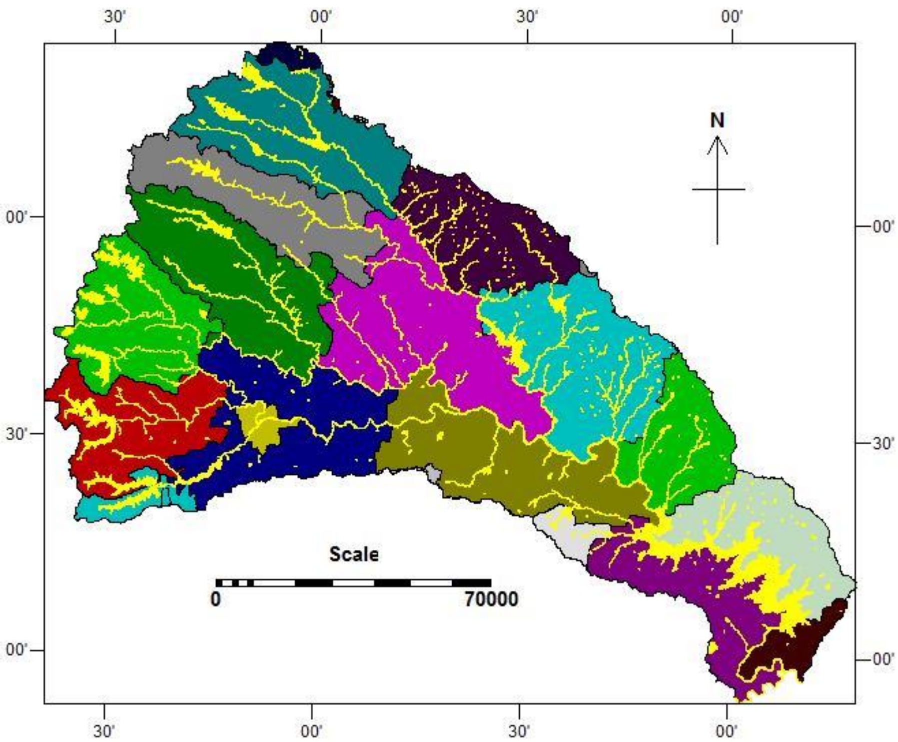


Figure – 3.1: Upper Bhima basin up to Ujjani dam

3.2.1 Rainfall in Upper Bhima Basin

The heavy rainfall of the Western Ghats is the main source of supply in the study basin. The Western Ghats run almost parallel to the sea coast at a distance of 80 to 160 km from the sea. Precipitous on the western side, they fall away more gradually to the east. The heaviest rainfall occurs on the peak of the ridge, the intensity of the rainfall rapidly decreasing as we go eastwards. The rivers rise in the valleys close to the Ghats which divides the flow into two parts: the smaller portion falling westwards into the Arabian sea and the other flowing through rivers eastwards to the Bay of Bengal.

Western Ghats region receives high rainfall. Western Ghats receives >4000 mm of average annual rainfall. Plains of Deccan Plateau in east receive <500 mm of average annual rainfall. Average annual rainfall is 872 mm. Nearly 80- 90% rainfall occurs in monsoon months of June to October.

3.2.2 Land Use and Population in Upper Bhima Basin

Upper Bhima basin has a multi-purpose multi-reservoir system with catchment area of 14,914 sq. km. There are 18 reservoir projects in the basin with total storage of 17.4 MCM and hydropower generation capacity of 318 MW. Major part of the basin is drought prone with extensive groundwater exploitation. Ten percent (10%) of the basin area is forested whereas agriculture is practiced on 76% of the basin area out of which 64% is irrigated. The major land use of the basin is presented in Table – 3.1. The human and cattle population of Upper Bhima basin, as per the 1991 census, is 31.65 Lakh and 12.00 Lakh approximately.

Table – 3.1
Major land uses in Upper Bhima basin

Land use category	Area (sq. km)
Urban area	222
Rainfed agriculture	3170
Irrigated agriculture	2773
Forest land	1262
Barren land	6899
Water bodies	617

3.2.3 Water Resources Development in Upper Bhima Basin

There are 16 G&D sites maintained by CWC and State Irrigation Department in Upper Bhima basin. The list of gauging stations considered in the present study along with their sub-basin ID, river segment on which located and the river bed levels is presented in Table – 3.2.

Table – 3.2
List of G&D Stations considered in study in Upper Bhima Basin

Sub-basin_ID	Station Name	River segment on which located	River bed level (m)
1	Shirur	218	550
2	Aamdabad	173	563
3	Chaskman	95	604
4	Askheda	87	603
5	Nighoje	85	563
6	Budhwadi	76	605
7	Pimpal Gurav	40	546
8	Paud	26	562
9	Dattawadi	17	542
10	Pulgaon	104	542
11	Wegre	7	602
12	Khamgaon	60	515
13	Rakshewadi	126	510
14	Pargaon	129	510
15	Kashti	253	506
16	Dhond	256	498

There are 15 major irrigation/hydropower projects in the basin. The list of water resources projects considered along with their associated ET station and sub-basin in which located is given in Table – 3.3.

Table – 3.3
Major existing projects in Upper Bhima basin (1992-01)

Project_ID	Name	ET_Stn	Sub-basin	Live Stor (MCM)	Ini. Stor (MCM)	Area at FRL (Sq. km)
1	Manikdoh	1	1	288	30	18.43
2	Yedgaon	2	1	79.27	10	14.6
3	Wadaj	1	2	33.2	7	4.67
4	Dimbhe	3	2	355	35	17.55
5	Chaskaman	3	3	214.05	34	20.62
6	Shiravata	4	6	192	20	16.40
7	Pawana	4	7	291	25	23.05
8	Mulshi	7	8	560	30	46.57
9	Warasgaon	8	9	0	0	0
10	Panchet	8	9	0	0	0

Project_ID	Name	ET_Stn	Sub-basin	Live Stor (MCM)	Ini. Stor (MCM)	Area at FRL (Sq. km)
11	Khadakwasla	8	9	680	100	47.25
12	Ghod	10	15	154.8	30	31.1
13	Visapur	10	15	33.32	4	8
14	Ujjani	13	17	1520	500	336.25
15	Andhra Tank	4	5	352	40	32.427
16	Walwhan	4	5	72.12	10	10.80

3.3 Database Development for Basin Simulation Model

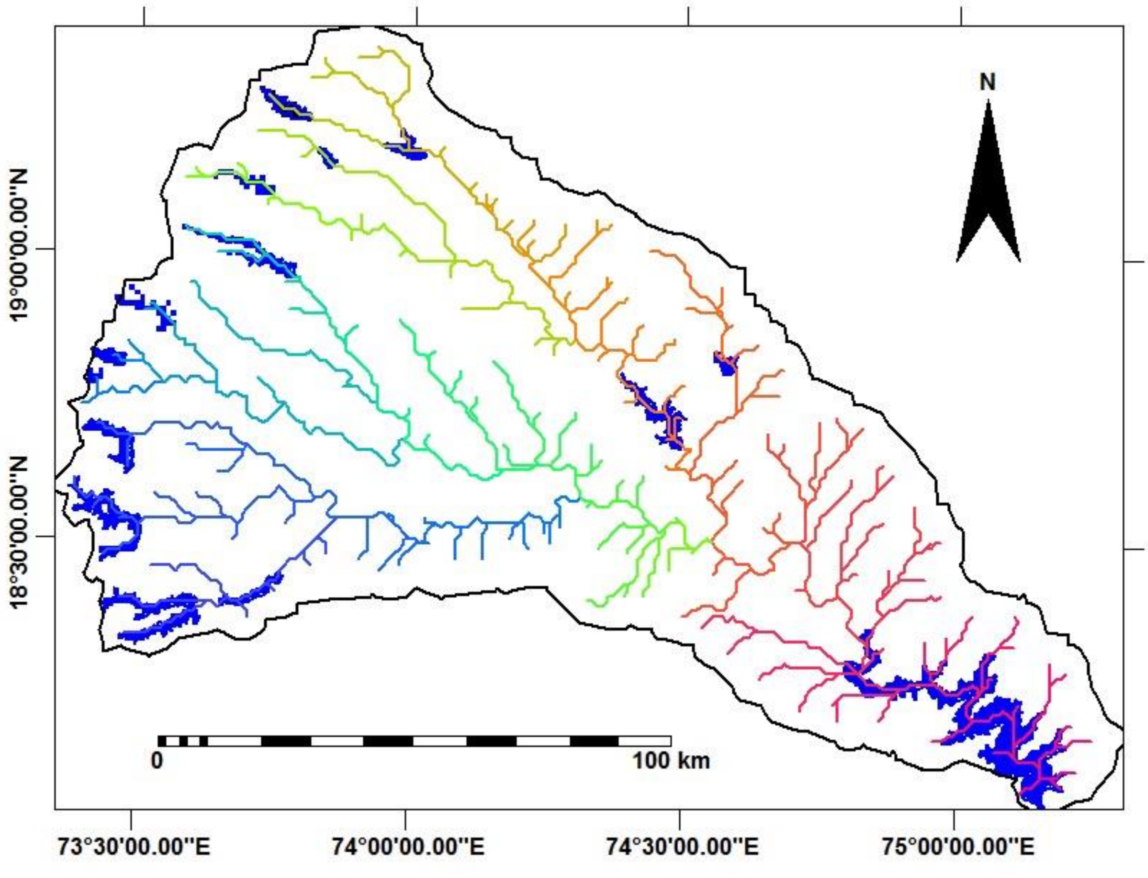
Various types of spatial, attribute, and dynamic data are integrated by the model. Spatial database includes maps related to basin boundary, cities, river network, elevation, slope, flow direction, land use, soil type, cropping pattern, irrigable command areas, reservoir waterspread areas, groundwater depth, sub-basins, districts, and Thiessen polygons of RF and ET stations. Attribute database includes crop properties, soil properties, details of hydraulic structures, river and reservoir network connectivity, D & I standards, details of cities, and details of different gauging sites. Dynamic data include daily rainfall and evapo-transpiration at different gauging stations, water transfers from/to rivers and reservoirs within or outside the basin, observed river flows at different gauging sites, and groundwater levels in different observation wells in the basin. In the following sections, all these databases for Upper Bhima basin have been discussed.

3.3.1 Spatial Data

Most of the spatially distributed data have been developed in GIS. ILWIS GIS system, a system in public domain, has been used. In view of the large size of Upper Bhima river basin (around 14,914 sq. km), the grid size of analysis has been taken as 1 km. All the data layers have been generated with “LCC” projection, ellipsoid “WGS 84”, datum “WGS 84 and origin coordinates as 76.50 degree E longitude and 18.533 degree N latitude. The whole basin up to Ujjani dam is covered in 151 rows and 206 columns. Generation of each layer is described below.

a) Basin Boundary, DEM, Slope, Flow-Direction, Drainage, Sub-basin

Maps related to basin boundary, slope, flow direction, drainage network, and sub-basin can be derived from the GIS analysis of digital elevation map of a river basin. In the present study, these maps for the Upper Bhima River basin have been generated by using the “DEM Hydro-processing" module of ILWIS. The SRTM data for the Upper Bhima basin at 90 m resolution has been downloaded from the internet and it is geo-referenced using boundary coordinates. Then, this elevation map is aggregated to 1000 m resolution by averaging the elevations using nearest neighborhood resampling method in specified coordinate system. Using the digital elevation map, DEM Hydro-processing module generates the slope map, flow direction map, drainage network, flow accumulation map and drainage area map (at given points). In the present study, the Upper Bhima basin up to Ujjani dam has been considered. So, the basin area corresponding to the outlet (coordinates of the Ujjani dam) has been obtained. The basin boundary map of Upper Bhima basin up to Ujjani dam along with extracted drainage network map is presented in Figure – 3.2. Digital elevation map of the basin is shown in Figure – 3.3 and the slope map of the basin is presented in Figure – 3.4. The sub-basin map corresponding to different gauging stations is depicted in Figure – 3.5. The flow direction map is presented in Figure – 3.6.



Figure–3.2: Basin boundary of UB with extracted drainage from SRTM

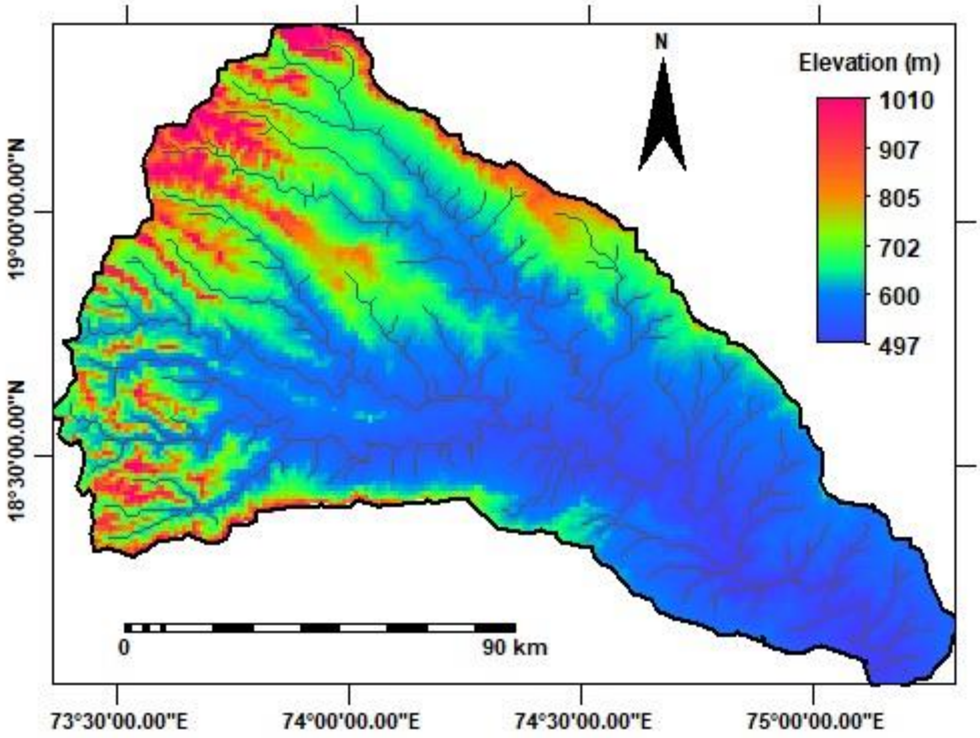


Figure – 3.3: SRTM DEM of Upper Bhima Basin at 1 km resolution

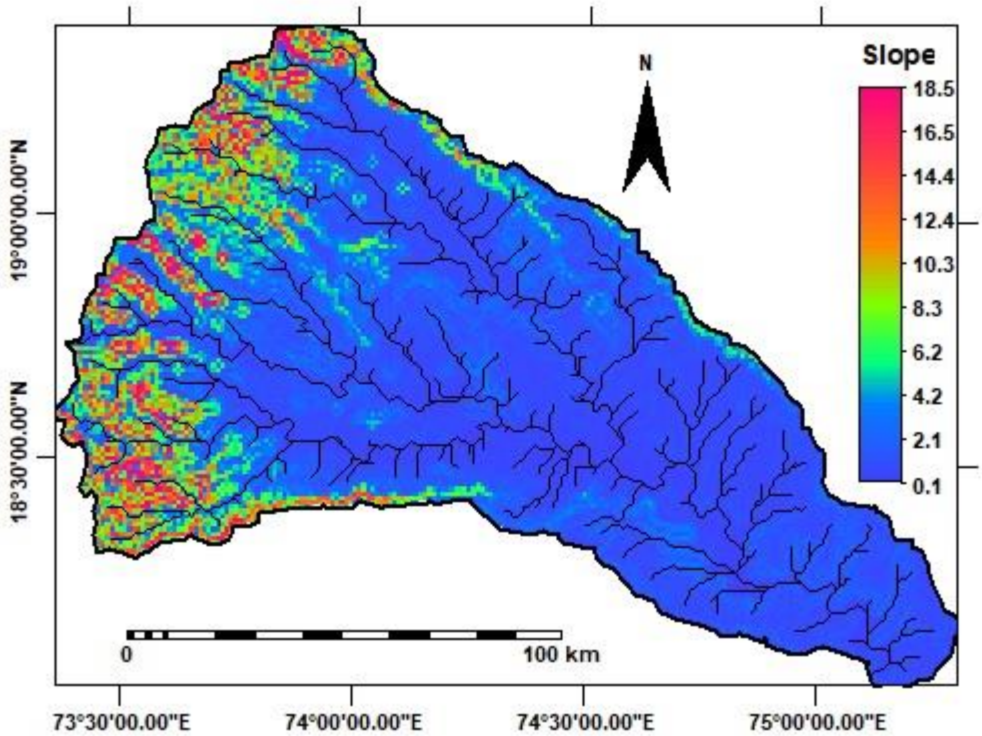


Figure – 3.4: Slope map of Upper Bhima Basin at 1 km resolution

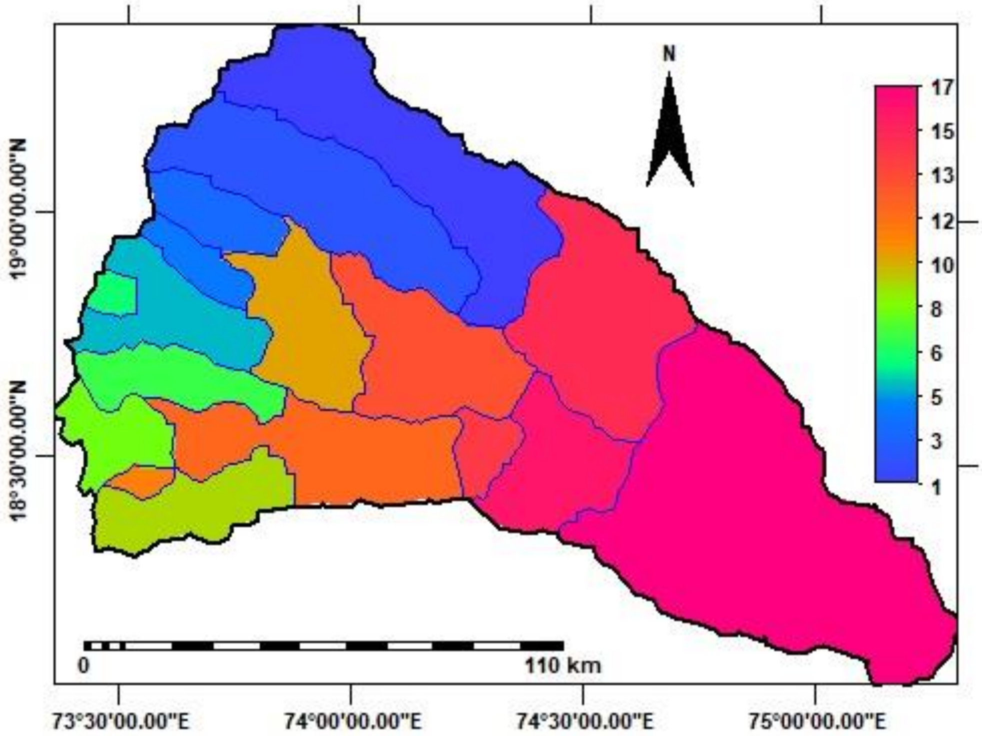


Figure – 3.5: Sub-basin map of Upper Bhima Basin

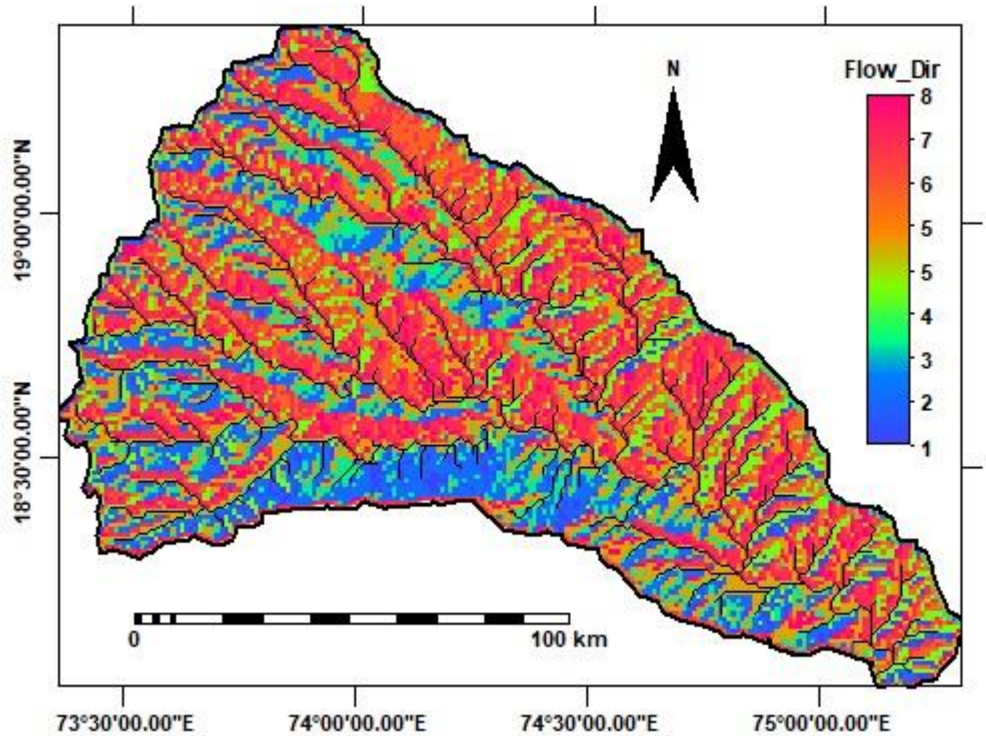


Figure – 3.6: Flow direction map of Upper Bhima Basin

In the sub-basin map, the gauging sites corresponding to different sub-basins (with numeric identity) are specified in Table – 3.2. In the flow direction map, flow directions corresponding to different numeric identities are: 1 – NW, 2 – N, 3 – NE, 4 – W, 5 – E, 6 – SW, 7 – S, and 8 – SE.

b) Thiessen Polygon of Rainfall and ET stations

For present study, daily rainfall data of 65 stations within/around the basin are available for the period from 1992 – 96 and data of 56 stations within/around the basin are available for the period from 1997 – 2001 and the same has been utilized. Thiessen polygon map of rainfall stations for these two scenarios is depicted in Figure – 3.7 and Figure – 3.8.

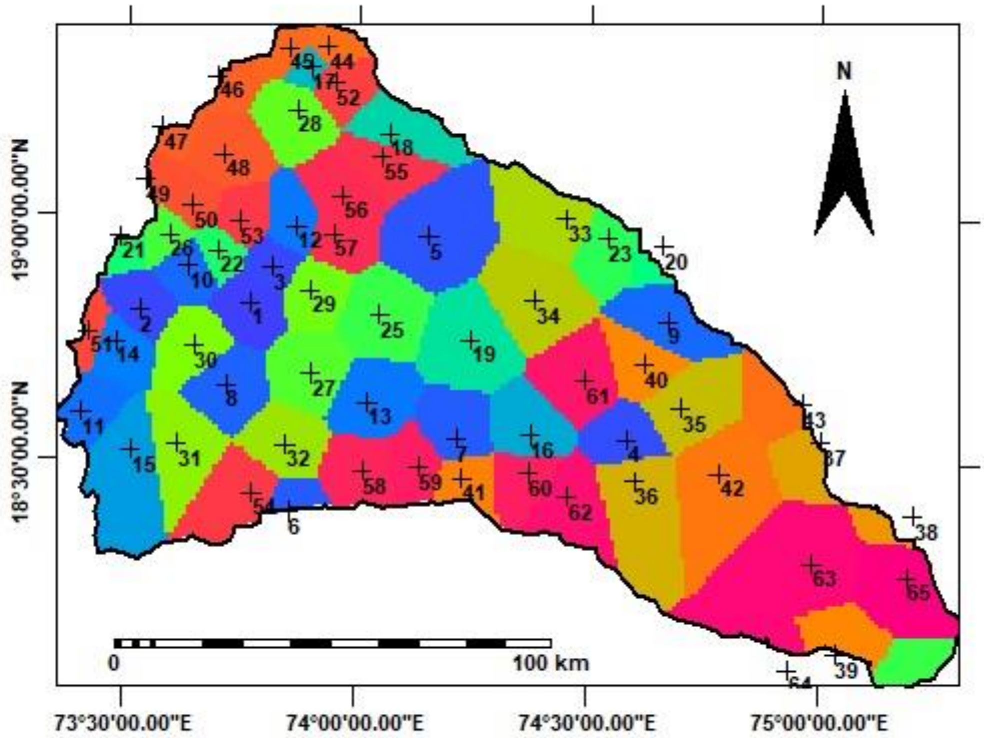


Figure – 3.7: Rainfall Thiessen polygon (1992-96) map of U. Bhima Basin

Names of various rainfall stations corresponding to their numeric identity for 1992-96 are presented in Table – 3.4.

Table – 3.4
Numeric identity of different rainfall stations in Upper Bhima basin (1992-96)

Numeric Identity	Rainfall Station	Numeric Identity	Rainfall Station	Numeric Identity	Rainfall Station
1	Askheda	23	Supa	45	Sablewadi
2	Budhawadi	24	Tembhurni	46	Ghatghar
3	Kadus	25	Thitewadi	47	Ahupe

Numeric Identity	Rainfall Station	Numeric Identity	Rainfall Station	Numeric Identity	Rainfall Station
4	Kashti	26	Whiram	48	Wachape
5	Kathapur	27	Alandi	49	Bhimashankar
6	Katraj Tunnel	28	Junnar	50	Shendruli
7	Khamgaon	29	Khed	51	Walwan
8	Kiwale	30	Vadgaon Maval	52	Dingore
9	Kolgaon	31	Paud	53	Wada
10	Koliye	32	Pune	54	Khadakwasla
11	Kumbheri	33	Parner	55	Wadgaon Sahani
12	Kurwandi	34	Sirur	56	Kalamb
13	Lonikand	35	Shrigonda	57	Bibi
14	Malawali	36	Dhond	58	Loni Kalbhar
15	Mulshi	37	Karajat	59	Urali Kanchan
16	Pargaon	38	Karmala	60	Kedgaon
17	Pimpalgaon joga	39	Indapur	61	Chinchani Camp
18	Pimpalwadi	40	Belwandi	62	Patas
19	Ranjangaon	41	Kasurdi	63	Parwadi Tank
20	SarolaKasar	42	Taju Project	64	Nimgaon Ketki
21	Savale	43	Walwad	65	Kondej Tank
22	Shive	44	Khetewadi		

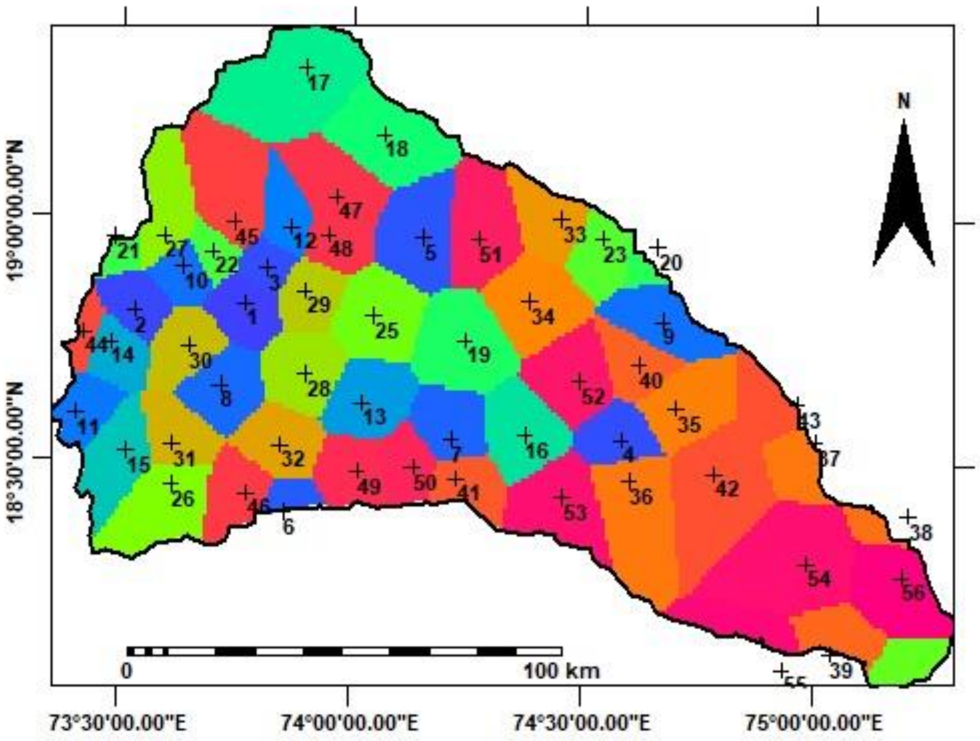


Figure – 3.8: Rainfall Thiessen polygon (1997-01) map of U. Bhima Basin

Names of various rainfall stations corresponding to their numeric identity for 1997-01 are presented in Table – 3.5.

Table – 3.5
Numeric identity of different rainfall stations in Upper Bhima basin (1997-01)

Numeric Identity	Rainfall Station	Numeric Identity	Rainfall Station	Numeric Identity	Rainfall Station
1	Askheda	20	SarolaKasar	39	Indapur
2	Budhawadi	21	Savale	40	Belwandi
3	Kadus	22	Shive	41	Kasurdi
4	Kashti	23	Supa	42	Taju Project
5	Kathapur	24	Tembhurni	43	Walwad
6	Katraj Tunnel	25	Thitewadi	44	Walwan
7	Khamgaon	26	Wegre	45	Wada
8	Kiwale	27	Whiram	46	Khadakwasla
9	Kolgaon	28	Alandi	47	Kalamb
10	Koliye	29	Khed	48	Bibi
11	Kumbheri	30	Vadgaon Maval	49	Loni Kalbhar
12	Kurwandi	31	Paud	50	Urali Kanchan
13	Lonikand	32	Pune	51	Nighoje
14	Malawali	33	Parner	52	Chinchani Camp
15	Mulshi	34	Sirur	53	Patas
16	Pargaon	35	Shrigonda	54	Parwadi Tank
17	Pimpalgaon joga	36	Dhond	55	Nimgaon Ketki
18	Pimpalwadi	37	Karajat	56	Kondej Tank
19	RanjangaonG	38	Karmala		

Thiessen polygon map for the 13 ET stations is depicted in Figure – 3.9. Names of various ET stations corresponding to their numeric identity for 1992-01 are presented in Table – 3.6.

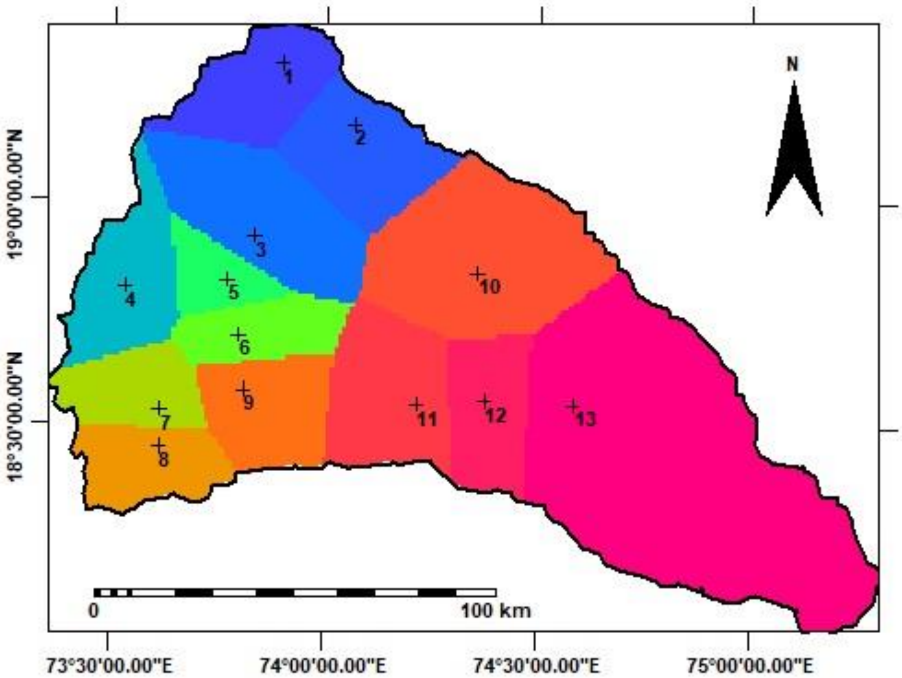


Figure – 3.9: ET Thiessen polygon (1992-01) map of Upper Bhima Basin

Table – 3.6
Numeric identity of different ET stations in Upper Bhima basin (1992-01)

Numeric Identity	ET Station	Numeric Identity	ET Station	Numeric Identity	ET Station
1	Pimpalgaon-Joga	6	Nighoje	11	Khamgaon
2	Pimpalwandi	7	Paud	12	Pargaon
3	Chaskman	8	Wegre	13	Kashti
4	Budhwadi	9	Pimpal Gurav		
5	Askheda	10	Shirur		

c) District, City, and soil map

There are three districts, namely Pune, Ahmadnagar, and Sholapur in the study area. However, major part of the area is covered in the Pune district. Further, population related information was available at the basin scale from Irrigation Department. Hence, district map was not generated as it was of no use. There are 28 cities located in the basin from the landuse map with total area of 222 sq. km. Pune is the major city. The city map of the basin is shown in Figure – 3.10.

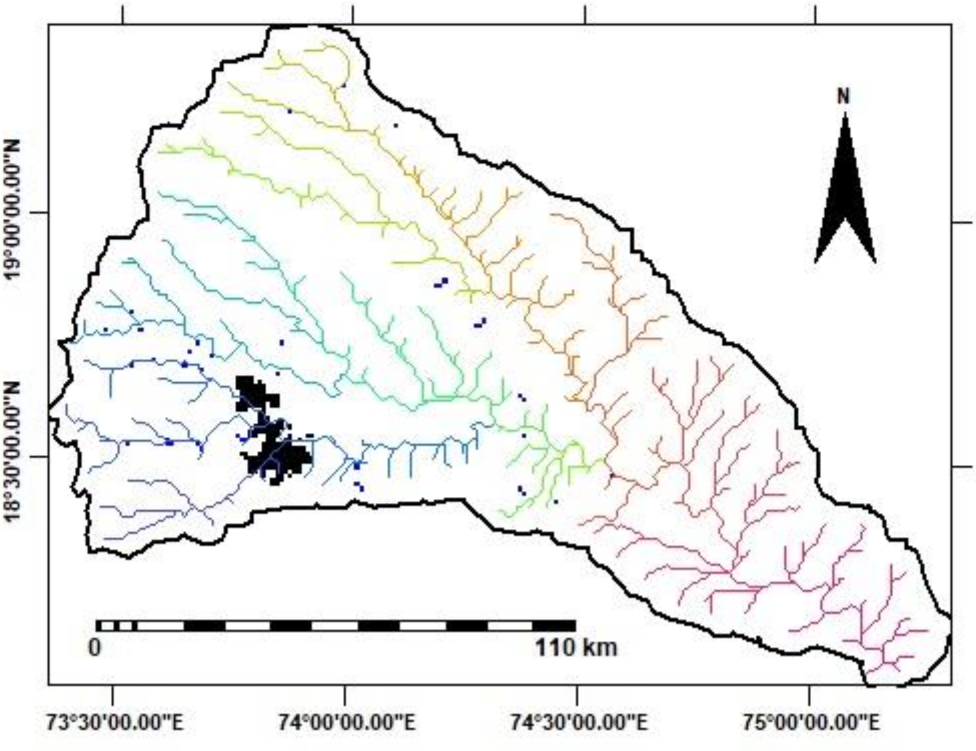


Figure – 3.10: City map of Upper Bhima Basin

The soil map for the Upper Bhima basin was obtained from the National Bureau of Soil Survey and Land Use Planning (NBSSLUP). 40 different soil classes map were digitized as shown in Figure – 3.11.

Hydraulic properties (FC, PWP, Conductivity, hydrologic soil group) were also obtained from Soil bulletin of NBSSLUP.

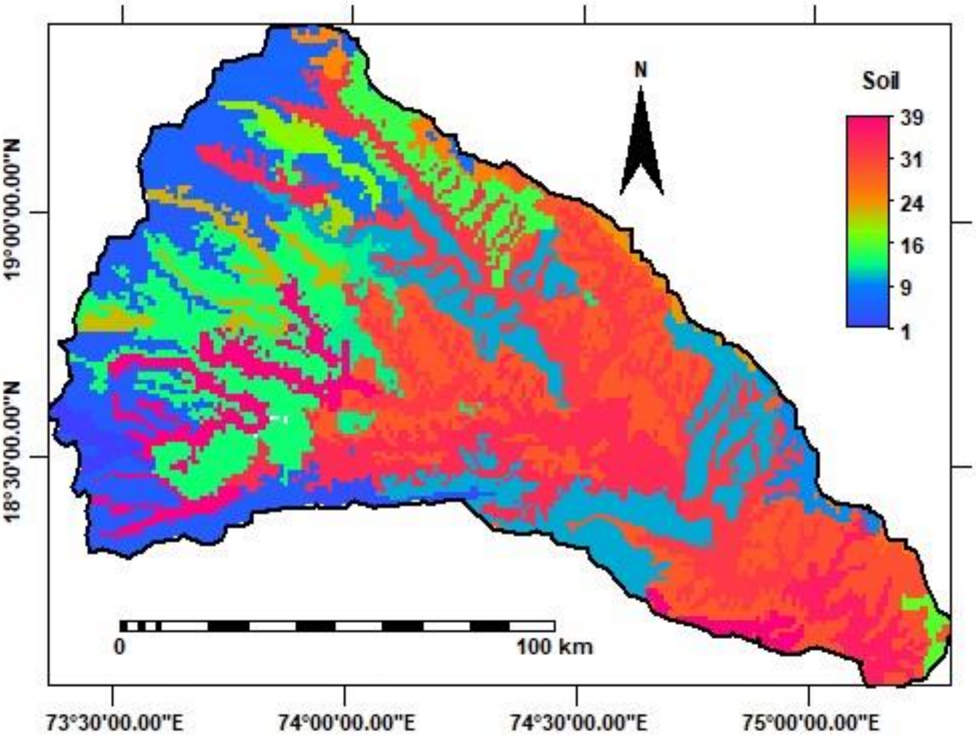


Figure – 3.11: Soil map of Upper Bhima Basin as obtained from NBSSLUP

The attribute properties of the soil considered in the present study are given in Table – 3.7.

Table – 3.7
Hydraulic soil properties considered in Upper Bhima basin

Soil Class	Sp. Gravity	Porosity	Field capacity	Wilting point	Hydraulic conductivity
S46	2.55	0.475	30.00	22.60	0.06
S75	2.70	0.501	22.80	14.60	0.68
S76	2.65	0.464	20.80	11.70	0.20
S77	2.63	0.398	30.10	16.50	0.30
S83	2.55	0.475	37.80	24.70	0.06
S95	2.65	0.464	26.30	13.30	0.20
S107	2.55	0.475	29.00	20.00	0.06
S110	2.63	0.398	24.60	14.30	0.30
S113	2.63	0.398	16.10	9.50	0.30
S115	2.63	0.398	19.30	11.50	0.30
S116	2.63	0.398	19.30	11.50	0.30
S117	2.65	0.464	25.20	15.70	0.20
S118	2.63	0.398	21.00	10.20	0.30
S122	2.55	0.430	12.70	10.10	0.12
S126	2.63	0.398	20.10	12.40	0.30
S128	2.55	0.475	30.80	20.40	0.06

Soil Class	Sp. Gravity	Porosity	Field capacity	Wilting point	Hydraulic conductivity
S129	2.55	0.475	26.70	17.10	0.06
S143	2.55	0.475	27.60	18.30	0.06
S146	2.55	0.475	27.60	18.30	0.06
S149	2.55	0.475	31.00	20.50	0.06
S151	2.55	0.475	35.50	25.50	0.06
S157	2.55	0.475	35.50	25.50	0.06
S165	2.55	0.475	30.60	20.20	0.06
S175	2.65	0.464	27.40	18.90	0.20
S176	2.55	0.475	40.00	24.35	0.06
S193	2.55	0.475	37.80	25.50	0.06
S202	2.55	0.475	21.30	12.20	0.06
S211	2.55	0.475	31.00	20.50	0.06
S216	2.55	0.475	51.00	31.70	0.06
S217	2.55	0.475	36.80	27.95	0.06
S236	2.55	0.475	46.06	28.90	0.06
S241	2.55	0.475	42.75	31.95	0.06
S243	2.55	0.475	40.00	24.35	0.06
S244	2.55	0.475	41.20	30.06	0.06
S248	2.55	0.475	31.33	20.50	0.06
S254	2.55	0.475	31.33	20.50	0.06
S258	2.55	0.475	34.22	24.05	0.06
S259	2.55	0.475	31.33	20.50	0.06
S266	2.55	0.475	29.70	19.66	0.06
S281	2.55	0.430	18.90	12.20	0.12

d) Reservoirs and command areas

Location of various reservoirs was obtained from TM image as shown in Figure – 3.12. Features of different projects is shown in Table – 3.3.

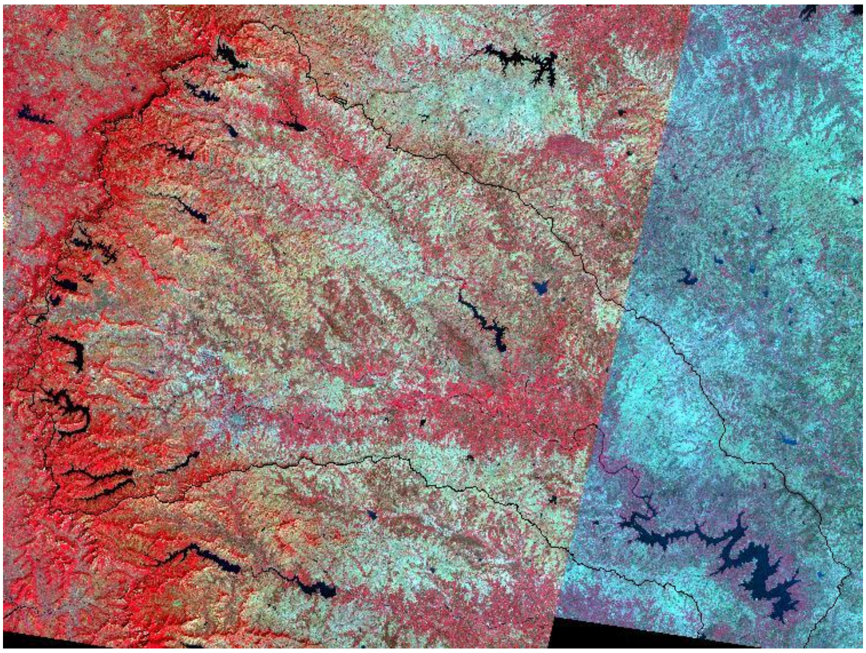


Figure – 3.12: Mosaic of TM image for Upper Bhima Basin

Boundaries of the command areas of different projects were obtained from India-WRIS. The command area map from WRIS was imported in ILWIS GIS system and then registered with the study area and layout of different command areas were marked. The registered map is shown in Figure – 3.13 and the location of various projects along with their commands is shown in Figure – 3.14.

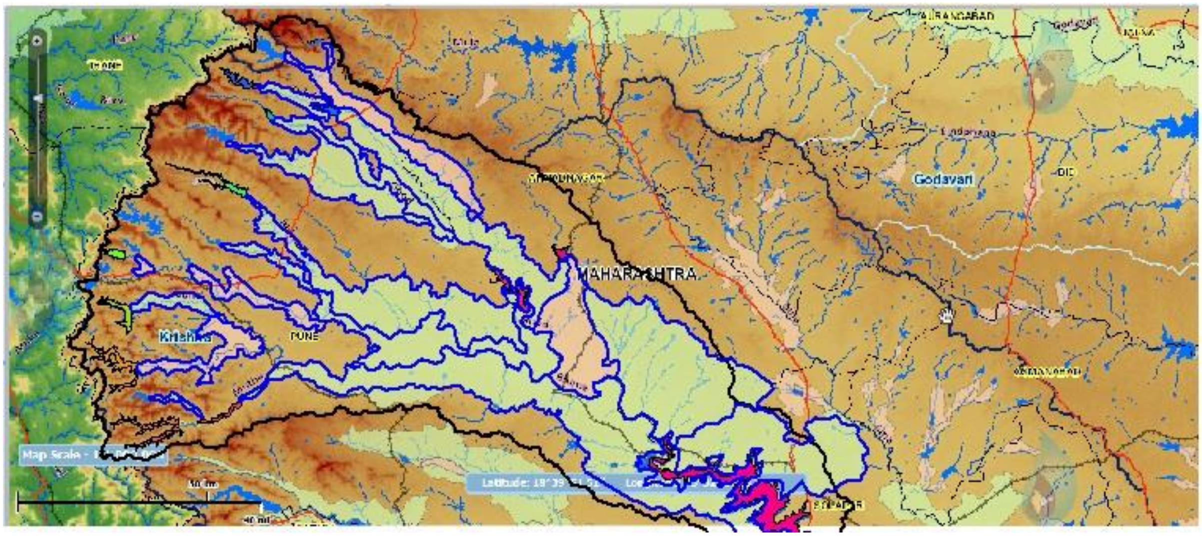


Figure – 3.13: Registered India-WRIS map of command of different projects

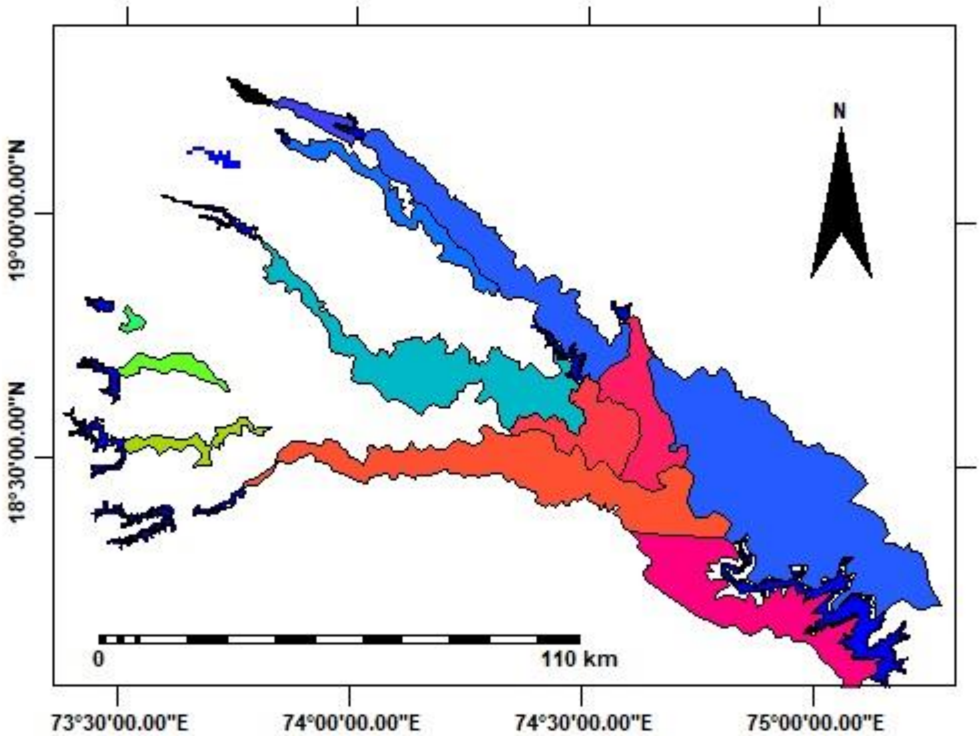


Figure – 3.14: Command area map of different projects in U. Bhima basin *d) Landuse map*

Land use affects the generation of overland flow, evapo-transpiration losses, soil water storage, water demands for irrigation, and groundwater recharge. So, land use map is an important consideration in the basin simulation model. For the Upper Bhima basin, Land use map has been obtained from NRSC. The map was available at 56 m resolution and there were 16 classes: Built-up area, Kharif, Rabi, Zaid, Double crop, current fallow, plantations, 3 kind of forests, mangrove, grassland, wasteland, scrubland, water bodies. The map aggregated to 1 km resolution. 16 landuse classes were merged into 6 major classes: Urban (1), RF_agri (2), Irr_agri (3), forest (4), barren (5), and water body (6). The NRSC map is shown in Figure – 3.15 while the resampled and re-classified map is shown in Figure – 3.16.

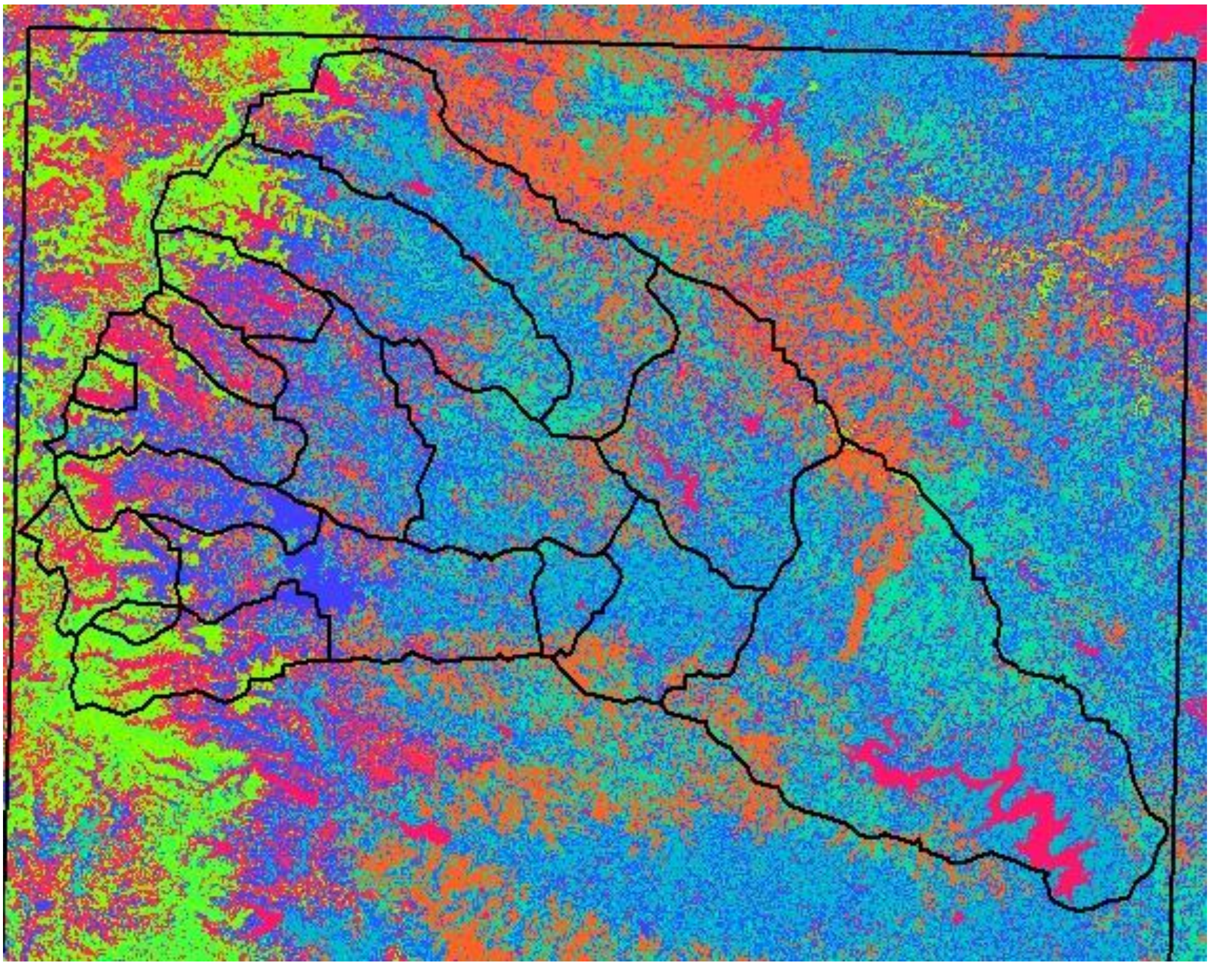


Figure – 3.15: Landuse map of Upper Bhima basin (2011) at 56m resolution

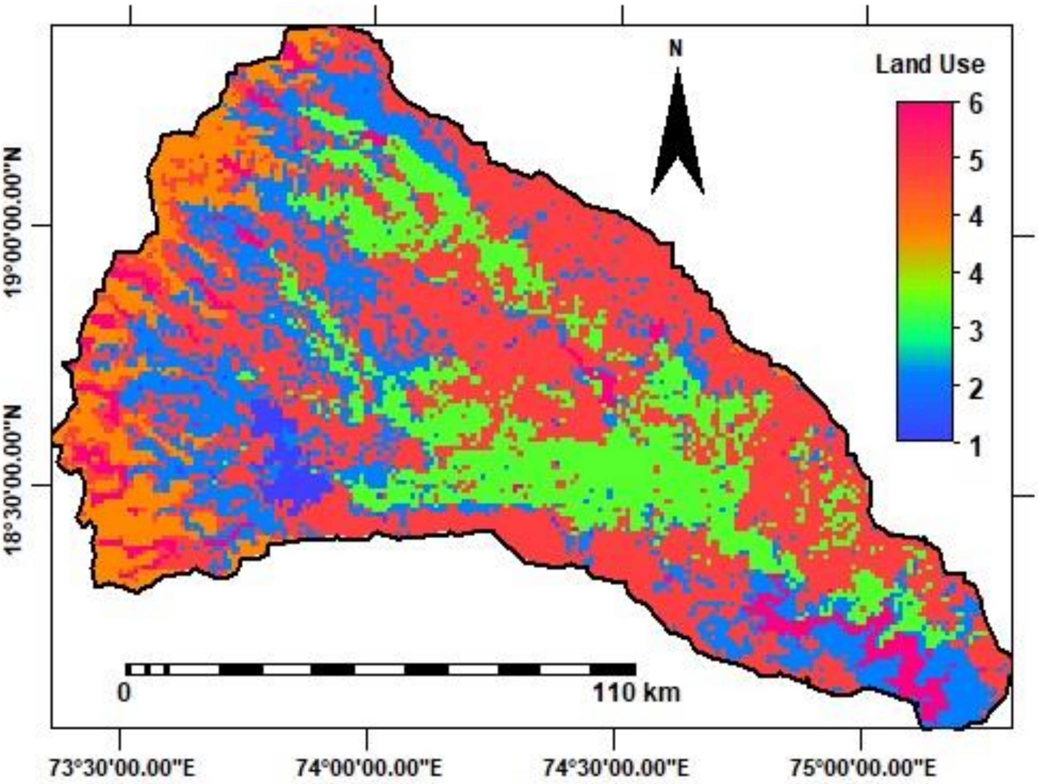


Figure – 3.16: Resampled & reclassified Landuse map of UB basin

3.3.2 Attribute Data

Attribute data specifies the properties of crops and soil prevalent in the basin, domestic and industrial demand standards, attributes of different cities, characteristics of hydraulic structures in the basin, characteristics of river segments in the basin and their connectivity, and the details of gauging sites. For the Upper Bhima basin, these have been obtained from different sources and are discussed in the following:

a) Crop attributes

Crop map for the study area were not available. However, the acreage of different crops in the study area and few related properties were available from Irrigation Commission report as given in Table – 3.8. Further, irrigated crop area in the basin was found from the landuse map in different command areas and the acreage of different crops in commands of different projects were estimated. The annual crop acreage is estimated to be around 11300 sq. km while the irrigated (SW & GW) crop area is around 5943 sq. km. From the landuse map, irrigated crop area in different commands have been worked out. Attribute properties of crops are given in Table – 3.9.

Table – 3.8
Crop acreage (sq. km) in Upper Bhima basin

Crop_ID	Crop Name	Area in Kharif (Sq. km)	Area in Rabi (Sq. km)
1	Paddy	440	
2	Sorghum	80	
3	Pearl Millet	1770	
4	Pigeon Pea	90	
5	Sugarcane	330	
6	Groundnut	310	
7	Soyabean	70	
8	Other ceral	220	
9	Other pulse	400	
10	Sunflower	130	
11	Orchard	1800	
12	Wheat		500
13	Sorghum		4230
14	Gram		300
15	Sugarcane		330
16	Safflower		300

Table – 3.9
Attribute properties of different crops considered in Upper Bhima basin

	Stress Fraction	Rt_Depth (mm)	Time to root max (week)	Depth for land prep (mm)	Time of land Prep (week)	Start Week	Crop period (week)	Standing water req. (mm)	Time of stand. Water (week)	Bund Ht (mm)	Ann_ Carry-Over	
Rice												
	1	500	9	150	1	29	18	100	15	150	0	
Crop_Factor	1.06	1.06	1.1	1.1	1.1	1.1	1.12	1.12	1.15	1.15	1.15	1.15
Crop_Factor	1.04	1.04	0.98	0.98	0.98	0.98						
Sorghum												
	0.55	800	6	50	1	25	17	0	0	0	0	
Crop_Factor	0.48	0.48	0.59	0.59	0.82	0.82	1.02	1.02	1.05	1.05	1.05	1.05
Crop_Factor	0.92	0.92	0.63	0.63	0.63							
Pearlmillet												
	0.55	800	7	50	1	27	13	0	0	0	0	
Crop_Factor	0.48	0.48	0.59	0.59	0.82	0.82	1.02	1.02	1.05	1.05	0.92	0.92
Crop_Factor	0.63											
Pigeonpea												
	0.55	700	9	50	1	25	23	0	0	0	0	
Crop_Factor	0.4	0.4	0.47	0.47	0.65	0.65	0.99	0.99	0.99	1.03	1.03	1.03
Crop_Factor	1.03	1.03	1.03	1.03	1.03	1.03	0.83	0.83	0.83	0.48	0.48	
Sugarcane												
	0.65	1000	15	50	1	51	51	0	0	0	1	
Crop_Factor	0.53	0.53	0.55	0.55	0.57	0.57	0.59	0.59	0.61	0.61	0.64	0.64
Crop_Factor	0.66	0.66	0.7	0.7	0.75	0.75	0.81	0.81	0.87	0.87	0.92	0.92
Crop_Factor	0.96	0.96	1	1	1.05	1.05	1.09	1.09	1.1	1.1	1.1	1.1
Crop_Factor	1.1	1.1	1.1	1.1	1.1	1.06	1.06	1.02	1.02	1	1	0.98

	Stress Fraction	Rt_Depth (mm)	Time to root max (week)	Depth for land prep (mm)	Time of land Prep (week)	Start Week	Crop period (week)	Standing water req. (mm)	Time of stand. Water (week)	Bund Ht (mm)	Ann_ Carry-Over	
Crop_Factor	0.98	0.51	0.51									
Groundnut												
	0.4	750	6	50	1	27	17	0	0	0	0	
Crop_Factor	0.48	0.48	0.54	0.54	0.82	0.82	0.97	0.97	1	1	1	1
Crop_Factor	0.93	0.93	0.93	0.69	0.69							
Soyabean												
	0.5	800	9	50	1	27	16	0	0	0	0	
Crop_Factor	0.44	0.44	0.63	0.63	0.63	0.91	0.91	1	1	1	1	1
Crop_Factor	1	0.66	0.66	0.93								
Othercereals												
	0.55	800	6	50	1	25	17	0	0	0	0	
Crop_Factor	0.48	0.48	0.59	0.59	0.82	0.82	1.02	1.02	1.05	1.05	1.05	1.05
Crop_Factor	0.92	0.92	0.63	0.63	0.63							
Otherpulses												
	0.55	700	9	50	1	26	13	0	0	0	0	
Crop_Factor	0.5	0.5	0.75	0.75	0.75	1.1	1.1	1.1	1.1	1.1	0.65	0.65
Crop_Factor	0.65											
Sunflower												
	0.55	700	9	50	1	27	15	0	0	0	0	
Crop_Factor	0.44	0.44	0.63	0.63	0.91	0.91	1	1	1	1	1	1
Crop_Factor	0.66	0.66	0.66									
Orchard												
	0.55	2000	10	50	1	21	27	0	0	0	0	
Crop_Factor	0.65	0.65	0.65	0.65	0.65	0.65	0.65	0.65	0.66	0.69	0.7	0.71
Crop_Factor	0.72	0.72	0.73	0.74	0.75	0.74	0.73	0.73	0.72	0.7	0.7	0.7
Crop_Factor	0.69	0.67	0.65									
Wheat												
	0.55	800	9	50	1	47	17	0	0	0	1	
Crop_Factor	0.31	0.31	0.42	0.42	0.8	0.8	1.08	1.08	1.1	1.1	1.1	1.07
Crop_Factor	1.07	0.87	0.87	0.5	0.5							
Sorghum1												
	0.55	800	6	50	1	47	19	0	0	0	1	
Crop_Factor	0.48	0.48	0.59	0.59	0.82	0.82	1.02	1.02	1.05	1.05	1.05	1.05
Crop_Factor	1.05	0.92	0.92	0.63	0.63	0.63	0.63					
Gram												
	0.55	700	9	50	1	47	16	0	0	0	1	
Crop_Factor	0.23	0.23	0.29	0.29	0.83	0.83	1.05	1.05	1.05	1.05	0.96	0.96
Crop_Factor	0.68	0.68	0.42	0.42								
Sugarcane1												
	0.65	1000	15	50	1	51	51	0	0	0	1	
Crop_Factor	0.53	0.53	0.55	0.55	0.57	0.57	0.59	0.59	0.61	0.61	0.64	0.64
Crop_Factor	0.66	0.66	0.7	0.7	0.75	0.75	0.81	0.81	0.87	0.87	0.92	0.92
Crop_Factor	0.96	0.96	1	1	1.05	1.05	1.09	1.09	1.1	1.1	1.1	1.1
Crop_Factor	1.1	1.1	1.1	1.1	1.1	1.06	1.06	1.02	1.02	1	1	0.98
Crop_Factor	0.98	0.51	0.51									
Safflower												
	0.55	800	6	50	1	47	19	0	0	0	1	
Crop_Factor	0.31	0.31	0.48	0.48	0.5	0.5	1.09	1.09	1.1	1.1	1.1	1.1
Crop_Factor	1.09	1.09	1.09	0.93	0.93	0.52	0.52					

c) Domestic and Industrial (D&I) demand & city attributes

District-wise statistics for all the districts under consideration for the year 1991 have been taken from the Statistical Directorates of the States of Maharashtra, M.P., and Gujarat. The data has been modified on the pro-rata basis. Consumptive use factor of 0.8 has been taken signifying that 20 % of water used is consumed and 80 % is returned back to the system. Standards of water use for urban, rural, and cattle population have been taken as 140, 70, and 50 lpcd (liters per capita per day) respectively.

For 28 cities, the attributes mainly include the district in which located and the dam/river segment from which water is withdrawn. These have been obtained from GIS and specified.

e) River network attributes

There are 342 river segments in Upper Bhima basin. For each segment, attribute data includes segment identity, stream order (for each successive stream, it is one higher than highest stream order of upstream segments), type of structure located at the downstream (0– nothing, 1– gauging site, 2– diversion, 3– storage reservoir), its node number, number of segments immediately upstream and their node numbers. River network attributes for a few selected segments is presented in Table – 3.14.

Table – 3.10
River network attributes for a few river segments

Riv_id	Str_Odr	Typ_Str	Str_id	No. of u/s Seg	Id of 1st seg	Id of 2nd seg
1	1	3	10	0		
2	2	0	0	1	1	
3	1	3	9	0		
4	2	0	0	1	3	
5	3	0	0	2	2	4
6	1	0	0	0		
7	2	1	11	1	6	
8	4	0	0	2	5	7
9	1	0	0	0		
10	5	0	0	2	8	9
11	1	0	0	0		
12	6	3	11	2	10	11
13	7	0	0	1	12	
14	1	0	0	0		
15	8	0	0	2	13	14
16	1	0	0	0		
17	9	1	9	2	15	16
18	1	0	0	0		
19	1	0	0	0		
20	2	0	0	2	18	19
21	1	0	0	0		
1	1	3	10	0		
2	2	0	0	1	1	

f) Hydraulic structure attributes

Hydraulic structure attributes are already specified in Table 3.3. It needs to be mentioned that a few projects send water out of the basin (Mulshi, Andhra Tank, and) for hydropower development. For these projects, out-of-basin demands are expressed as monthly exports from these projects. Further, the spill from the Pawana project is also send out of basin. Water is utilized in Pawana for hydropower generation also. Since there is no such provision in the present model, the same is specified in the minimum flow requirements.

In actual practice depending on the canal network layout, only a part of the culturable command area (CCA) is supplied with irrigation water from a reservoir. Further, it is quite possible that there might be some errors in the delineation of command areas of few hydraulic structures. In these two cases, some of the crop water demands are wrongly met from the reservoir, thereby affecting the reservoir operation and modifying the water availability in the downstream river segments. To account for these errors, concept of PPA (proposed profitable area) has been introduced. Initially, PPA is taken as 100 (all the crops within the command area are assumed to be supplied irrigation water from the hydraulic structure) and the total irrigation demands from the reservoir are estimated. After running the model for a few years of record, average annual irrigation demands from a reservoir are estimated and compared with the design demands. If estimated demands are higher than the design demands, then it means that larger (than actual) command area has been considered for the reservoir. For such cases, PPA is lowered so that the estimated demands match with the design demands. In the model, PPA is used to proportionately reduce the at-field irrigation demands of all the crops within the command area of a reservoir so that reduced irrigation supply is demanded from the reservoir. Rest of the irrigation demands are met from the groundwater. PPA for each reservoir is finalized after a number of trial runs of the simulation model.

g) Gauging station attributes

Gauging station attributes are presented in Table – 3.2. The location of different gauging stations is shown in Figure – 3.17.

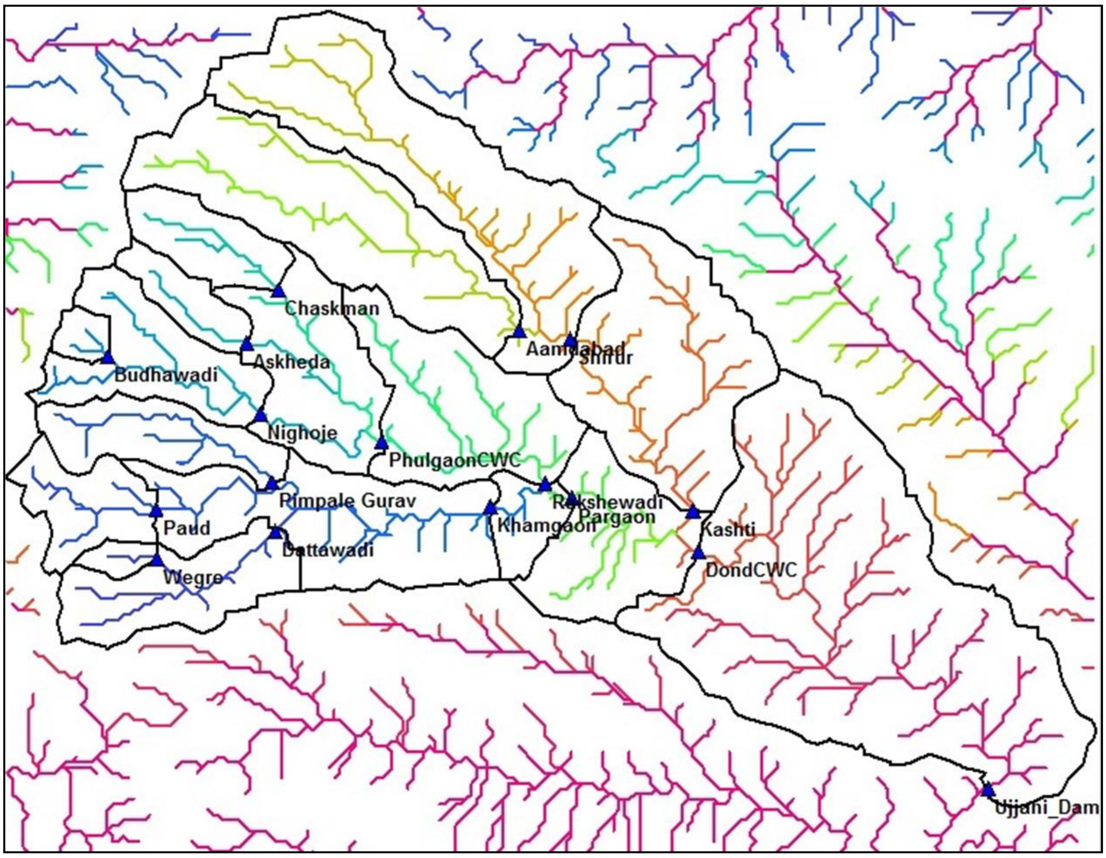


Figure – 3.17: Location of different G&D stations in Upper Bhima basin

3.3.3 Dynamic Data

Dynamic data specifies time series data of rainfall, reference evapo-transpiration, and import/export in the river basin. For the Upper Bhima basin, these have been obtained from different sources.

The developed model integrates varied types of data to evaluate the water resources of a river basin. Efforts have been made to prepare the database as close to reality as possible. However, a number of assumptions have been made and ancillary techniques/methods have been used wherever direct field observations are either not available or difficult to collect at the individual level. Database development for a river basin is a rigorous exercise that needs extensive support of different departments, project authorities, and river basin organisation.

* * *

Chapter – 4
RESULTS AND DISCUSSION

4.1 General

The river basin simulation model developed at NIH has been applied to the Upper Bhima basin to check for its computational algorithm, performance analysis and applicability in different field conditions. Spatial, attribute, and dynamic data has been collected for the Upper Bhima basin. Sixteen 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. Maharashtra Irrigation Commission data has been used to get the cropping pattern and population related information in the study area. India WRIS data has been used for delineating irrigable command areas of different reservoirs. Landsat TM data of the basin has been used for locating various reservoirs in the basin. Attribute data of crops, soils, gauging sites, various hydraulic structures etc. have been obtained from a variety of sources. Dynamic data of rainfall from 1992-93 to 2000-01 has been obtained from CWC, IMD and Maharashtra State department.

It needs to be mentioned here that database requirement of the model is quite extensive. Since this study is mainly concerned with the model testing for a river basin, individual efforts have been made by the study team to gather the information for the Upper Bhima basin as accurately as possible. In some cases, when the actual field details could not be obtained, the same have been generated by using different ancillary means. However, since the model involves multi-dimensional data that is covered by a number of departments/agencies (Central Water Commission, Central Ground Water Board, Indian Meteorological Department, Agriculture Department, Statistical Directorate, Project authorities in the river basin etc.), there is a strong need for close collaboration of these departments/ agencies for the successful execution of the model for a river basin.

This chapter describes the model application for the Upper Bhima basin and discussion of type of results generated by the model. Based on the basin characteristics, a number of limitations of the model have been identified which can be subsequently refined.

4.2 Sample Output of Basin Simulation Model

The model runs at daily time step and completes the analysis for one complete month in a single run. At the end of each day, the soil moisture at each grid in the basin and the storage in each reservoir are saved in a temporary file which is re-written for each subsequent day. At the end of a month, the files containing spatial soil moisture information and reservoir storage are generated which become input for the next month.

The model generates three spatial outputs which can be imported in ILWIS GIS system and visualized as images. These images are: monthly recharge (+) and withdrawal (-), final soil moisture content at the end of the month, and the actual monthly evapo-transpiration in the basin. Monthly recharge/withdrawal (presented in Figure – 4.1) in mm units is used as input for the groundwater simulation model for generating revised groundwater table for the subsequent month. The map shown below is generated for September 30, 1992.

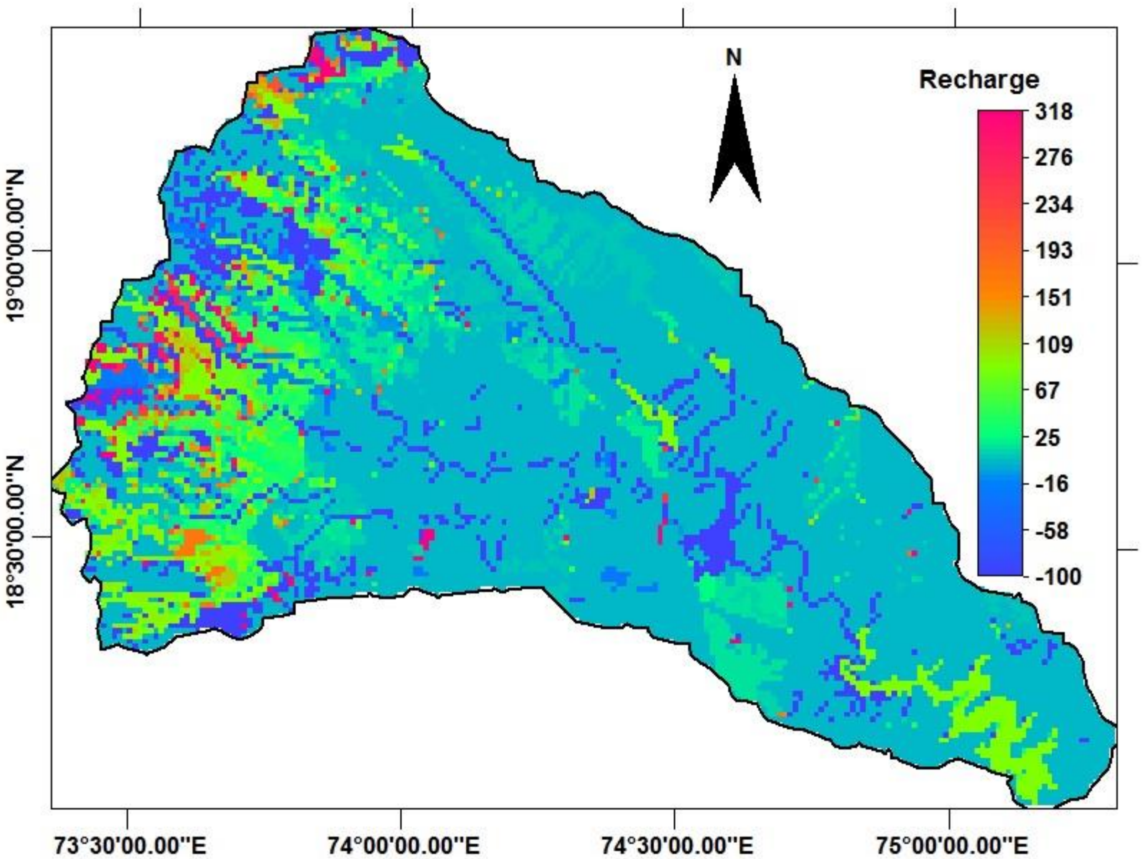


Figure – 4.1: Monthly recharge map generated in Upper Bhima basin

The final soil moisture status map (presented in Figure – 4.2) is used as input for the subsequent month analysis for defining initial soil moisture conditions. The map shown below corresponds to September 30, 1992.

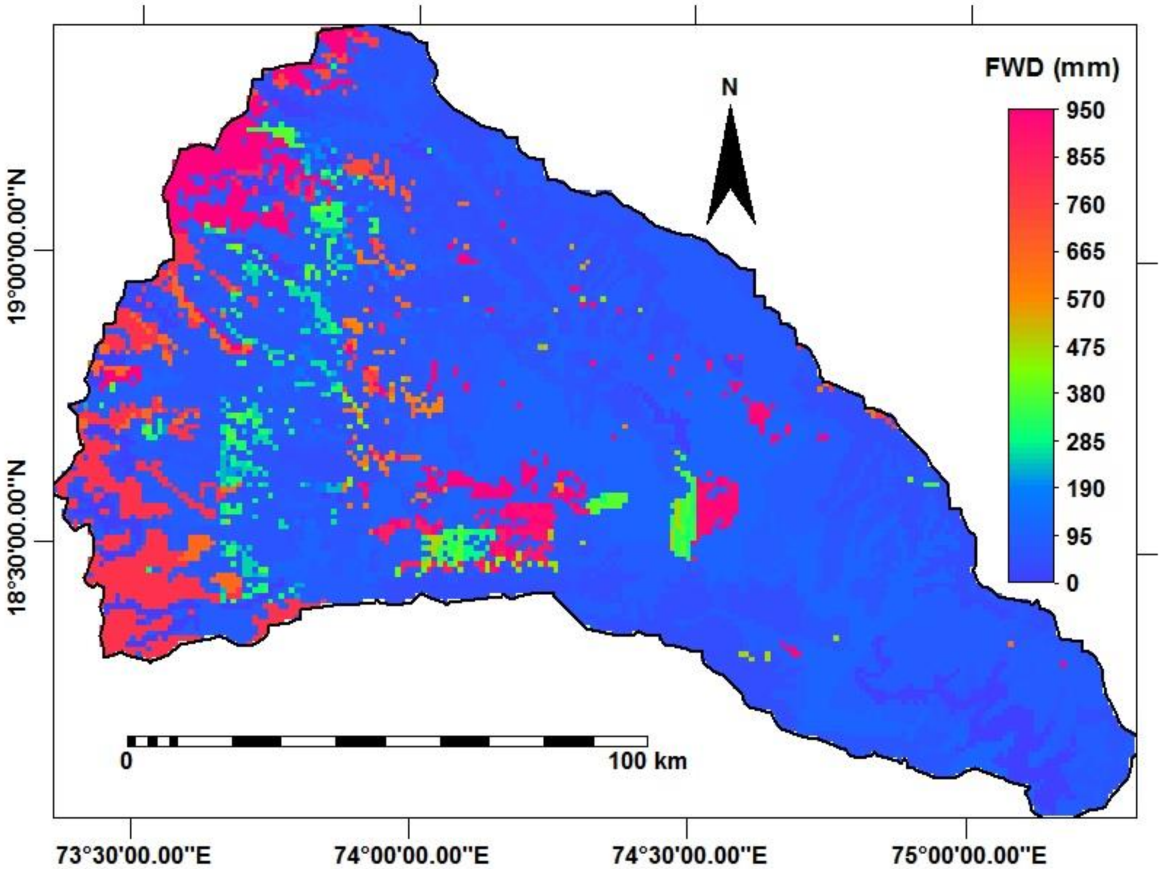


Figure – 4.2: Monthly soil moisture map generated in Upper Bhima basin

The actual evapo-transpiration map (shown in Figure – 4.3) represents the areas having major ET losses in the basin. The sample map shows the spatial distribution of computed AET in September, 1992 study area.

In addition to spatial maps, the model generates output in the form of tables. For each month analysis, five tables are generated: daily flows at different gauging stations, monthly flows at different gauging stations, daily working table of each reservoir in the basin, monthly working table of each reservoir in the basin, and hydrological details for each sub-basin (related to domestic demands and supply, irrigation demands and supply, hydrological variables for each land use, and summary of reservoirs in the sub-basin). A sample monthly flow table for different gauging sites is shown in Table – 4.1.

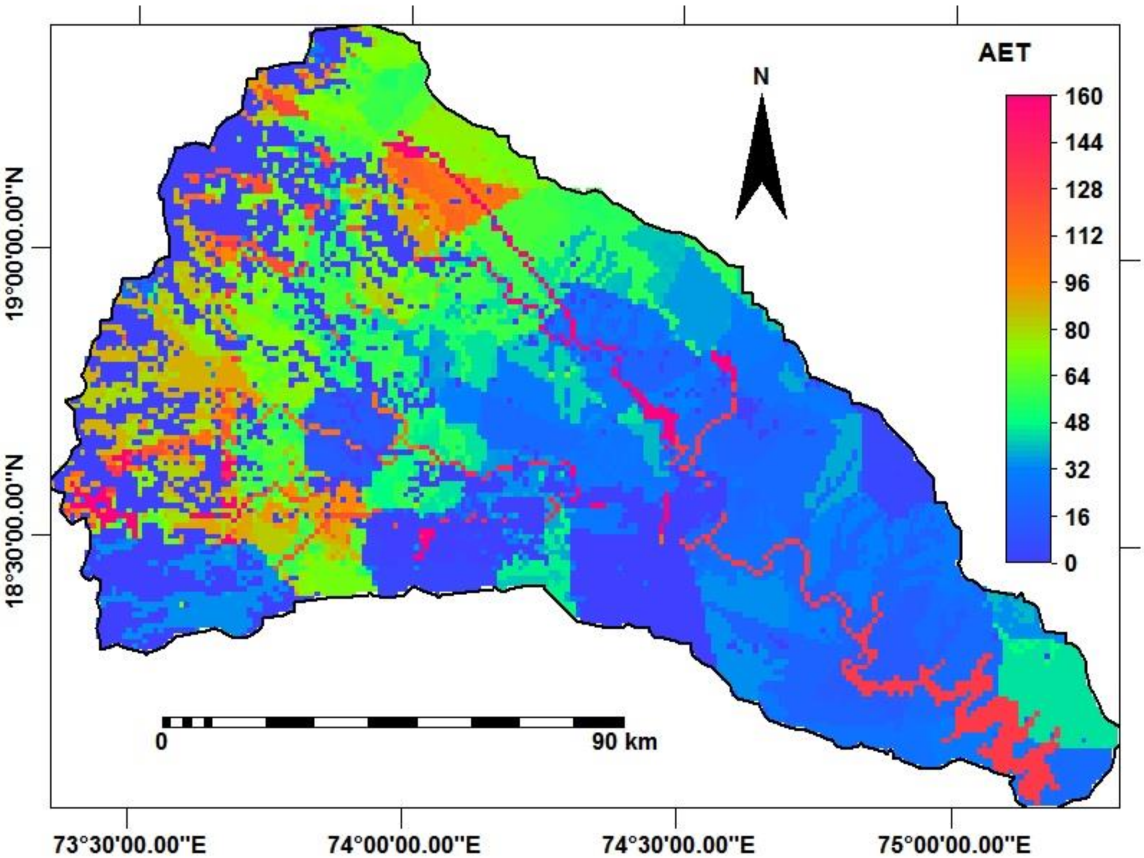


Figure – 4.3: Monthly AET (mm) map generated in Upper Bhima basin

Table – 4.1
Sample monthly flow table at gauging stations

Monthly Flow (Mm3) Results for Year 1992 and Month 09

St_Code	St_Name	Bas_Flow	Tot_Flow	Tot_Rainfall
11	Wegre	.0001	35.194	17.176
09	Dattawadi	.0010	249.221	108.515
08	Paud	.0004	29.012	98.270
07	PimpaleGura	.0003	131.450	124.980
12	Khamgaon	.0098	514.367	117.967
06	Budhwadi	.0001	74.744	39.254
05	Nighoje	.0006	371.696	188.941
04	Askheda	.0002	66.030	73.766
03	Chaskman	.0005	259.101	135.937
10	Pulgaon	.0075	727.212	101.115
13	Rakshewadi	.0147	865.184	131.355
14	Pargaon	.0276	1407.216	23.543
02	Aamdabad	.0020	270.846	299.087
01	Shirur	.0022	398.858	217.249
15	Kashti	.0560	571.008	138.406
16	Dhond	.1209	2071.739	58.328

Here, the SBas_Rainfall represents the rainfall in the sub-basin only which excludes the rainfall in upstream catchments. However, Tot_Flow represents total flow during the month that has passed through the station.

A sample daily working table of Khadakwasla reservoir for September, 1992 is presented in Table – 4.2. A sample monthly working table of 16 reservoirs for the sample September, 1992 is presented in Table – 4.3. The table shows the cumulative sum of the daily demands, supplies, spills, evaporation, inflows, import, export etc. for the entire month.

Table – 4.2

Daily Operation Simulation of Khadakwasla Reservoir (Mm3) for Sept, 1992

Day	Ini_St	Inflow	Import	Evap	WS_Dem	Mn_Dem	Ir_Dem	WS_Sup	Mn_Sup	Ir_Sup	Spill	Export	Fin_St
01	679.147	21.344	.000	.184	.264	.000	.149	.264	.000	.149	19.893	.000	680.000
02	680.000	19.129	.000	.180	.264	.000	.116	.264	.000	.116	18.569	.000	680.000
03	680.000	54.647	.000	.184	.264	.000	.064	.264	.000	.064	54.134	.000	680.000
04	680.000	28.015	.000	.189	.264	.000	.313	.264	.000	.313	27.248	.000	680.000
05	680.000	18.472	.000	.189	.264	.000	.309	.264	.000	.309	17.710	.000	680.000
06	680.000	11.627	.000	.194	.264	.000	.408	.264	.000	.408	10.761	.000	680.000
07	680.000	9.427	.000	.189	.264	.000	.510	.264	.000	.510	8.464	.000	680.000
08	680.000	2.500	.000	.189	.264	.000	.427	.264	.000	.427	1.620	.000	680.000
09	680.000	2.003	.000	.184	.264	.000	.433	.264	.000	.433	1.121	.000	680.000
10	680.000	.055	.000	.189	.264	.000	.456	.264	.000	.456	.000	.000	679.146
11	679.146	.000	.000	.193	.264	.000	.492	.264	.000	.492	.000	.000	678.197
12	678.197	.000	.000	.198	.264	.000	.531	.264	.000	.531	.000	.000	677.203
13	677.203	.000	.000	.198	.264	.000	.632	.264	.000	.632	.000	.000	676.109
14	676.109	.014	.000	.197	.264	.000	.554	.264	.000	.554	.000	.000	675.107
15	675.107	.000	.000	.188	.264	.000	.558	.264	.000	.558	.000	.000	674.096
16	674.096	.000	.000	.192	.264	.000	.621	.264	.000	.621	.000	.000	673.018
17	673.018	.000	.000	.201	.264	.000	.572	.264	.000	.572	.000	.000	671.981
18	671.981	.000	.000	.196	.264	.000	.501	.264	.000	.501	.000	.000	671.020
19	671.020	.000	.000	.196	.264	.000	.567	.264	.000	.567	.000	.000	669.993
20	669.993	.000	.000	.196	.264	.000	.467	.264	.000	.467	.000	.000	669.066
21	669.066	.014	.000	.195	.264	.000	.492	.264	.000	.492	.000	.000	668.128
22	668.128	.000	.000	.200	.264	.000	.542	.264	.000	.542	.000	.000	667.122
23	667.122	.000	.000	.190	.264	.000	.531	.264	.000	.531	.000	.000	666.136
24	666.136	2.000	.000	.195	.264	.000	.635	.264	.000	.635	.000	.000	667.042
25	667.042	.000	.000	.195	.264	.000	.609	.264	.000	.609	.000	.000	665.974
26	665.974	.000	.000	.190	.264	.000	.503	.264	.000	.503	.000	.000	665.016
27	665.016	.000	.000	.194	.264	.000	.550	.264	.000	.550	.000	.000	664.008
28	664.008	12.695	.000	.193	.264	.000	.443	.264	.000	.443	.000	.000	675.804
29	675.804	19.661	.000	.208	.264	.000	.355	.264	.000	.355	14.638	.000	680.000
30	680.000	16.122	.000	.208	.264	.000	.278	.264	.000	.278	15.371	.000	680.000

The sample table showing the hydrological details for various sub-basins is presented in Table – 4.4. The table is generated for the September month of the year 1992-93. This table describes the basin hydrology in detail. The effect of climate change variables (rainfall and its temporal or spatial distribution, meteorological parameters, cropping pattern, land use change, development of new water resources projects, groundwater development etc.) can be analyzed from this table. In addition to domestic demand/supply, hydrological variables for different land uses, irrigation demand/supply, and reservoir details, a section in each sub-basin describes the outflow out of the basin, or outflow to another sub-basin, or stagnated flow. These conditions arise because of some GIS approximations while rasterizing a sub-basin map, or while computing the flow direction map.

Table – 4.3
Monthly Operation Simulation of various reservoirs (Mm3) for Sept, 1992

Reservoir	Ini_St	Inflow	Import	Evap	WS_Dem	Mn_Flo	Ir_Dem	WS_Sup	Mn_Sup	Ir_Sup	Spill	Export	Fin_St
Manikdoh	228.7	48.5	0.0	3.7	0.2	0.0	0.0	0.2	0.0	0.0	0.0	0.0	273.3
Yedgaon	79.3	102.7	0.0	3.7	0.0	0.0	0.0	0.0	0.0	0.0	98.9	0.0	79.3
Wadaj	33.2	38.4	0.0	1.0	0.0	0.0	0.3	0.0	0.0	0.3	37.1	0.0	33.2
Dimbhe	355.0	97.4	0.0	3.7	0.0	0.0	0.4	0.0	0.0	0.4	93.5	0.0	354.8
Chaskaman	214.1	236.1	0.0	4.3	0.0	0.0	2.2	0.0	0.0	2.2	229.6	0.0	214.1
Shiravata	191.1	80.9	0.0	5.7	2.8	0.0	0.0	2.8	0.0	0.0	50.4	30.7	192.0
Pawana	266.4	110.2	0.0	8.1	1.6	44.6	0.0	1.6	44.6	0.0	0.0	16.9	285.9
Mulshi	278.4	115.2	0.0	12.0	2.1	0.0	0.0	2.1	0.0	0.0	0.0	157.6	255.8
Warasgaon	0.0	24.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	24.5	0.0	0.0
Panchet	0.0	37.7	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	37.7	0.0	0.0
Khadakwasla	679.1	217.7	0.0	5.8	7.9	0.0	13.6	7.9	0.0	13.6	189.5	0.0	680.0
Ghod	154.8	465.4	0.0	7.8	0.0	0.0	5.7	0.0	0.0	5.7	451.9	0.0	154.8
Visapur	33.2	24.6	0.0	2.0	0.0	0.0	0.0	0.0	0.0	0.0	23.0	0.0	32.8
Ujjani	1520.0	2338.0	0.0	73.9	0.0	0.0	0.0	0.0	0.0	0.0	2264.1	0.0	1520.0
AndhraTank	351.5	74.4	0.0	5.7	0.0	0.0	0.0	0.0	0.0	0.0	56.2	11.9	352.0
Walwhan	22.5	5.6	0.0	0.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	4.3	23.2

Table – 4.4
Sample table showing Hydrological details of different sub-basins

Sub-basin --- Shirur

Domestic & Industrial Demands and Supply (Mm3)

Total WS Demand in Rural Area	=	.5589
Total WS Demand in Urban Area	=	.5754
Total GW Withdrawal for meeting WS Demand	=	.8877
Total SW Supply for meeting WS Demand	=	.2466
Total GW Recharge from WS Discharge	=	.0789
Total Overland Flow from WS Discharge	=	.2762

Hydrological Details Under Different Landuses (Mm3)

	Urban	RFed_Agr	Irr_Agr	Forest	Barren	Water	Total
Area (Sq. km)	6	393	300	98	865	51	1713
Rainfall	.6060	46.0900	29.9050	33.1520	93.9650	13.5310	203.7180
Surface Inflow	.0260	9.9120	1.1610	6.9740	21.2000	.0000	39.2730
GW Contribution	.0000	.3080	4.3721	.0000	1.7442	.0000	6.4243
Irr. Application	.0000	.0000	.0000	.0000	.0000	.0000	.0000
Evapo-Transpiration	.3522	27.2703	21.9851	.0000	52.4955	4.3602	102.1031
Runoff	.2728	61.1092	11.3844	38.5206	104.2387	.0000	215.5258
Rt Zn Soil Mois. Inc.	.1059	1.7476	1.2405	.0000	2.9102	.0000	6.0042
GW Recharge	.0194	-34.5566	.3650	1.6054	-43.0480	2.1600	-75.6148

Irrigation Demands and Supply (Mm3)

Total Irr. Demand in SW_Irr Area	=	.0000
Total Irr. Demand in GW_Irr Area	=	.0000
Total SW Supply in SW_Irr Area	=	.0000
Total GW Supply in SW_Irr Area	=	.0000
Total GW Supply in GW_Irr Area	=	.0000

Runoff Stagnated or Out of Sub-basin (Mm3)

Runoff Out of the Basin	=	.0000
Runoff Out of the Sub-basin	=	.0201
Runoff Stagnated in the Sub-basin	=	.0000

Cumulative Results of Different Reservoirs in the Subbasin (Mm3)

Number of Reservoirs in the Subbasin	=	2
Initial Storage in Reservoirs	=	307.9450
Total Riverflows to the Reservoirs	=	100.7718
Total RF Contribution to the Reservoirs	=	9.8830
Total Peripheral Inflow to the Reservoirs	=	40.5852
Total Imports to the Reservoirs	=	.0000
Total Evaporation losses from Reservoirs	=	7.4151
Total WS Demand from the Reservoirs	=	.2466
Total Min_Flow Demand from the Reservoirs	=	.0000
Total Irrigation Demand from the Reservoirs	=	.0000

Total Release for WS from the Reservoirs	=	.2466
Total Release for Mn_Flo from Reservoirs	=	.0000
Total Release for Irr. from the Reservoirs	=	.0000
Total Spill from the Reservoirs	=	98.9279
Total Exports from the Reservoirs	=	.0000
Final Storage in the Reservoirs	=	352.5930

Sub-basin --- Aamdabad

Domestic & Industrial Demands and Supply (Mm3)

Total WS Demand in Rural Area	=	.4844
Total WS Demand in Urban Area	=	.4932
Total GW Withdrawal for meeting WS Demand	=	.9776
Total SW Supply for meeting WS Demand	=	.0000
Total GW Recharge from WS Discharge	=	.0000
Total Overland Flow from WS Discharge	=	.2367

Hydrological Details Under Different Landuses (Mm3)

	Urban	RFed_Agr	Irr_Agr	Forest	Barren	Water	Total
Area (Sq. km)	3	270	330	282	536	21	1442
Rainfall	.2790	54.0460	61.4520	87.9580	91.3010	4.0510	295.0360
Surface Inflow	.0000	38.7850	5.1410	49.0380	33.7300	.0000	126.6940
GW Contribution	.0000	.4125	1.4837	.0000	1.7385	.0000	3.6347
Irr. Application	.0000	.0000	.1740	.0000	.0000	.0000	.1740
Evapo-Transpiration	.1694	10.1994	15.5195	.7212	35.4453	2.3195	62.0547
Runoff	.1619	92.2904	38.3735	148.5857	122.0150	.0000	401.4265
Rt Zn Soil Mois. Inc.	.0069	-1.7875	-10.0445	.0000	.5691	.0000	-11.2560
GW Recharge	.0000	-21.0592	6.7903	-12.1624	-31.0397	1.6200	-57.4710

Irrigation Demands and Supply (Mm3)

Total Irr. Demand in SW_Irr Area	=	.1740
Total Irr. Demand in GW_Irr Area	=	.0000
Total SW Supply in SW_Irr Area	=	.1740
Total GW Supply in SW_Irr Area	=	.0000
Total GW Supply in GW_Irr Area	=	.0000

Runoff Stagnated or Out of Sub-basin (Mm3)

Runoff Out of the Basin	=	.0000
Runoff Out of the Sub-basin	=	.0251
Runoff Stagnated in the Sub-basin	=	.0000

Cumulative Results of Different Reservoirs in the Subbasin (Mm3)

Number of Reservoirs in the Subbasin	=	2
Initial Storage in Reservoirs	=	388.2000
Total Riverflows to the Reservoirs	=	106.4823
Total RF Contribution to the Reservoirs	=	5.4740
Total Peripheral Inflow to the Reservoirs	=	23.8923
Total Imports to the Reservoirs	=	.0000
Total Evaporation losses from Reservoirs	=	4.6860
Total WS Demand from the Reservoirs	=	.0000
Total Min_Flow Demand from the Reservoirs	=	.0000
Total Irrigation Demand from the Reservoirs	=	.6447
Total Release for WS from the Reservoirs	=	.0000
Total Release for Mn_Flo from Reservoirs	=	.0000
Total Release for Irr. from the Reservoirs	=	.6447
Total Spill from the Reservoirs	=	130.6710
Total Exports from the Reservoirs	=	.0000
Final Storage in the Reservoirs	=	388.0485

Sub-basin --- Chaskman

Domestic & Industrial Demands and Supply (Mm3)

Total WS Demand in Rural Area	=	.1183
Total WS Demand in Urban Area	=	.0000
Total GW Withdrawal for meeting WS Demand	=	.1183
Total SW Supply for meeting WS Demand	=	.0000
Total GW Recharge from WS Discharge	=	.0000
Total Overland Flow from WS Discharge	=	.0000

Hydrological Details Under Different Landuses (Mm3)

	Urban	RFed_Agr	Irr_Agr	Forest	Barren	Water	Total
Area (Sq. km)	0	140	6	84	121	19	370
Rainfall	.0000	43.3950	1.2750	44.7460	40.8690	5.6520	130.2850
Surface Inflow	.0000	62.0610	.9380	19.8000	27.1370	.0000	109.9360
GW Contribution	.0000	.0000	.0000	.0000	.0000	.0000	.0000
Irr. Application	.0000	.0000	.0000	.0000	.0000	.0000	.0000
Evapo-Transpiration	.0000	5.4928	.0540	.0000	9.0886	2.0313	14.6354
Runoff	.0000	139.3036	2.6849	71.3620	149.4100	.0000	362.7606
Rt Zn Soil Mois. Inc.	.0000	-12.5626	-.4893	.0000	-.2394	.0000	-13.2913
GW Recharge	.0000	-44.4207	-.7050	-6.8159	-94.9362	1.4400	-146.8778

Irrigation Demands and Supply (Mm3)

Total Irr. Demand in SW_Irr Area	=	.0000
Total Irr. Demand in GW_Irr Area	=	.0000
Total SW Supply in SW_Irr Area	=	.0000
Total GW Supply in SW_Irr Area	=	.0000
Total GW Supply in GW_Irr Area	=	.0000

Runoff Stagnated or Out of Sub-basin (Mm3)

Runoff Out of the Basin	=	.0000
Runoff Out of the Sub-basin	=	.6296
Runoff Stagnated in the Sub-basin	=	.0000

Cumulative Results of Different Reservoirs in the Subbasin (Mm3)

Number of Reservoirs in the Subbasin	=	1
Initial Storage in Reservoirs	=	214.0500
Total Riverflows to the Reservoirs	=	172.3471
Total RF Contribution to the Reservoirs	=	8.8740
Total Peripheral Inflow to the Reservoirs	=	54.9102
Total Imports to the Reservoirs	=	.0000
Total Evaporation losses from Reservoirs	=	4.3322
Total WS Demand from the Reservoirs	=	.0000
Total Min_Flow Demand from the Reservoirs	=	.0000
Total Irrigation Demand from the Reservoirs	=	2.2070
Total Release for WS from the Reservoirs	=	.0000
Total Release for Mn_Flo from Reservoirs	=	.0000
Total Release for Irr. from the Reservoirs	=	2.2070
Total Spill from the Reservoirs	=	229.5921
Total Exports from the Reservoirs	=	.0000
Final Storage in the Reservoirs	=	214.0500

Sub-basin --- Askheda

Domestic & Industrial Demands and Supply (Mm3)

Total WS Demand in Rural Area	=	.0437
Total WS Demand in Urban Area	=	.0000
Total GW Withdrawal for meeting WS Demand	=	.0437
Total SW Supply for meeting WS Demand	=	.0000
Total GW Recharge from WS Discharge	=	.0000
Total Overland Flow from WS Discharge	=	.0000

Hydrological Details Under Different Landuses (Mm3)

	Urban	RFed_Agr	Irr_Agr	Forest	Barren	Water	Total
Area (Sq. km)	0	54	0	46	117	17	234
Rainfall	.0000	16.8020	.0000	17.2230	34.4660	5.2750	68.4910
Surface Inflow	.0000	8.2850	.0000	3.8530	14.5940	.0000	26.7320
GW Contribution	.0000	.0000	.0000	.0000	.0000	.0000	.0000
Irr. Application	.0000	.0000	.0000	.0000	.0000	.0000	.0000
Evapo-Transpiration	.0000	2.8598	.0000	.0000	8.8610	.6059	11.7209
Runoff	.0000	32.3695	.0000	17.1022	46.9979	.0000	96.4696
Rt Zn Soil Mois. Inc.	.0000	-2.4698	.0000	.0000	.5415	.0000	-1.9282
GW Recharge	.0000	-11.8987	.0000	3.9738	-7.3405	.0000	-15.2654

Irrigation Demands and Supply (Mm3)

Total Irr. Demand in SW_Irr Area	=	.0000
Total Irr. Demand in GW_Irr Area	=	.0000
Total SW Supply in SW_Irr Area	=	.0000
Total GW Supply in SW_Irr Area	=	.0000
Total GW Supply in GW_Irr Area	=	.0000

Runoff Stagnated or Out of Sub-basin (Mm3)

Runoff Out of the Basin	=	.0000
Runoff Out of the Sub-basin	=	.0000
Runoff Stagnated in the Sub-basin	=	.0000

Cumulative Results of Different Reservoirs in the Subbasin (Mm3)

Number of Reservoirs in the Subbasin	=	0
Initial Storage in Reservoirs	=	.0000
Total Riverflows to the Reservoirs	=	.0000
Total RF Contribution to the Reservoirs	=	.0000
Total Peripheral Inflow to the Reservoirs	=	.0000
Total Imports to the Reservoirs	=	.0000
Total Evaporation losses from Reservoirs	=	.0000
Total WS Demand from the Reservoirs	=	.0000
Total Min_Flow Demand from the Reservoirs	=	.0000
Total Irrigation Demand from the Reservoirs	=	.0000
Total Release for WS from the Reservoirs	=	.0000
Total Release for Mn_Flo from Reservoirs	=	.0000
Total Release for Irr. from the Reservoirs	=	.0000
Total Spill from the Reservoirs	=	.0000
Total Exports from the Reservoirs	=	.0000
Final Storage in the Reservoirs	=	.0000

Sub-basin --- Nighoje

Domestic & Industrial Demands and Supply (Mm3)

Total WS Demand in Rural Area	=	.1426
Total WS Demand in Urban Area	=	1.5618
Total GW Withdrawal for meeting WS Demand	=	.4714
Total SW Supply for meeting WS Demand	=	.0000
Total GW Recharge from WS Discharge	=	.3946
Total Overland Flow from WS Discharge	=	.7497

Hydrological Details Under Different Landuses (Mm3)

	Urban	RFed_Agr	Irr_Agr	Forest	Barren	Water	Total
Area (Sq. km)	5	197	7	97	300	37	643
Rainfall	1.6390	61.6600	1.3730	33.5610	81.7480	8.9600	179.9810
Surface Inflow	3.6770	65.6350	.0000	.2950	44.0940	.0000	113.7010
GW Contribution	.0000	.5876	.1632	.0000	.4981	.0000	1.2489
Irr. Application	.0000	.0000	.0000	.0000	.0000	.0000	.0000
Evapo-Transpiration	.4485	11.0995	.4388	.1752	22.5797	2.4591	34.7416
Runoff	4.1191	160.8566	.9420	23.6512	252.3576	.0000	441.9266
Rt Zn Soil Mois. Inc.	.0192	-7.7269	-.0048	.0000	1.4534	.0000	-6.2591
GW Recharge	.8280	-48.1547	.1601	9.6303	-155.7552	1.9800	-193.2915

Irrigation Demands and Supply (Mm3)

Total Irr. Demand in SW_Irr Area	=	.0000
Total Irr. Demand in GW_Irr Area	=	.0000
Total SW Supply in SW_Irr Area	=	.0000
Total GW Supply in SW_Irr Area	=	.0000
Total GW Supply in GW_Irr Area	=	.0000

Runoff Stagnated or Out of Sub-basin (Mm3)

Runoff Out of the Basin	=	.0000
Runoff Out of the Sub-basin	=	.0000
Runoff Stagnated in the Sub-basin	=	.0000

Cumulative Results of Different Reservoirs in the Subbasin (Mm3)

Number of Reservoirs in the Subbasin	=	2
Initial Storage in Reservoirs	=	374.0080
Total Riverflows to the Reservoirs	=	.0000
Total RF Contribution to the Reservoirs	=	8.3810
Total Peripheral Inflow to the Reservoirs	=	71.5710
Total Imports to the Reservoirs	=	.0000
Total Evaporation losses from Reservoirs	=	6.3752
Total WS Demand from the Reservoirs	=	.0000
Total Min_Flow Demand from the Reservoirs	=	.0000
Total Irrigation Demand from the Reservoirs	=	.0000
Total Release for WS from the Reservoirs	=	.0000
Total Release for Mn_Flo from Reservoirs	=	.0000
Total Release for Irr. from the Reservoirs	=	.0000
Total Spill from the Reservoirs	=	56.2110
Total Exports from the Reservoirs	=	16.2000
Final Storage in the Reservoirs	=	375.1707

Sub-basin --- Budhwadi

Domestic & Industrial Demands and Supply (Mm3)

Total WS Demand in Rural Area	=	.0024
Total WS Demand in Urban Area	=	.0411
Total GW Withdrawal for meeting WS Demand	=	.0024
Total SW Supply for meeting WS Demand	=	2.7948
Total GW Recharge from WS Discharge	=	.0132
Total Overland Flow from WS Discharge	=	.0197

Hydrological Details Under Different Landuses (Mm3)

	Urban	RFed_Agr	Irr_Agr	Forest	Barren	Water	Total
Area (Sq. km)	0	4	0	49	18	19	90
Rainfall	.0000	1.7520	.0000	20.3760	7.9760	9.1500	30.1040
Surface Inflow	.0000	.2510	.0000	.7430	2.5950	.0000	3.5890
GW Contribution	.0000	.0000	.0000	.0000	.0000	.0000	.0000
Irr. Application	.0000	.0000	.0000	.0000	.0000	.0000	.0000
Evapo-Transpiration	.0000	.0876	.0000	.1752	1.5588	1.1599	1.8216
Runoff	.0000	1.2091	.0000	16.6234	18.9016	.0000	36.7341
Rt Zn Soil Mois. Inc.	.0000	-.6345	.0000	.0000	-.0057	.0000	-.6402
GW Recharge	.0000	.7239	.0000	3.8592	-10.9039	.9000	-6.3208

Irrigation Demands and Supply (Mm3)

Total Irr. Demand in SW_Irr Area	=	.0000
Total Irr. Demand in GW_Irr Area	=	.0000
Total SW Supply in SW_Irr Area	=	.0000
Total GW Supply in SW_Irr Area	=	.0000
Total GW Supply in GW_Irr Area	=	.0000

Runoff Stagnated or Out of Sub-basin (Mm3)

Runoff Out of the Basin	=	.0000
Runoff Out of the Sub-basin	=	.0000
Runoff Stagnated in the Sub-basin	=	.0000

Cumulative Results of Different Reservoirs in the Subbasin (Mm3)

Number of Reservoirs in the Subbasin	=	1
Initial Storage in Reservoirs	=	191.1430
Total Riverflows to the Reservoirs	=	47.5268
Total RF Contribution to the Reservoirs	=	12.1680
Total Peripheral Inflow to the Reservoirs	=	21.1907
Total Imports to the Reservoirs	=	.0000
Total Evaporation losses from Reservoirs	=	5.7431
Total WS Demand from the Reservoirs	=	2.7948
Total Min_Flow Demand from the Reservoirs	=	.0000
Total Irrigation Demand from the Reservoirs	=	.0000
Total Release for WS from the Reservoirs	=	2.7948
Total Release for Mn_Flo from Reservoirs	=	.0000
Total Release for Irr. from the Reservoirs	=	.0000
Total Spill from the Reservoirs	=	50.4243
Total Exports from the Reservoirs	=	30.7429
Final Storage in the Reservoirs	=	192.0000

Sub-basin --- Pimpal Gurav

Domestic & Industrial Demands and Supply (Mm3)

Total WS Demand in Rural Area	=	.1539
Total WS Demand in Urban Area	=	3.2058
Total GW Withdrawal for meeting WS Demand	=	.1539
Total SW Supply for meeting WS Demand	=	1.6440
Total GW Recharge from WS Discharge	=	1.0258
Total Overland Flow from WS Discharge	=	1.5388

Hydrological Details Under Different Landuses (Mm3)

	Urban	RFed_Agr	Irr_Agr	Forest	Barren	Water	Total
Area (Sq. km)	60	205	0	77	127	26	495
Rainfall	10.4490	47.9070	.0000	25.6240	32.5030	8.4970	116.4830
Surface Inflow	.4110	16.5560	.0000	1.7670	15.6500	.0000	34.3840
GW Contribution	.0000	.0000	.0000	.0000	.0000	.0000	.0000
Irr. Application	.0000	.0000	.0000	.0000	.0000	.0000	.0000
Evapo-Transpiration	3.6907	9.9366	.0000	.0876	11.4290	2.5530	25.1440
Runoff	7.6911	63.1923	.0000	23.2323	72.3861	.0000	166.5018
Rt Zn Soil Mois. Inc.	-.4999	-9.8194	.0000	.0000	-.9452	.0000	-11.2645
GW Recharge	1.1619	-7.3588	.0000	3.9207	-34.9140	2.0700	-37.1901

Irrigation Demands and Supply (Mm3)

Total Irr. Demand in SW_Irr Area	=	.0000
Total Irr. Demand in GW_Irr Area	=	.0000
Total SW Supply in SW_Irr Area	=	.0000
Total GW Supply in SW_Irr Area	=	.0000
Total GW Supply in GW_Irr Area	=	.0000

Runoff Stagnated or Out of Sub-basin (Mm3)

Runoff Out of the Basin	=	.0000
Runoff Out of the Sub-basin	=	.0000
Runoff Stagnated in the Sub-basin	=	.0000

Cumulative Results of Different Reservoirs in the Subbasin (Mm3)

Number of Reservoirs in the Subbasin	=	1
Initial Storage in Reservoirs	=	266.3790
Total Riverflows to the Reservoirs	=	.0000
Total RF Contribution to the Reservoirs	=	21.1600
Total Peripheral Inflow to the Reservoirs	=	89.0067
Total Imports to the Reservoirs	=	.0000
Total Evaporation losses from Reservoirs	=	8.1229
Total WS Demand from the Reservoirs	=	1.6440
Total Min_Flow Demand from the Reservoirs	=	44.5824
Total Irrigation Demand from the Reservoirs	=	.0000
Total Release for WS from the Reservoirs	=	1.6440
Total Release for Mn_Flo from Reservoirs	=	44.5824
Total Release for Irr. from the Reservoirs	=	.0000
Total Spill from the Reservoirs	=	.0000
Total Exports from the Reservoirs	=	16.8557
Final Storage in the Reservoirs	=	285.8605

Sub-basin --- Paud

Domestic & Industrial Demands and Supply (Mm3)

Total WS Demand in Rural Area	=	.0413
Total WS Demand in Urban Area	=	.4110
Total GW Withdrawal for meeting WS Demand	=	.0413
Total SW Supply for meeting WS Demand	=	2.1372
Total GW Recharge from WS Discharge	=	.1315
Total Overland Flow from WS Discharge	=	.1973

Hydrological Details Under Different Landuses (Mm3)

	Urban	RFed_Agr	Irr_Agr	Forest	Barren	Water	Total
Area (Sq. km)	3	57	0	193	95	49	397
Rainfall	.6090	11.7510	.0000	48.6770	24.5920	12.6410	85.6290
Surface Inflow	.0000	1.7160	.0000	17.4910	2.5710	.0000	21.7780
GW Contribution	.1169	.0000	.0000	.0000	.0000	.0000	.1169
Irr. Application	.0000	.0000	.0000	.0000	.0000	.0000	.0000
Evapo-Transpiration	.3164	2.9514	.0000	.3274	8.1694	6.1706	11.7646
Runoff	.4483	8.8998	.0000	62.4195	36.3188	.0000	108.0863
Rt Zn Soil Mois. Inc.	-.0077	-4.3948	.0000	.0000	-.7386	.0000	-5.1411
GW Recharge	.0281	1.6802	.0000	3.5112	-16.3574	4.1400	-11.1381

Irrigation Demands and Supply (Mm3)

Total Irr. Demand in SW_Irr Area	=	.0000
Total Irr. Demand in GW_Irr Area	=	.0000
Total SW Supply in SW_Irr Area	=	.0000
Total GW Supply in SW_Irr Area	=	.0000
Total GW Supply in GW_Irr Area	=	.0000

Runoff Stagnated or Out of Sub-basin (Mm3)

Runoff Out of the Basin	=	.0000
Runoff Out of the Sub-basin	=	.0000
Runoff Stagnated in the Sub-basin	=	.0000

Cumulative Results of Different Reservoirs in the Subbasin (Mm3)

Number of Reservoirs in the Subbasin	=	1
Initial Storage in Reservoirs	=	278.3780
Total Riverflows to the Reservoirs	=	26.9079
Total RF Contribution to the Reservoirs	=	27.2560
Total Peripheral Inflow to the Reservoirs	=	61.0306
Total Imports to the Reservoirs	=	.0000
Total Evaporation losses from Reservoirs	=	12.0356
Total WS Demand from the Reservoirs	=	2.1372
Total Min_Flow Demand from the Reservoirs	=	.0000
Total Irrigation Demand from the Reservoirs	=	.0000
Total Release for WS from the Reservoirs	=	2.1372
Total Release for Mn_Flo from Reservoirs	=	.0000
Total Release for Irr. from the Reservoirs	=	.0000

Total Spill from the Reservoirs	=	.0000
Total Exports from the Reservoirs	=	157.6000
Final Storage in the Reservoirs	=	255.8139

Sub-basin --- Dattawadi

Domestic & Industrial Demands and Supply (Mm3)

Total WS Demand in Rural Area	=	.1037
Total WS Demand in Urban Area	=	1.4385
Total GW Withdrawal for meeting WS Demand	=	.1037
Total SW Supply for meeting WS Demand	=	7.9323
Total GW Recharge from WS Discharge	=	.4603
Total Overland Flow from WS Discharge	=	.6905

Hydrological Details Under Different Landuses (Mm3)

	Urban	RFed_Agr	Irr_Agr	Forest	Barren	Water	Total
Area (Sq. km)	35	128	0	235	169	49	616
Rainfall	6.0500	17.7720	.0000	47.9920	26.9380	9.7630	98.7520
Surface Inflow	.3330	162.8410	.0000	9.7530	81.4050	.0000	254.3320
GW Contribution	.2751	.2834	.0000	.0000	.0826	.0000	.6411
Irr. Application	.0000	.0000	.0000	.0000	.0000	.0000	.0000
Evapo-Transpiration	2.6744	5.1668	.0000	.3015	7.5955	1.5792	15.7382
Runoff	4.9435	259.1583	.0000	55.8272	172.5398	.0000	492.4688
Rt Zn Soil Mois. Inc.	.3181	.1489	.0000	.0000	.6767	.0000	1.1437
GW Recharge	-.5875	-85.1252	.0000	.4965	-73.2780	4.0500	-158.4941

Irrigation Demands and Supply (Mm3)

Total Irr. Demand in SW_Irr Area	=	.0000
Total Irr. Demand in GW_Irr Area	=	.0000
Total SW Supply in SW_Irr Area	=	.0000
Total GW Supply in SW_Irr Area	=	.0000
Total GW Supply in GW_Irr Area	=	.0000

Runoff Stagnated or Out of Sub-basin (Mm3)

Runoff Out of the Basin	=	.0000
Runoff Out of the Sub-basin	=	.0000
Runoff Stagnated in the Sub-basin	=	.0000

Cumulative Results of Different Reservoirs in the Subbasin (Mm3)

Number of Reservoirs in the Subbasin	=	3
Initial Storage in Reservoirs	=	679.1470
Total Riverflows to the Reservoirs	=	203.9736
Total RF Contribution to the Reservoirs	=	14.3690
Total Peripheral Inflow to the Reservoirs	=	61.5178
Total Imports to the Reservoirs	=	.0000
Total Evaporation losses from Reservoirs	=	5.7927
Total WS Demand from the Reservoirs	=	7.9323
Total Min_Flow Demand from the Reservoirs	=	.0000
Total Irrigation Demand from the Reservoirs	=	13.6214
Total Release for WS from the Reservoirs	=	7.9323
Total Release for Mn_Flo from Reservoirs	=	.0000
Total Release for Irr. from the Reservoirs	=	13.6214
Total Spill from the Reservoirs	=	251.6632
Total Exports from the Reservoirs	=	.0000
Final Storage in the Reservoirs	=	680.0000

Sub-basin --- Pulgaon

Domestic & Industrial Demands and Supply (Mm3)

Total WS Demand in Rural Area	=	.3467
Total WS Demand in Urban Area	=	.5754
Total GW Withdrawal for meeting WS Demand	=	.8810
Total SW Supply for meeting WS Demand	=	.0000
Total GW Recharge from WS Discharge	=	.0132
Total Overland Flow from WS Discharge	=	.2762

Hydrological Details Under Different Landuses (Mm3)

	Urban	RFed_Agr	Irr_Agr	Forest	Barren	Water	Total
Area (Sq. km)	3	299	132	1	344	0	779
Rainfall	.2490	42.2590	16.2340	.2140	42.1590	.0000	101.1150
Surface Inflow	.0000	2.3070	.8540	.0000	3.9750	.0000	7.1360
GW Contribution	.0000	.6271	1.2226	.0000	1.7634	.0000	3.6131
Irr. Application	.0000	.0000	.0000	.0000	.0000	.0000	.0000
Evapo-Transpiration	.0848	8.9281	4.1013	.0000	16.0104	.0000	29.1246
Runoff	.1855	24.2636	8.6669	.2140	22.7888	.0000	56.1189
Rt Zn Soil Mois. Inc.	.0073	4.0721	2.7012	.0000	3.6785	.0000	10.4591
GW Recharge	.0306	4.3848	1.3267	.0000	5.5773	.0000	11.3194

Irrigation Demands and Supply (Mm3)

Total Irr. Demand in SW_Irr Area	=	.0000
Total Irr. Demand in GW_Irr Area	=	.0000
Total SW Supply in SW_Irr Area	=	.0000
Total GW Supply in SW_Irr Area	=	.0000
Total GW Supply in GW_Irr Area	=	.0000

Runoff Stagnated or Out of Sub-basin (Mm3)

Runoff Out of the Basin	=	.0000
Runoff Out of the Sub-basin	=	.0743
Runoff Stagnated in the Sub-basin	=	.0000

Cumulative Results of Different Reservoirs in the Subbasin (Mm3)

Number of Reservoirs in the Subbasin	=	0
Initial Storage in Reservoirs	=	.0000
Total Riverflows to the Reservoirs	=	.0000
Total RF Contribution to the Reservoirs	=	.0000
Total Peripheral Inflow to the Reservoirs	=	.0000
Total Imports to the Reservoirs	=	.0000
Total Evaporation losses from Reservoirs	=	.0000
Total WS Demand from the Reservoirs	=	.0000
Total Min_Flow Demand from the Reservoirs	=	.0000
Total Irrigation Demand from the Reservoirs	=	.0000
Total Release for WS from the Reservoirs	=	.0000
Total Release for Mn_Flo from Reservoirs	=	.0000
Total Release for Irr. from the Reservoirs	=	.0000
Total Spill from the Reservoirs	=	.0000
Total Exports from the Reservoirs	=	.0000
Final Storage in the Reservoirs	=	.0000

Sub-basin --- Wegre

Domestic & Industrial Demands and Supply (Mm3)

Total WS Demand in Rural Area	=	.0032
Total WS Demand in Urban Area	=	.0000
Total GW Withdrawal for meeting WS Demand	=	.0032
Total SW Supply for meeting WS Demand	=	.0000
Total GW Recharge from WS Discharge	=	.0000
Total Overland Flow from WS Discharge	=	.0000

Hydrological Details Under Different Landuses (Mm3)

	Urban	RFed_Agr	Irr_Agr	Forest	Barren	Water	Total
Area (Sq. km)	0	4	0	60	10	3	77
Rainfall	.0000	.7970	.0000	13.5750	2.1050	.6990	16.4770
Surface Inflow	.0000	.6970	.0000	1.9310	.0600	.0000	2.6880
GW Contribution	.0000	.0000	.0000	.0000	.0000	.0000	.0000
Irr. Application	.0000	.0000	.0000	.0000	.0000	.0000	.0000
Evapo-Transpiration	.0000	.1005	.0000	.0000	.3350	.0000	.4355
Runoff	.0000	5.0150	.0000	15.2599	5.1777	.0000	25.4525
Rt Zn Soil Mois. Inc.	.0000	-.2382	.0000	.0000	.0300	.0000	-.2082
GW Recharge	.0000	-3.6217	.0000	.2461	-3.3777	.0000	-6.7532

Irrigation Demands and Supply (Mm3)

Total Irr. Demand in SW_Irr Area	=	.0000
Total Irr. Demand in GW_Irr Area	=	.0000
Total SW Supply in SW_Irr Area	=	.0000
Total GW Supply in SW_Irr Area	=	.0000
Total GW Supply in GW_Irr Area	=	.0000

Runoff Stagnated or Out of Sub-basin (Mm3)

Runoff Out of the Basin	=	.0000
Runoff Out of the Sub-basin	=	.2330
Runoff Stagnated in the Sub-basin	=	.0000

Cumulative Results of Different Reservoirs in the Subbasin (Mm3)

Number of Reservoirs in the Subbasin	=	0
Initial Storage in Reservoirs	=	.0000
Total Riverflows to the Reservoirs	=	.0000
Total RF Contribution to the Reservoirs	=	.0000
Total Peripheral Inflow to the Reservoirs	=	.0000
Total Imports to the Reservoirs	=	.0000
Total Evaporation losses from Reservoirs	=	.0000
Total WS Demand from the Reservoirs	=	.0000
Total Min_Flow Demand from the Reservoirs	=	.0000
Total Irrigation Demand from the Reservoirs	=	.0000
Total Release for WS from the Reservoirs	=	.0000
Total Release for Mn_Flo from Reservoirs	=	.0000

Total Release for Irr. from the Reservoirs	=	.0000
Total Spill from the Reservoirs	=	.0000
Total Exports from the Reservoirs	=	.0000
Final Storage in the Reservoirs	=	.0000

Sub-basin --- Khamgaon

Domestic & Industrial Demands and Supply (Mm3)

Total WS Demand in Rural Area	=	.3686
Total WS Demand in Urban Area	=	5.0553
Total GW Withdrawal for meeting WS Demand	=	.6151
Total SW Supply for meeting WS Demand	=	.0000
Total GW Recharge from WS Discharge	=	1.5387
Total Overland Flow from WS Discharge	=	2.4266

Hydrological Details Under Different Landuses (Mm3)

	Urban	RFed_Agr	Irr_Agr	Forest	Barren	Water	Total
Area (Sq. km)	99	294	178	28	526	1	1126
Rainfall	17.8050	33.7810	6.4420	5.2820	54.4720	.1850	117.7820
Surface Inflow	.3830	18.0060	25.0780	.0850	38.1160	.0000	81.6680
GW Contribution	.8064	1.9906	1.2412	.0000	1.3369	.0000	5.3752
Irr. Application	.0000	.0000	1.5598	.0000	.0000	.0000	1.5598
Evapo-Transpiration	8.5220	11.5625	2.9126	.0000	23.3305	.0736	46.3276
Runoff	11.1227	45.1091	31.3204	2.7989	105.1849	.0000	195.5360
Rt Zn Soil Mois. Inc.	1.0380	-6.0643	-2.4385	.0000	3.5888	.0000	-3.8761
GW Recharge	.2072	-5.1687	-3.2644	2.5681	-38.0606	.0132	-43.7184

Irrigation Demands and Supply (Mm3)

Total Irr. Demand in SW_Irr Area	=	1.5598
Total Irr. Demand in GW_Irr Area	=	.0000
Total SW Supply in SW_Irr Area	=	1.5598
Total GW Supply in SW_Irr Area	=	.0000
Total GW Supply in GW_Irr Area	=	.0000

Runoff Stagnated or Out of Sub-basin (Mm3)

Runoff Out of the Basin	=	.0000
Runoff Out of the Sub-basin	=	.7486
Runoff Stagnated in the Sub-basin	=	.1989

Cumulative Results of Different Reservoirs in the Subbasin (Mm3)

Number of Reservoirs in the Subbasin	=	0
Initial Storage in Reservoirs	=	.0000
Total Riverflows to the Reservoirs	=	.0000
Total RF Contribution to the Reservoirs	=	.0000
Total Peripheral Inflow to the Reservoirs	=	.0000
Total Imports to the Reservoirs	=	.0000
Total Evaporation losses from Reservoirs	=	.0000
Total WS Demand from the Reservoirs	=	.0000
Total Min_Flow Demand from the Reservoirs	=	.0000
Total Irrigation Demand from the Reservoirs	=	.0000
Total Release for WS from the Reservoirs	=	.0000
Total Release for Mn_Flo from Reservoirs	=	.0000
Total Release for Irr. from the Reservoirs	=	.0000
Total Spill from the Reservoirs	=	.0000
Total Exports from the Reservoirs	=	.0000
Final Storage in the Reservoirs	=	.0000

Sub-basin --- Rakshewadi

Domestic & Industrial Demands and Supply (Mm3)

Total WS Demand in Rural Area	=	.3661
Total WS Demand in Urban Area	=	.1644
Total GW Withdrawal for meeting WS Demand	=	.5305
Total SW Supply for meeting WS Demand	=	.0000
Total GW Recharge from WS Discharge	=	.0000
Total Overland Flow from WS Discharge	=	.0789

Hydrological Details Under Different Landuses (Mm3)

	Urban	RFed_Agr	Irr_Agr	Forest	Barren	Water	Total
Area (Sq. km)	0	181	271	0	527	2	981
Rainfall	.0000	28.1730	35.1730	.0000	67.7640	.2450	131.1100
Surface Inflow	.0000	8.4060	34.8360	.0000	16.2390	.0000	59.4810
GW Contribution	.0000	.1161	2.7767	.0000	.1213	.0000	3.0142
Irr. Application	.0000	.0000	.0000	.0000	.0000	.0000	.0000
Evapo-Transpiration	.0000	6.7172	9.6603	.0000	18.6741	.0528	35.0515
Runoff	.0000	33.1587	80.2539	.0000	82.1741	.0000	195.5866
Rt Zn Soil Mois. Inc.	.0000	2.0582	3.5634	.0000	4.4850	.0000	10.1066
GW Recharge	.0000	-5.4276	-20.6925	.0000	-21.1309	.0000	-47.2510

Irrigation Demands and Supply (Mm3)

Total Irr. Demand in SW_Irr Area	=	.0000
Total Irr. Demand in GW_Irr Area	=	.0000
Total SW Supply in SW_Irr Area	=	.0000
Total GW Supply in SW_Irr Area	=	.0000
Total GW Supply in GW_Irr Area	=	.0000

Runoff Stagnated or Out of Sub-basin (Mm3)

Runoff Out of the Basin	=	.0000
Runoff Out of the Sub-basin	=	.0000
Runoff Stagnated in the Sub-basin	=	.0669

Cumulative Results of Different Reservoirs in the Subbasin (Mm3)

Number of Reservoirs in the Subbasin	=	0
Initial Storage in Reservoirs	=	.0000
Total Riverflows to the Reservoirs	=	.0000
Total RF Contribution to the Reservoirs	=	.0000
Total Peripheral Inflow to the Reservoirs	=	.0000
Total Imports to the Reservoirs	=	.0000
Total Evaporation losses from Reservoirs	=	.0000
Total WS Demand from the Reservoirs	=	.0000
Total Min_Flow Demand from the Reservoirs	=	.0000
Total Irrigation Demand from the Reservoirs	=	.0000
Total Release for WS from the Reservoirs	=	.0000
Total Release for Mn_Flo from Reservoirs	=	.0000
Total Release for Irr. from the Reservoirs	=	.0000
Total Spill from the Reservoirs	=	.0000
Total Exports from the Reservoirs	=	.0000
Final Storage in the Reservoirs	=	.0000

Sub-basin --- Pargaon

Domestic & Industrial Demands and Supply (Mm3)

Total WS Demand in Rural Area	=	.1361
Total WS Demand in Urban Area	=	.0000
Total GW Withdrawal for meeting WS Demand	=	.1361
Total SW Supply for meeting WS Demand	=	.0000
Total GW Recharge from WS Discharge	=	.0000
Total Overland Flow from WS Discharge	=	.0000

Hydrological Details Under Different Landuses (Mm3)

	Urban	RFed_Agr	Irr_Agr	Forest	Barren	Water	Total
Area (Sq. km)	0	12	156	0	44	3	215
Rainfall	.0000	1.1220	17.7860	.0000	4.4350	.2000	23.3430
Surface Inflow	.0000	.0000	8.3130	.0000	.0000	.0000	8.3130
GW Contribution	.0000	.0000	1.2813	.0000	.2785	.0000	1.5598
Irr. Application	.0000	.0000	.5028	.0000	.0000	.0000	.5028
Evapo-Transpiration	.0000	.2154	4.3085	.0000	1.9832	.0400	6.5072
Runoff	.0000	.3848	26.6385	.0000	2.0262	.0000	29.0495
Rt Zn Soil Mois. Inc.	.0000	.5045	5.5885	.0000	.6275	.0000	6.7205
GW Recharge	.0000	.0172	-10.4224	.0000	.0766	.0000	-10.3285

Irrigation Demands and Supply (Mm3)

Total Irr. Demand in SW_Irr Area	=	.4440
Total Irr. Demand in GW_Irr Area	=	.2940
Total SW Supply in SW_Irr Area	=	.4440
Total GW Supply in SW_Irr Area	=	.0000
Total GW Supply in GW_Irr Area	=	.0588

Runoff Stagnated or Out of Sub-basin (Mm3)

Runoff Out of the Basin	=	.0000
Runoff Out of the Sub-basin	=	.0000
Runoff Stagnated in the Sub-basin	=	.0000

Cumulative Results of Different Reservoirs in the Subbasin (Mm3)

Number of Reservoirs in the Subbasin	=	0
Initial Storage in Reservoirs	=	.0000
Total Riverflows to the Reservoirs	=	.0000
Total RF Contribution to the Reservoirs	=	.0000
Total Peripheral Inflow to the Reservoirs	=	.0000
Total Imports to the Reservoirs	=	.0000
Total Evaporation losses from Reservoirs	=	.0000
Total WS Demand from the Reservoirs	=	.0000
Total Min_Flow Demand from the Reservoirs	=	.0000
Total Irrigation Demand from the Reservoirs	=	.0000
Total Release for WS from the Reservoirs	=	.0000
Total Release for Mn_Flo from Reservoirs	=	.0000

Total Release for Irr. from the Reservoirs	=	.0000
Total Spill from the Reservoirs	=	.0000
Total Exports from the Reservoirs	=	.0000
Final Storage in the Reservoirs	=	.0000

Sub-basin --- Kashti

Domestic & Industrial Demands and Supply (Mm3)

Total WS Demand in Rural Area	=	.3475
Total WS Demand in Urban Area	=	.0000
Total GW Withdrawal for meeting WS Demand	=	.3475
Total SW Supply for meeting WS Demand	=	.0000
Total GW Recharge from WS Discharge	=	.0000
Total Overland Flow from WS Discharge	=	.0000

Hydrological Details Under Different Landuses (Mm3)

	Urban	RFed_Agr	Irr_Agr	Forest	Barren	Water	Total
Area (Sq. km)	0	141	288	2	924	46	1401
Rainfall	.0000	13.2390	33.9400	.1440	86.0940	4.9890	133.4170
Surface Inflow	.0000	2.9070	48.4780	.0000	34.4480	.0000	85.8330
GW Contribution	.0000	.9271	2.5250	.0000	1.3234	.0000	4.7755
Irr. Application	.0000	.0000	.1713	.0000	.0000	.0000	.1713
Evapo-Transpiration	.0000	4.5428	6.6686	.0000	30.4082	6.1786	41.6196
Runoff	.0000	17.6516	112.3573	.0584	118.9616	.0000	249.0289
Rt Zn Soil Mois. Inc.	.0000	-.7988	2.9996	.0347	2.7041	.0000	4.9396
GW Recharge	.0000	-6.1299	-38.9412	.0509	-29.7533	3.4200	-74.7735

Irrigation Demands and Supply (Mm3)

Total Irr. Demand in SW_Irr Area	=	.1713
Total Irr. Demand in GW_Irr Area	=	.0000
Total SW Supply in SW_Irr Area	=	.1713
Total GW Supply in SW_Irr Area	=	.0000
Total GW Supply in GW_Irr Area	=	.0000

Runoff Stagnated or Out of Sub-basin (Mm3)

Runoff Out of the Basin	=	.0000
Runoff Out of the Sub-basin	=	.0000
Runoff Stagnated in the Sub-basin	=	.0000

Cumulative Results of Different Reservoirs in the Subbasin (Mm3)

Number of Reservoirs in the Subbasin	=	2
Initial Storage in Reservoirs	=	188.0000
Total Riverflows to the Reservoirs	=	453.5558
Total RF Contribution to the Reservoirs	=	4.9830
Total Peripheral Inflow to the Reservoirs	=	31.4007
Total Imports to the Reservoirs	=	.0000
Total Evaporation losses from Reservoirs	=	9.7446
Total WS Demand from the Reservoirs	=	.0000
Total Min_Flow Demand from the Reservoirs	=	.0000
Total Irrigation Demand from the Reservoirs	=	5.6519
Total Release for WS from the Reservoirs	=	.0000
Total Release for Mn_Flo from Reservoirs	=	.0000
Total Release for Irr. from the Reservoirs	=	5.6519
Total Spill from the Reservoirs	=	474.9767
Total Exports from the Reservoirs	=	.0000
Final Storage in the Reservoirs	=	187.5661

Sub-basin --- Dhond

Domestic & Industrial Demands and Supply (Mm3)

Total WS Demand in Rural Area	=	.3451
Total WS Demand in Urban Area	=	1.1919
Total GW Withdrawal for meeting WS Demand	=	1.5370
Total SW Supply for meeting WS Demand	=	.0000
Total GW Recharge from WS Discharge	=	.0000
Total Overland Flow from WS Discharge	=	.5721

Hydrological Details Under Different Landuses (Mm3)

	Urban	RFed_Agr	Irr_Agr	Forest	Barren	Water	Total
Area (Sq. km)	7	43	384	0	298	2	734
Rainfall	.6420	1.5390	40.5980	.0000	15.5490	.0000	58.3280
Surface Inflow	1.2160	.0000	20.8740	.0000	12.1590	.0000	34.2490
GW Contribution	.0000	.0000	1.8928	.0000	.1262	.0000	2.0190
Irr. Application	.0000	.0000	2.3301	.0000	.0000	.0000	2.3301
Evapo-Transpiration	.0980	.2450	6.2198	.0000	3.7256	.0000	10.2884
Runoff	4.0710	4.6647	94.0616	.0000	37.1229	.0000	139.9202
Rt Zn Soil Mois. Inc.	.0449	-.0953	-9.0414	.0000	1.3403	.0000	-7.7516
GW Recharge	-2.2178	-3.5097	-44.3319	.0000	-13.9398	.0000	-63.9991

```
      Irrigation Demands and Supply (Mm3)
     ------------------------------------
Total Irr. Demand in SW_Irr Area  =      2.3301
Total Irr. Demand in GW_Irr Area  =       .0000
Total SW Supply in SW_Irr Area    =      2.3301
Total GW Supply in SW_Irr Area    =       .0000
Total GW Supply in GW_Irr Area    =       .0000

      Runoff Stagnated or Out of Sub-basin (Mm3)
     -------------------------------------------
Runoff Out of the Basin            =       .0000
Runoff Out of the Sub-basin        =       .0000
Runoff Stagnated in the Sub-basin  =       .2322

 Cumulative Results of Different Reservoirs in the Subbasin (Mm3)
------------------------------------------------------------------
    Number of Reservoirs in the Subbasin        =       0
    Initial Storage in Reservoirs               =       .0000
    Total Riverflows to the Reservoirs          =       .0000
    Total RF Contribution to the Reservoirs     =       .0000
    Total Peripheral Inflow to the Reservoirs   =       .0000
    Total Imports to the Reservoirs             =       .0000
    Total Evaporation losses from Reservoirs    =       .0000
    Total WS Demand from the Reservoirs         =       .0000
    Total Min_Flow Demand from the Reservoirs   =       .0000
    Total Irrigation Demand from the Reservoirs =       .0000
    Total Release for WS from the Reservoirs    =       .0000
    Total Release for Mn_Flo from Reservoirs    =       .0000
    Total Release for Irr. from the Reservoirs  =       .0000
    Total Spill from the Reservoirs             =       .0000
    Total Exports from the Reservoirs           =       .0000
    Final Storage in the Reservoirs             =       .0000
```

4.3 Model Application for Upper Bhima Basin (1992-2000)

Basin simulation model has been run continuously for the Upper Bhima basin from June 1992 to May 2001. At the beginning of June, the soil moisture has been assumed in-between the field capacity and wilting point and different reservoirs have been roughly assumed to be around 10 - 15 % of their live storage capacities. The PPA (proposed profitable area) for each reservoir has been assumed to be 100 % and the SWFAC and BSFAC have been taken as 1. The flow volumes have been simulated and compared at various gauging sites. Next, the SWFAC and BSFAC for different sub-basins have been modified by comparing the computed and observed flows, so as to match the flows as closely as possible. Finally the SWFAC has been considered as 1.2 while the BSFAC varies from 0.8 to 1. Further, the adjustments have been made in the surface water efficiency so that the computed and available average annual irrigation demands from different projects are comparable.

The observed and the simulated flows at the 16 gauging sites are plotted in Figure – 4.4 (a – o). It needs to be mentioned that operation of the Ujjani dam (last or terminal structure in the basin) is not simulated as its command area (which lies outside of the study area) and consequent irrigation demands and withdrawals cannot be simulated. It needs to be mentioned that in most cases at gauging sites, values are available only in very few months while they have been plotted as continuous charts.

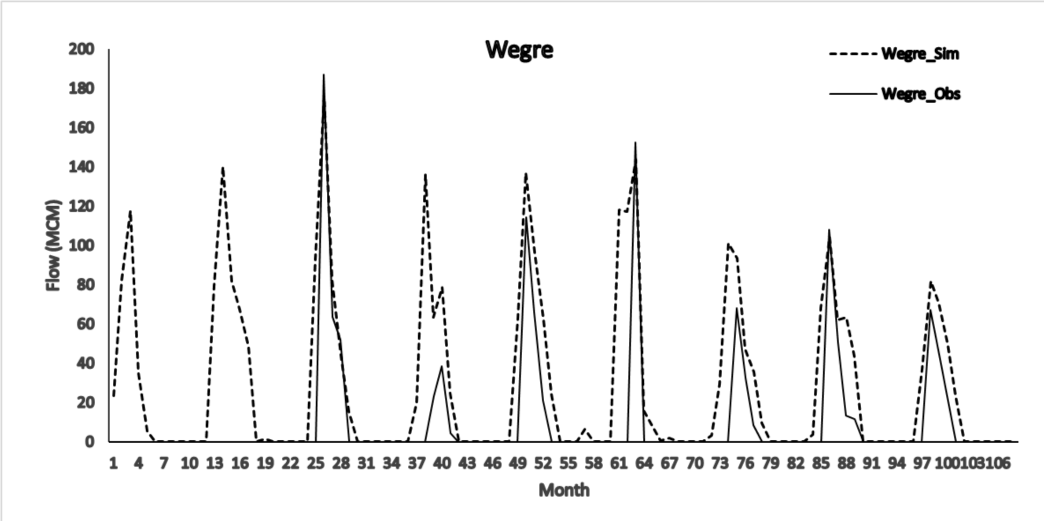


Figure – 4.4a: Observed and computed monthly flows (MCM) at Wegre

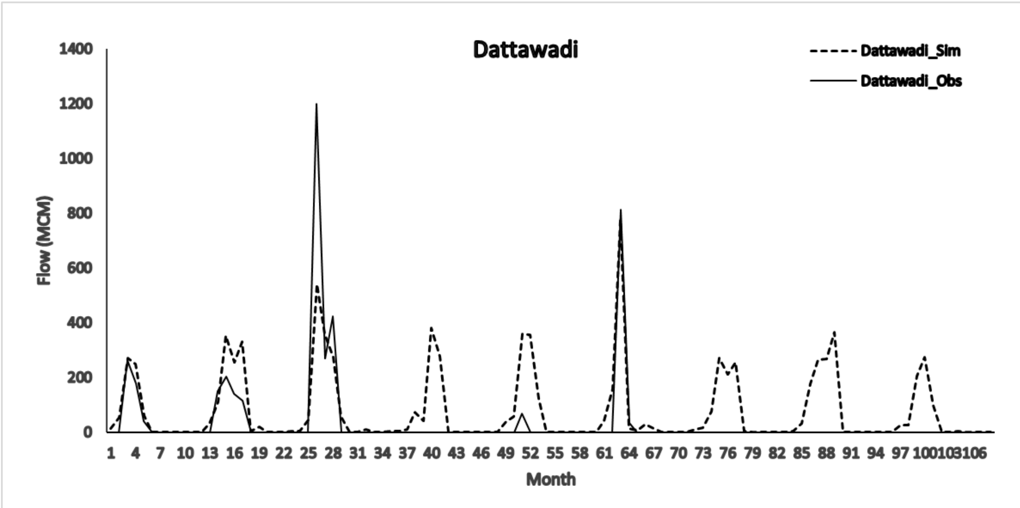


Figure – 4.4b: Observed and computed monthly flows (MCM) at Dattawadi

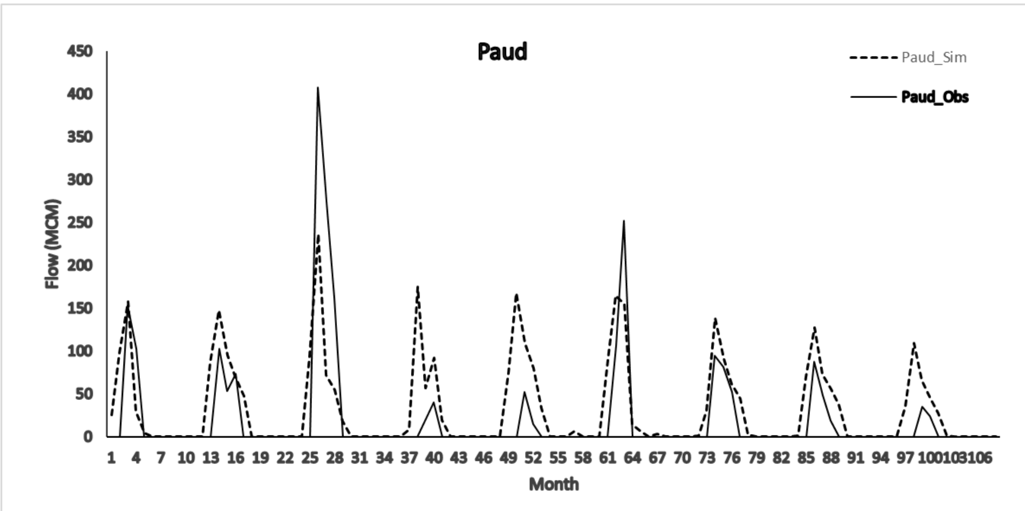


Figure – 4.4c: Observed and computed monthly flows (MCM) at Paud

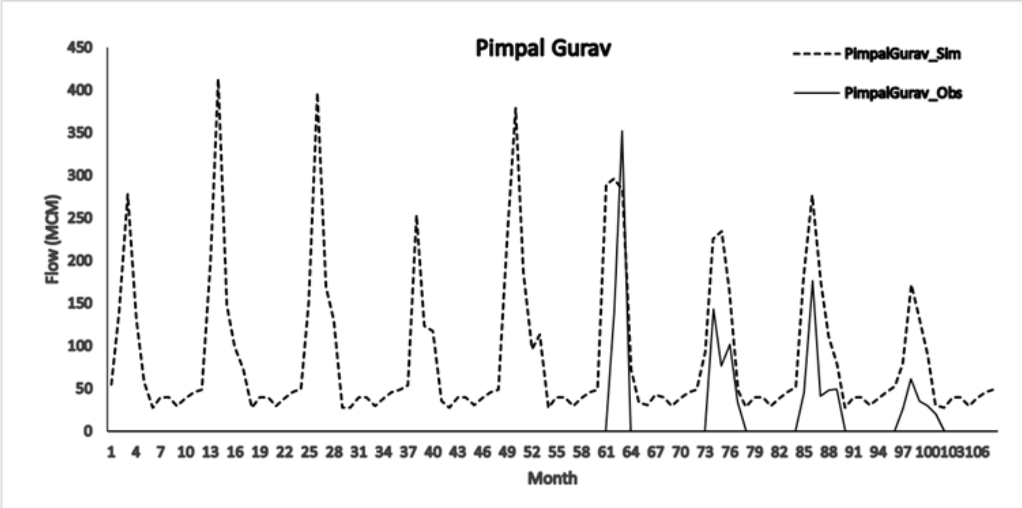
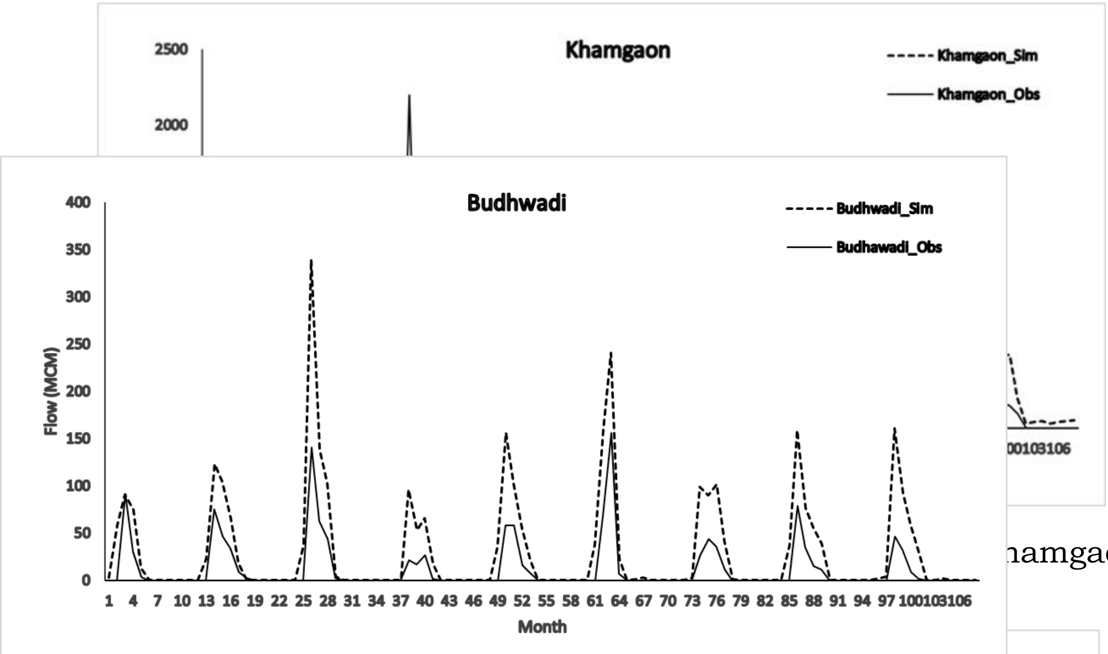


Figure – 4.4d: Observed & computed monthly flows (MCM) at Pimpal Gurav



hamgaon

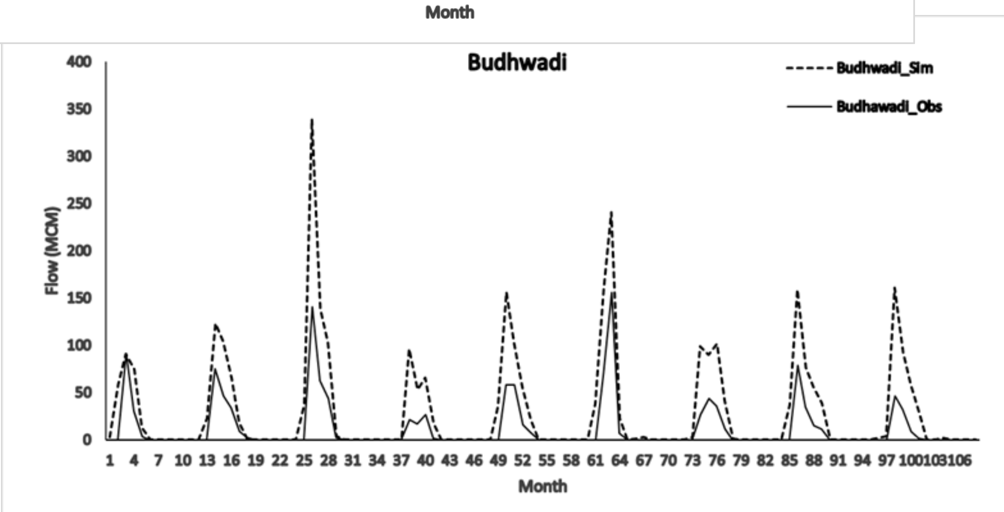


Figure – 4.4f: Observed & computed monthly flows (MCM) at Budhwadi

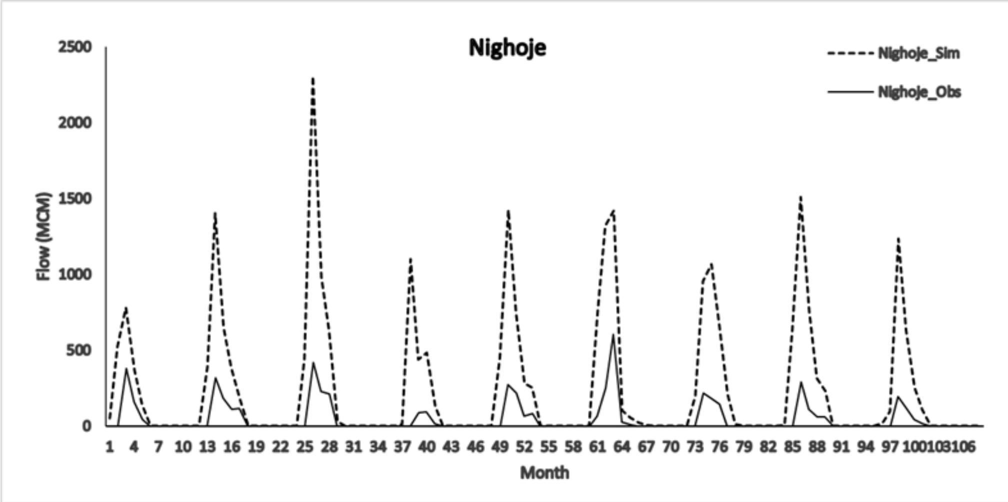


Figure – 4.4g: Observed & computed monthly flows (MCM) at Nighoje

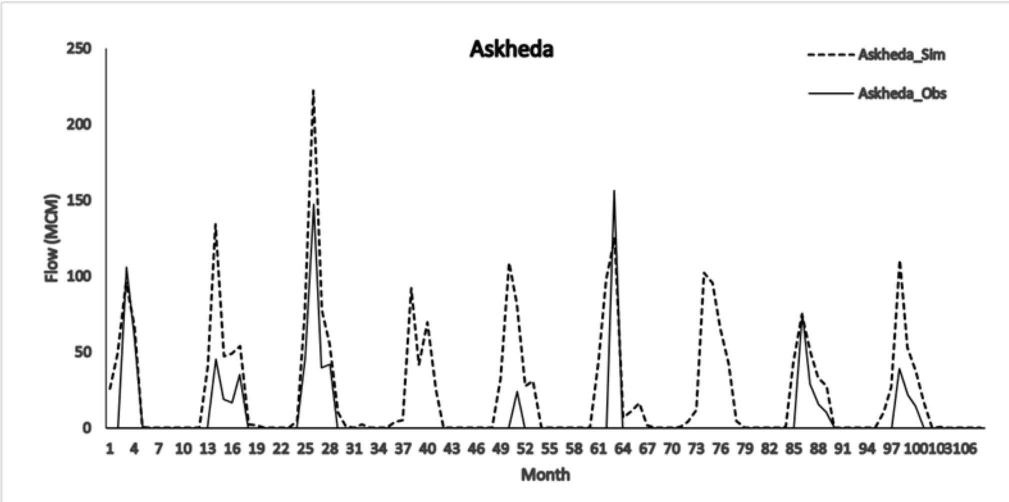


Figure – 4.4h: Observed & computed monthly flows (MCM) at Askheda

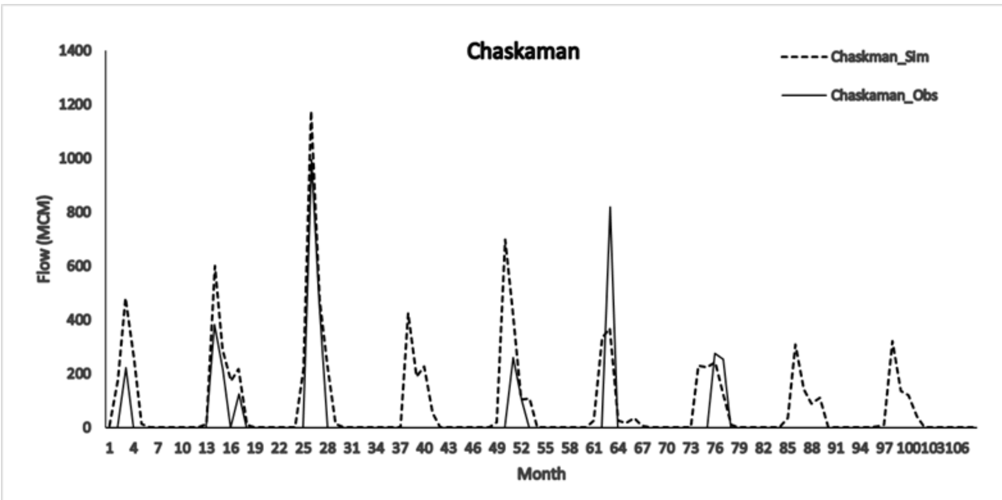


Figure – 4.4i: Observed & computed monthly flows (MCM) at Chaskaman

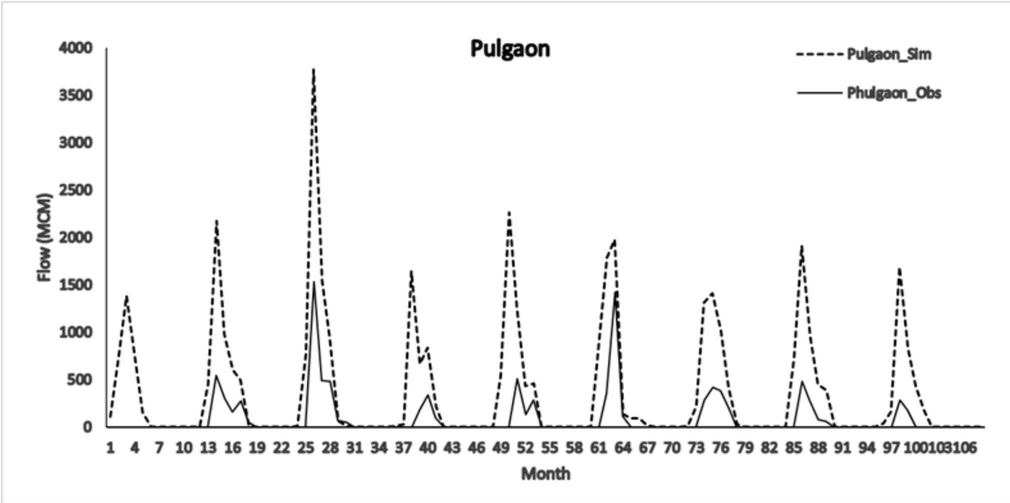


Figure – 4.4j: Observed & computed monthly flows (MCM) at Pulgaon

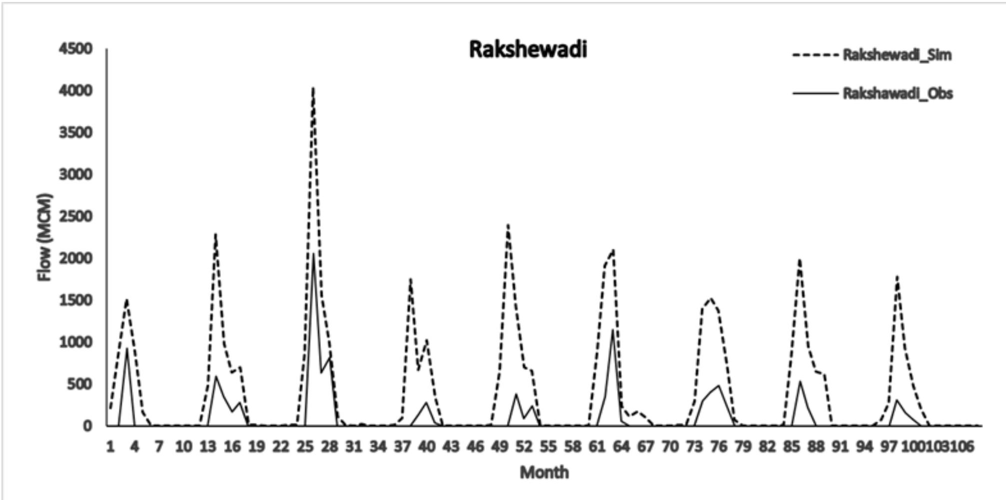


Figure – 4.4k: Observed & computed monthly flow (MCM) at Rakshewadi

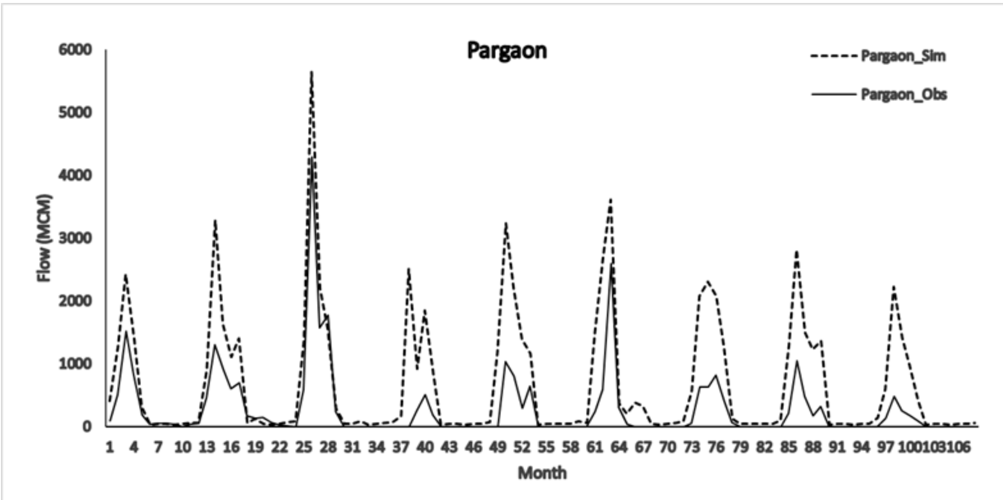


Figure – 4.4L: Observed & computed monthly flow (MCM) at Pargaon

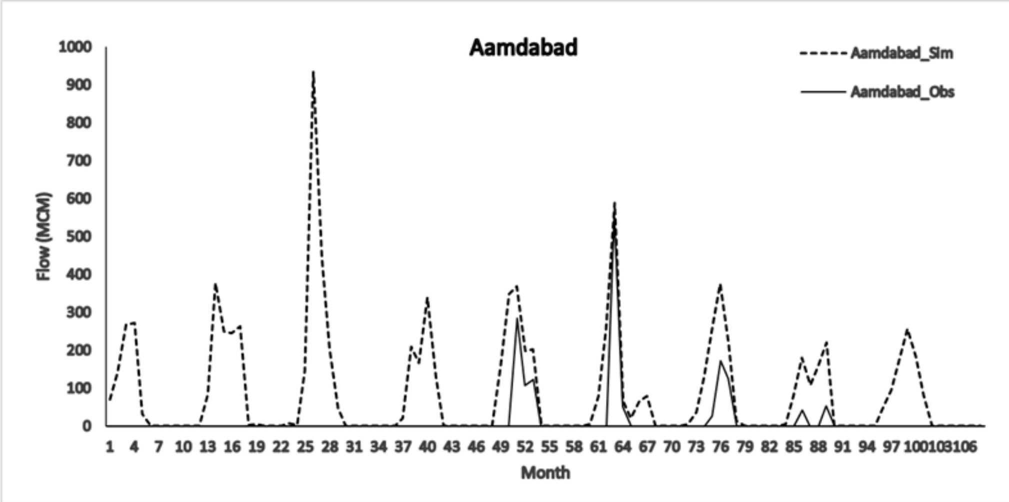


Figure – 4.4m: Observed & computed monthly flows (MCM) at Amdabad

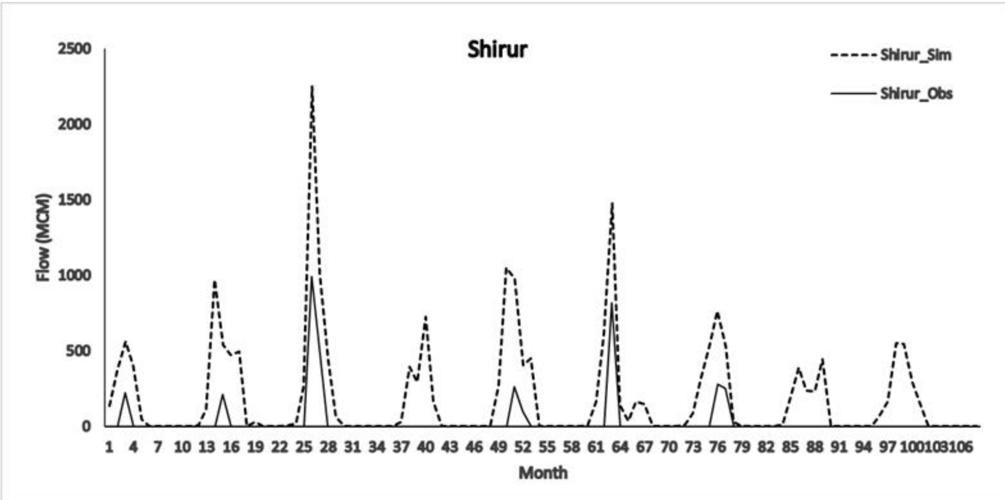


Figure – 4.4n: Observed & computed monthly flows (MCM) at Shirur

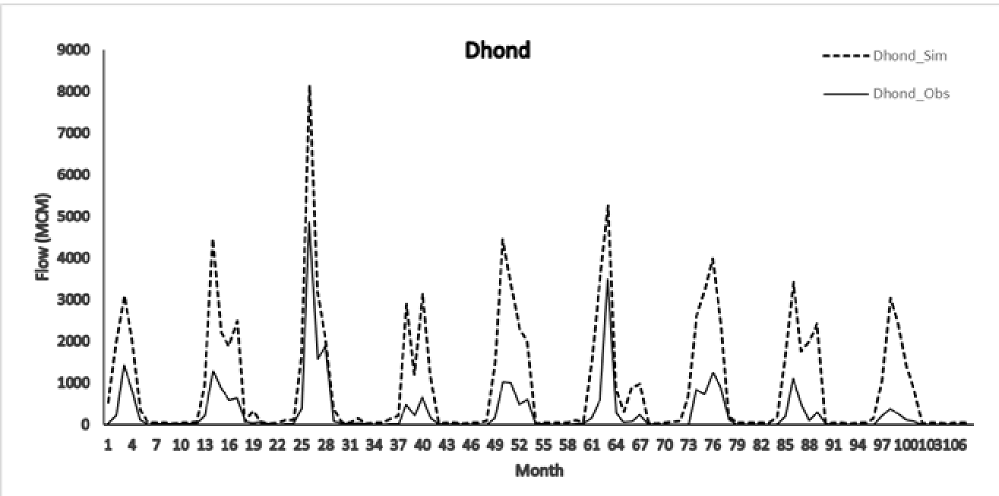


Figure – 4.4o: Observed & computed monthly flows (MCM) at Dhond

In addition, the irrigation demands in different command areas of projects with major irrigation requirements have been aggregated from daily to monthly to annual time steps and average annual irrigation demands have been worked out and compared with the average annual irrigation demands from the projects. The comparison is shown in Table – 4.5.

Table – 4.5
Comparison of observed & simulated average annual irrigation demands

Reservoir	Computed annual irrigation demands (MCM)	Observed annual irrigation demands (MCM)
Yedgaon	221.090	245.000
Wadaj	43.034	37.000
Dimbhe	240.082	226.000
Chaskaman	81.906	70.000
Khadakwasla	730.119	625.000
Ghod	215.160	177.000
Visapur	19.194	12.000

4.4 Discussion of Results

Graphical representation of observed and simulated flows at different gauging sites suggest that though there are some close match of observed and simulated flows in different years, yet in general, generated flows exceed the observed flows in most of the instances. Some of the reasons that can be attributed for this behavior could be as follows:

a) There is very high rainfall just close to the ridge which sharply reduces towards the east. In the present case, thiessen polygon of rainfall stations have been considered and any grid within a polygon gets the same rainfall as at the station. Though it is virtually not possible or practicable to use spatially distributed rainfall map at daily time step, the problem may get reduced if gridded rainfall data of IMD at 0.25 degree is used rather than the thiessen polygon map. Difference in the results need to be invested with the two approaches.
b) At present, the model assumes linear variation of area and capacity between MDDl and FRL. Since the shape is non-linear (may be parabolic), this assumption results in decreased capacity causing greater spill from the projects and consequently greater flows in the downstream. There is an urgent need to modify the model so as to consider actual elevation-area-capacity table of the reservoirs.

c) There are a number of pick-up weirs in the Maharashtra State downstream of the projects and releases from the projects are diverted through these weirs for various purposes. In the present model, though a factor (BSFAC) has been incorporated to take care of the unknown withdrawals in the basin, the extent of these withdrawals through these pick-up weirs may affect the computation of flows at the downstream locations.
d) In the present study, the sub-basins have been marked according to the location of the gauging stations which are mostly located in the downstream of the reservoirs. Actual releases from reservoirs affect the observed flows at these gauging sites. On the contrary, the model releases the water to the downstream only when the reservoir level exceeds FRL. To sort this problem out, it is felt that reservoir locations should also be treated as gauging points for sub-basin delineation.

In addition there are some limitations of the present application and some assumptions made which are discussed in the next section.

4.5 Assumptions and Limitations of the Study

In the present study, spatially distributed basin simulation model has been applied to the Upper Bhima River Basin. Some assumptions and limitations of the present study are:

a) In the present study crop map was not available. Rather, cropping pattern in the study area were obtained from State Govt. report. Approximate crop map was generated by developing a small program based on the available information. Now, crop information affects the irrigation demands, which in turn affect the reservoir operation and hence the computation of flows and groundwater withdrawals.
b) The groundwater was also not adequately represented in the model. Based on the observation from a few wells in the study area, the average GW depth of 8 m was used. Further, using a specific yield of 0.02 (specified for the area) and average average water table variation of 4 – 6 m, GW potential of 600 cubic meter per day per grid was used. Groundwater table was not revised for each month (requiring GW simulation using MODFLO), which becomes a very cumbersome exercise at the scale of river basin. It is suggested that a simpler approach for GW utilization for river basin planning and management should be adopted.

c) Some of the reservoirs in the present system have significant hydropower utilization while it is not simulated in the present model. There is a strong need to incorporate the hydropower simulation in the model. Further, the spill from the Pawana reservoir is sent out-of-basin. Further, the water is sent out-of-basin from the Shirawta, Walwhan, Andhra, and Mulshi projects. There is no provision to consider actual out-of-basin transfer though weekly import/export option is available. Therefore, average weekly out-of-basin diversions have been worked out and specified as export. There should be option in the model to consider actual time series data of demands and withdrawals from the projects, if they are available.
d) Since hydropower release from Pawana dam is in-basin, average weekly values have been worked out and specified as environmental flows because hydropower release are non-consumptive in nature.
e) There may be significant industrial demands from projects but they could not be considered because of no model provision. Provision for industrial demands should be added in the model.
f) Domestic demands computation need to be revised in the model. As per present approach, urban demands in a district are uniformly distributed in various city grids. In the present study, Pune is a large city with considerable population while the population of other cities may not be so dense. Option should be added in the model to specify the population of individual city.

With these limitation and assumptions, the model has reasonably simulated the flows at different gauging stations. Further modification to the application can be carried out considering the following aspects:

a) Use of gridded IMD rainfall rather than thiessen polygon.
b) Use of cropping map from NRSC in different project commands.
c) More accurate representation of GW conditions at sub-basin scale.
d) Revision of sub-basins to include reservoirs with gauging sites.
e) Use of industrial demands and city population

4.6 Suggestions for modification in the existing distributed model

In view of the experience gained from the application of distributed basin model for the Upper Bhima basin, some modification are suggested in the existing model to make it more robust and useful. These are discussed below.

a) Specification of EAC tables or corresponding relationships for various storage structures,
b) Rule-curve based operation of reservoirs so that different operation and management policies of the system can be simulated,
c) Option of hydropower simulation of reservoirs in the basin,
d) Simplified representation of groundwater computation at the basin scale as groundwater modeling aspects at the scale of river basins are a difficult task.
e) At present, the model is run for each month after transferring the storage in reservoirs and soil moisture from previous months. This is done mainly to estimate the revised groundwater conditions at the end of a month corresponding to grid-wise pumping and recharge. This becomes a very cumbersome exercise. There should be option of continuous simulation of the system for the entire period with simplified representation of groundwater.
f) Specification of out-of-basin transfer of any release from reservoirs.
g) Option to specify city population to individual cities rather than uniformly distributing the urban population to different city grids. Further in continuous simulation, the city population growth at specified rates and corresponding demands should be considered.
h) Option to specify the industrial demands and their variation with time along with withdrawals and discharge sources.
i) During the period of simulation, different projects may come up at different times. Options may be made in the continuous simulation to invoke the projects as and when they are operationalized.
j) Groundwater potential growth with time need to be simulated.
k) There may be option to specify the available information of demands/ withdrawals for different purposes from the reservoirs. At present, demands are estimated and known demands are not considered.
l) The model should be developed in a WINDOWS interface for data file preparation and its application. Further, the free-domain ILWIS software can also be linked with the interface.
m) Limitations on the number of land uses, soil types, rainfall stations, ET stations, and hydraulic structures need to be enhanced for its application to large river basins.

* * *

Chapter – 5
CONCLUSION

A conceptual spatially distributed water balance model, developed earlier at NIH, has been applied to the Upper Bhima basin in Maharashtra State. Various types of spatial, attribute, and dynamic data are integrated by the model to perform the water balance analysis and to simulate various components of hydrologic cycle such as rainfall, actual evapo-transpiration, runoff, groundwater recharge, soil moisture change etc. for various land uses and soil types in different sub-basins of a river basin. 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. Using this model, various scenarios of water availability in a river basin can be generated and analyzed. By taking repeated runs of the model for longer time periods, sustainability of various water resources management plans can be examined.

It is aim of the application to get insight into the development of the distributed model and its application in different river basins so that it can act as a decision support tool for river basin authorities in evaluating the water resources of a river basin. Through this experience, different modification requirements in the developed model can be identified to make it more robust and useful.

Spatial, attribute, and dynamic data for the study area have been collected. Sixteen 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. Maharashtra Irrigation Commission data has been used to get the cropping pattern and population related information in the study area. India WRIS data has been used for delineating command boundaries of different projects. Landsat TM data of the basin has been used for locating extent of various reservoirs in the basin. Attribute data of crops, soils, gauging sites, various hydraulic structures etc. have been obtained from a variety of sources. Dynamic data of rainfall from 1992-93 to 2000-01 has been obtained from CWC, IMD and Maharashtra State department. The model results for different sub-basins of Upper Bhima basin up to Ujjani dam have been presented.

There are some assumptions and limitations of the study but the model has reasonably simulated the flows at different gauging stations. Some modifications to the application can be carried out considering mainly the use of gridded IMD rainfall rather than thiessen polygon, use of cropping map from NRSC in project commands, accurate representation of GW conditions at sub-basin scale, revision of sub-basins to include reservoirs with gauging sites, and use of industrial demands and city population.

In view of the experience gained from the application of distributed basin model for the Upper Bhima basin, some modifications are suggested in the existing model, some of which include: a) specification of EAC tables for storage structures, b) rule-curve based operation of reservoirs, c) option of hydropower simulation of reservoirs, d) simplified representation of groundwater computation at the basin scale, e) continuous mode of simulation for the entire period considering domestic, industrial growth and increasing groundwater potential, and f) development of WINDOWS interface for easy application of the model.

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REFERENCES

DHI (August 2004). *"MIKE BASIN"*, http://www.dhisoftware.com/mikebasin

Goel, M. K., Jain, S. K., Kumar, Vijay, Sharma, Anupama, and Agarwal, P. K. (2008), "*Holistic evaluation of a representative link – Development of a water availability and simulation model*", NIH report (under printing), National Institute of Hydrology, Roorkee.

ITC. (2007). "*ILWIS Open*", 52 North, International Institute for Aerospace Survey and Earth Sciences, Enschede, The Netherlands.

Landsat data downloaded from internet site www.glcf.umiacs.umd.edu/data

SRTM digital elevation data downloaded from internet site www.srtm.csi.cgiar.org/

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