Holistic Evaluation of a Representative Link – Development of a Water Availability & Simulation Model

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November, 2008

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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.

In the present approach of water availability estimation in a river basin, it is very difficult to account for the effect of land use change and climate change on the water resources scenario. Water requirement for different purposes (nature, food, and people) is not precisely estimated. Discharge is considered as the basic unit for water availability estimations which may be affected by a number of basin parameters and variables such as population, industrialization, change in the irrigated areas, improvement in irrigation efficiencies, availability and development of groundwater, change in land use (increase/ decrease in forest area, urban land, barren land etc.), change in the climate of the region (increase/decrease in temperature, precipitation etc.), construction of hydraulic structures etc. Therefore, a need was felt to develop a detailed model to assess the available water resources in a river basin and to estimate the demands for various purposes.

A conceptual spatially distributed water balance model has been developed to simulate various components of the hydrologic cycle at the scale of a river basin. Various types of spatial, attribute, and dynamic data are integrated by the model to perform the water balance analysis of a basin. Spatially distributed information include land-use map, crop map, soil map, Thiessen polygon map of rainfall and ET stations, district boundary map, map showing major cities in the basin, digital elevation map, slope map, flow direction map, groundwater depth map, river network map, storage/diversion structure map, irrigation source map, initial moisture map, and aquifer characteristics (storage coefficient and transmissivity) maps. Attribute information contains the properties and general information about to different types of crops, soils, hydraulic structures, river network, gauging sites, and domestic demand standards in the basin. Dynamic

information of the basin include daily rainfall and reference evapo-transpiration at different observation stations, observed monthly water flows at various gauging sites and groundwater levels in different observation wells in the basin.

The model computes various components of hydrologic cycle such as rainfall, 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. Further, 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/change in the design of existing projects, v) change in population and corresponding D&I demands on the basin water resources can be analyzed with the model.

The model has been applied to the Tapi basin up to Ukai dam. Extensive database has been generated for the basin and model runs have been taken from June 1992 to May 1996. Basin data has been used to check the model linkages. Various outputs of the model for the Tapi basin have been discussed in detail.

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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 interrelated 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 any 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

Remote sensing observations and spatial database can be integrated with mathematical models to analyze a variety of strategies for planning and management of river basins. A geo-simulation model uses geographically referenced data to enable different scenarios to be simulated. The objective of present study is to develop a generalized geo-simulation model for analyzing the water resources of a river basin. While developing the model, the aims are:

a) to integrate the spatial (topography, land use/land cover, cropping pattern, soil type, rainfall distribution, drainage network, irrigated/rainfed areas, water resources structures etc.) and temporal (rainfall, potential evapo-transpiration etc.) information with a basin-scale simulation model;
b) to integrate various processes of river basin planning such as runoff generation, estimation of various demands (agriculture, domestic and industrial), evapo-transpiration estimation from different land surfaces, soil moisture accounting, flow accumulation in the river network, groundwater recharge, operation of the reservoirs for domestic, irrigation, and minimum flow demands, and prediction of groundwater table;
c) to consider system details necessary for realistic analysis;
d) to develop a generalized and computationally efficient model that can be used for any river basin;
e) to be able to use the data generally available for Indian River basins;
f) to display the results in form of maps and tables for easy visualization, thereby allowing the river basin authority and the users to participate in the decision-making process.

It is envisaged that the developed model may act as a decision support tool for river basin authorities in evaluating the water resources of a river basin. 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. At present, only quantity aspect is considered for developing the linkages. Water quality can be incorporated in the subsequent stages of development.

After the development of distributed model, it is envisaged to test the model with the data of Tapi River basin. Database for the basin would be gathered from different sources and entered in the GIS system for model application. Various checks on the model output would be implemented and model results would be compared with the observed values at different gauging sites in the basin for few years of available record.

* * *

Chapter – 2
MODEL DESCRIPTION

2.1 General

Water being a precious, but limited, resource poses the question of how to best allocate the available resource to all the competing users efficiently and effectively. An integrated river basin planning and management approach (IRBPM) enables us to have knowledge in space and time of what water is needed for, where, and in what amount, thereby allowing for balancing out between the competing needs. Design of multi-dimensional, multi-objective water resources projects require formulation of sound water policies. Integrated planning and management may be the most promising means to provide the water requirements of all competing users. Through integrated approach, viable water policies compromising all stakeholders or satisfying all objectives can be formulated.

For integrated planning and management, first requirement is to simplify the problem and transform it into analytical form. Water policies need to be transformed into such forms that can be "understood" and "interpreted" using analytical tools such as computer models. Consequently, computer models are required that can accept different water policies in analytical or mathematical form to analyze various scenarios of water demands and allocation so as to best utilize the available resources. Over the past few decades, water resources professionals have witnessed the development of quite a number of water systems simulation models.

Wurbs (1995) points out that a tremendous amount of work has been accomplished during the past three decades in developing computer models for use in water resources planning and management. The majority of these models are simulation models. Simulation is the process of experimenting with a model to analyze the performance of the system under varying conditions. Simulation models approximate the behavior of the system with predefined operation rules. Alternative runs of a simulation model are made to evaluate various developmental and operational plans. Simulation models provide higher flexibility in detailed and realistic representation of complex systems. Concepts inherent in simulation approach are easier to understand and communicate than other modeling concepts (Simonovic, 1992).

2.2 Review of some IRBPM Models

Computer models for integrated water resources planning and management can be very important tools that are helpful for fast computations, easy data management and drawing conclusions about alternative water policies. As computing speed and ease is becoming more powerful, more complex yet more comprehensive computer models are being developed. Such computer models as MODSIM, RIBASIM, AQUATOOL, TERRA, MIKE BASIN, RiverWare, WaterWare, and BHIWA etc. have been used as Decision Support System (DSS) for integrated river basin planning and management. A DSS as an interactive computer-based support system that helps decision makers utilize data and models to solve unstructured problems. A brief description of these models is presented here:

2.2.1 MODSIM DSS

This DSS is widely referred for conjunctive management of water resources under the prior appropriation water right (Fredericks et al., 1998) which requires that water first be delivered by decree to senior (in time) water-right holders without regard to location on the river. It is designed as a computer-aided tool for developing improved basin-wise and regional strategies for river administration, drought contingency planning, evaluating groundwater exchange programs, managing recharge and augmentation projects and resolving conflicts between urban, agricultural and environmental concerns. It is constructed around the generalized river basin network flow model (MODSIM), providing an open architecture allowing access to input and output databases and modifications and verification at all levels of the modeling process. It operates under MS Windows, although an X-Window version under UNIX is also available.

It has three components: database management system, model base management system, and a user interface. The graphical user interface provides spatially referenced database capabilities whereby the user can create and link river-basin network objects on the screen and populate and import data for that object interactively. GIS tools are used to prepare grid-based spatial data for input into MODRSP, a modified version of the U.S. Geological Survey (USGS) three-dimensional finite-difference ground water model MODFLOW. All of the major input data files required for executing MODFLOW/MODRSP are prepared using GIS and database management techniques. The abilities to transfer vector based hydrography data from

USGS digital databases, rasterize or grid the data using GIS software, and overlay the results with other aquifer data to prepare a file directly readable by MODFLOW provide powerful computational tools.

A variety of menus are available to load and save a MODSIM network, run the model, import and export data, select and display graphs; create, edit and generate tabular reports; and access various utilities. The interface contains tools for creating nodes and links in the network, moving and deleting objects, annotating the network, merging/splitting the display of multiple links between nodes, generating graphical plot of data associated with objects. Once the system network is created and database prepared, the MODSIM model can be executed from the interface. An extensive variety of graphical and text output options are available for any combination of network objects and output data types. A scripting language for MODSIM DSS (SIMARGS) allows the users to develop customized output reports, graphical plots and color-coded graphical displays.

2.2.2 TERRA DSS

TERRA (TVA Environment and River Resource Aid) is a DSS developed for the Tennessee Valley Authority (TVA) and the Electric Power Research Institute (EPRI) (Reitsma, et al., 1996). It was developed for the management of TVA river, reservoir and power resources. TERRA has the following characteristics:

1. consists of geo-relational data base;
2. serves as the central data-storage and retrieval system;
3. records the TERRA information flow;
4. supports interfacing specialized data management software;
5. has various visualization tools; and
6. checks the data entering the database or data from both resident and non-resident models against various sets of operational constraints (environmental, recreational, special/emergency, navigational etc.)

TERRA consists of three components of a DSS: 1) management of state information of TVA river basin, 2) models for conducting simulations and optimizations, and 3) a comprehensive set of reporting and visualization tools for studying, analyzing and evaluating current and forecast states of the river system.

2.2.3 RIVER WARE

Developed by the Center for Advanced Decision Support for Water and Environmental Systems (CADSWES) at the University of Colorado, this DSS is designed for a general river basin modeling for wide range of applications (Zagona, 1998). It has three fundamental solution methods: simple simulation, rule-based simulation and optimization. To abate the problems of complicated water policies, a different programming language (from usual programming languages as FORTRAN and C/C++) called RiverWare Rule Language (RWRL) is used. Policy descriptions can be designed as structured rule sets in RWRL. Once these policy descriptions are saved as rule set files, a simulation may be guided by the rule set. The policies are interpreted during run-time, which makes the running time of the program longer.

General architecture of RiverWare program employs representation of a river basin by objects. The objects that are included in Riverware include the following (Zagona, et al., 1998):

- Storage Reservoir – mass balance, evaporation, bank storage, spill;
- Level Power Reservoir – storage reservoir plus hydropower, energy, tailwater, operating head;
- Sloped Power Reservoir – level power reservoir plus wedge storage for very long reservoirs;
- Pumped Storage Reservoir – level power reservoir plus pumped inflow from another reservoir;
- Reach – routing in a river reach, diversion and return flows;
- Aggregate Reach – many reach objects aggregated to save space;
- Confluence – brings together two inflows to a single outflow as in a river confluence;
- Canal – bi-directional flow in a canal between two reservoirs;
- Diversion – diversion structure with gravity or pumped diversion;
- Water User – depletion and return flow from a user of water;
- Aggregate Water User – multiple water users supplied by a diversion from a reach or reservoir;
- Aggregate Delivery Canal – generates demand and models supplies to off-line water users;
- Groundwater Storage Object – stores water from return flows;
- River Gage – specified flows imposed at a river node;
- Thermal Object – economics of thermal power system and value of hydropower;

- Data Object – user specified data: expression slots or data for policy statements.

2.2.4 AQUATOOL

Developed at the Universidad Politécnica de Valencia (UPV), Spain, AQUATOOL is a generalized DSS that has attracted several river basin agencies in Spain (Andreu, et al., 1996). AQUATOOL has various capabilities that can be used in water resource systems to:

1. screen design alternatives by means of an optimization module, obtaining criteria about the usefulness and performance of future water resource developments;
2. screen operational management alternatives;
3. check and refine the screened alternatives by a simulation module;
4. perform sensitivity analysis by comparing the results after changes in the design or in the operating rules;
5. use different models, once an alternative is implemented, for the operation of water resource system, mainly for water allocation among conflicting demands and to study the impacts of system changes; and
6. perform risk analysis for short and medium term operational management to decide, for instance, the appropriate time to apply restrictions and their extent.

AQUATOOL has been accepted by the Sagura and Tagus river basins agencies in Spain as a standard tool to develop their basin hydrologic plan and to manage the resource efficiently in the short to medium term (Andreu, et al., 1996).

2.2.5 WATER WARE

This DSS is a comprehensive model for integrated river basin planning. It has the capabilities of combining GIS, database technology, modeling techniques, optimization procedures and expert systems (Jamieson and Fedra, 1996). The aspects of integrated river basin management that this DSS incorporates are (Fedra and Jamieson, 1996):

1. Groundwater pollution control: simulation of flow and contaminant transport, and reduction of the level of contaminant in the aquifer and/or protecting groundwater resources.
2. Surface water pollution control: estimation of the level of effluent treatment required to meet the river water quality objectives.

3. Hydrologic processes: estimation of ungaged tributary for use in the water resources planning, assessment of daily water balance for ungaged sub-catchments, impact of land-use changes on runoff; and evaluation of effects of conjunctive use of surface and groundwater.
4. Demand forecasting: Use of rule-based inference models which use generic expert system.
5. Water resources planning component consisting of:
    a) a model capable of simulating the dynamics of demand, supply, reservoir operations and routing through the channel system; and
    b) a module for reservoir site selection which assesses ten problem classes including landscape and archeological or historical sites; land-use restrictions; drainage, soil and microclimate; natural habitats and associated communities; water quality, aquatic biology and ecology; water resources and cost implications; reservoir construction; reservoir operations; socio-economic effects of reservoir operations; and recreational provisions.

2.2.6 BHIWA

Basin-wide Holistic Integrated Water Management (BHIWA) Model is especially developed to provide an integrated computational framework for a basin level assessment of water resources with a view to evaluate water sector polices. The model considers the entire land phase of the hydrologic cycle and is capable of depicting human impacts such as changes in land and water use, as also impacts of water storage and depletion through withdrawals for various water uses and inter-basin water transfers. The model is especially useful for understanding existing as well as future water availability; assessing future water needs under different scenarios, and for analyzing impact of different policy options for an integrated and sustainable development of resources.

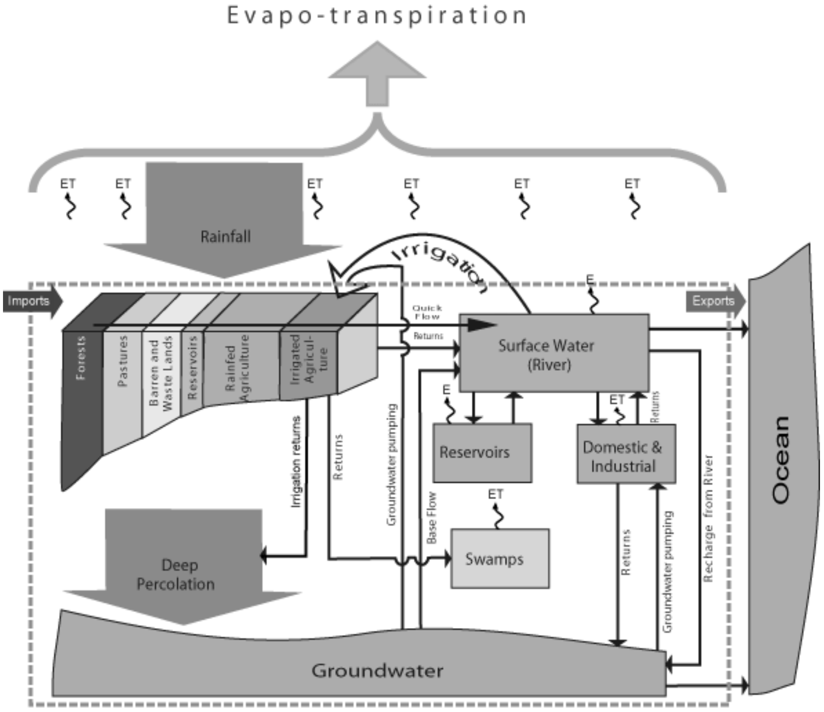
The model can be calibrated using data for past or present conditions for the given basin. Once calibrated, user can simulate and analyze alternate scenarios of future development and management of resources. Scenarios can be developed in terms of changes in land use, crop areas under rainfed and/or irrigated agriculture, cropping patterns, irrigation efficiencies, imports and exports of water, surface (reservoirs) storage, proportion of surface and groundwater withdrawals etc. By simulating past conditions, the model can also help in setting up minimum reference flows for maintenance and enhancement of river ecology and environment. Comparison of such flows with projected future river flows can help in setting limits on surface and ground water withdrawals, including extent of lowering of water tables to meet prescribed "environment flow" demands.

BHIWA is developed in MS EXCEL and has 9 computation modules. A river basin is first divided into hydrologically homogeneous sub-basins and each sub-basin into a number of land parcels each depicting a particular category/sub-category of land use. The model accommodates a maximum of 5 sub-basins and each sub-basin can be divided into a maximum of 25 land parcel types. The hydrologic computations are first performed for each land parcel in terms of water depth in mm over the area and then aggregated in volume units (million cubic meters) at the sub-basin level.

Module-1 calculates water balances for the upper and lower zones, viz. soil profile and groundwater system for each land parcel, given soil moisture holding capacity of the parcel, and areal average of rainfall, and reference evapo-transpiration for the sub-basin. Rainfall is partitioned into actual evapo-transpiration (ET) and excess water. The actual ET is calculated as a function of potential ET and the actual moisture availability. Excess water is further divided into deep percolation (natural recharge to groundwater) and quick runoff from land areas to the river. The quick runoff from all land parcels is aggregated to represent rainfall contribution to the river system. Likewise, natural groundwater recharge under various land categories is lumped representing rainfall contribution to groundwater.

Module-2 computes additional water demands for each irrigated land parcel using data from Module-1 on shortfalls to meet the Potential Evapo-transpiration (PET) requirements and source-wise net and gross irrigation requirements are computed. Module-3 computes the source-wise returns from the irrigation. Module-4 is designed for accounting ET by different use sectors. Module-5 computes the domestic and industrial water withdrawals, use, and returns. Module-6 aggregates all inputs to the river including quick run off, base flow and returns from irrigation, D&I withdrawals and computes balance flow taking into account given values of storage changes and requirements of environmental flow. Modules 7 – 9 are dedicated to groundwater balance computation with input as deep percolation from natural rainfall, return from irrigation and D&I withdrawals and induced recharge from the river. The output components of groundwater system include base flow to river and withdrawals through pumping from ground water reservoir to meet the surface water shortages. In addition to the above modules, there are worksheets to facilitate data inputs, and generation of aggregated results in the form of tables and charts.

The model runs on monthly time step simulating average hydrological year. In the calibration mode, however, a model can be applied either to a single year (good, average or dry) or to a sequence of years (maximum length 5 years). Logical sequence of BHIWA model is depicted in Figure – 2.1.



2.2.7 RIBASIM

RIBASIM (River Basin Simulation Model) is a generic model for analyzing the behavior of river basins under various hydrological conditions. It is a modeling instrument that follows a structured approach for river basin planning and management. The model links the hydrological water inputs at various locations with the specific water-users in the basin. RIBASIM enables the user to evaluate a variety of measures related to infrastructure, operational and demand management. It generates water distribution patterns and provides a basis for detailed water quality and sedimentation analyses in river reaches and reservoirs. It provides a source analysis, giving insight in the water's origin at any location of the basin.

The model has been applied for more than 20 years in a number of countries and in a wide variety of projects. Water management organizations world-wide use it to support their management and planning activities. Large and complex river basins have been modelled and simulated with RIBASIM. Separately modelled sub-basins can be combined into one main-basin. RIBASIM has a link with HYMOS database and modelling system. For detailed water quality process, it can be linked with DELWAQ model.

The model is designed for any analysis which requires the water balance of a basin to be simulated. The resulting water balance provides the basic information on the available quantity of water as well as the composition of the flow at every location and any time in the river basin. The model provides means to prepare such balances in required detail, taking into account drainage from agriculture, discharges from industry and the downstream re-use of water. A number of basin performance parameters are generated for evaluation of the simulated situations. Various hydrologic routing methods are available in RIBASIM e.g. Manning formula, Flow-level relation, 2-layered multi segmented Muskingum formula, Puls method and Laurenson non-linear “lag and route” method. The flow routing is executed on daily basis starting at any selected day for any number of days ahead.

The structure of RIBASIM is based on an integrated framework with a user-friendly, graphical, and GIS-oriented interface. GIS environment is used for the interactive preparation of the basin schematization, the entry of object attribute data and the evaluation of simulation results.

2.2.8 MIKE BASIN

MIKE BASIN is modeling tool for integrated river basin planning and management. It provides basin wide representation of water availability, sector water demands, multi-purpose reservoir operation, transfer/diversion schemes, and possible environmental constraints. It can assist decision makers in identifying a sustainable development of scarce water resources for competing uses, taking into account specified priorities, rural and urban characteristics, and socio-economic constraints. It provides a mathematical representation of the river basin encompassing the configuration of the main rivers and their tributaries, the hydrology of the basin in space and time, existing as well as potential major schemes and their various demands of water. It is structured as a river network model in which the river systems are represented by a network consisting of branches and nodes. Branches represent individual stream sections while the nodes represent confluences, locations where certain water activities may occur, or important locations where model results are required. Model results comprise information on the performance of individual reservoirs and demand schemes as well as the conditions in any part of the river system.

The model is integrated within ArcView GIS. The spatial approach is well-suited for water resources projects, because geographical information available in national resources databases can be utilized directly and also provides basis for display of future water resources developments. The GUI, which links MIKE BASIN with ArcView GIS uses all ArcView GIS functionalities. Basic input to the model consists of time series data of catchment run-off for each branch. Additional input files define reservoir characteristics and operation rules of each reservoir, meteorological time series, and data pertinent to water rights (water supply or irrigation) such as diversion requirements and other information describing return flows.

The natural river system is schematized and represented with a node-branch structure. River inflows are calculated at each node. The flow in a node at the downstream end of a particular branch is a function of flow in the nearest upstream node, runoff from the sub-catchment of upstream branch, and return flow and/or extraction of water taking place at the river node. Water demands are activities which can be incorporated in the model. There are two types of activities - irrigation area and public/industrial water supply. Extraction of water can be for several purposes. Most common are municipal water supply and industrial water supply. If a certain scheme for drawing water has been assigned to a node, attempts are made to do so as long as the water availability permits, and hence transferring only the remaining water to the downstream node. Under water shortage, all available water is extracted, leaving no water flows to downstream reaches. The actual performance of a water right is presented. The model allows defining priorities of river diversions and water extractions (water rights) from multiple reservoir systems as well as priorities for water allocation to multiple usage from individual extraction points.

MIKE BASIN accommodates multi-purpose multiple reservoir systems. The purpose of individual reservoirs is to simulate the performance for specified operating policies using associated rule curves. These define the desired storage volumes, water levels and releases at any time as a function of existing storage volumes, the time of the year, demand for water and possible expected inflows. Operating rules are often defined to include not only storage target levels, but also various storage allocation zones. A conveyance loss (proportional to the delivery through the branch) factor can be specified for each reservoir user. Water demands for the reservoir users are automatically increased according to the losses. Multiple reservoir systems allow for specifying water extraction from several reservoirs to a specific demand scheme in any order of priority.

Simulations can be carried out with any time step without consideration to the time intervals of input data. Model output comprises information on the performance of each individual reservoir and irrigation scheme within the entire simulation period, illustrating the magnitude and frequency of any water shortages. Furthermore, time series of river flow at all nodes are simulated enabling the user to determine the combined impact of selected schemes on river flows.

2.2.9 SWAT

SWAT (Soil and Water Assessment Tool) is a river basin scale model developed to quantify the impact of land management practices in large, complex watersheds. It is a public domain model with WINDOWS interface supported by the USDA Agricultural Research Service at Grassland, Soil and Water Research Laboratory, Texas, USA. Objective of the model is to predict the effects of climate and vegetative changes, reservoir management, groundwater withdrawals, water transfer etc. on the water, sediment, and chemical yields in large river basins. Various components of the model include weather, surface runoff, return flow, percolation, ET, transmission losses, pond and reservoir storage, crop growth and irrigation, groundwater flow, reach routing, nutrient and pesticide loading, water transfer. SWAT uses daily time step and can analyze watersheds and basins of several thousand square km.

SWAT is a spatially distributed model that accounts for differences in soils, land use, crops, topography, weather, etc. Model subdivides large river basins into homogenous parts and then analyzes each part and its interaction with the whole. The model simulates hydrology, pesticide and nutrient cycling, and erosion and sediment transport. Input to the model consists of files, information from databases and information from a GIS interface. More specific information can be entered singly, for each area or for the watershed as a whole. The SWAT hydrology model is based on the water balance equation. A distributed SCS curve number is generated for the computation of overland flow runoff volume, given by the standard SCS runoff equation (USDA, 1986). A soil database is used to obtain information on soil type, texture, depth, and hydrologic classification. Soil profiles can be divided into ten layers. Infiltration is taken as precipitation minus runoff. Infiltration moves into the soil profile where it is routed through the soil layers. A storage routing flow coefficient is used to predict flow through each soil layer, with flow occurring when a layer exceeds field capacity. When water percolates past the bottom layer, it enters the shallow aquifer zone (Arnold and others, 1993). Channel transmission loss and pond/reservoir seepage replenishes the shallow aquifer while the shallow aquifer interacts directly with the stream. Flow to the deep aquifer system is effectively lost and cannot return to the stream. The irrigation algorithm allows irrigation water to be transferred from any reach or reservoir in the watershed. Based on surface runoff calculated using the SCS runoff equation, excess surface runoff not lost to other functions makes its way to the channels where it is routed downstream. Water can be transferred from channels and reservoirs.

Sediment yield used for in-stream transport is determined from the Modified Universal Soil Loss Equation (MUSLE) (Arnold, 1992). For sediment routing in SWAT, deposition calculation is based on fall velocities of various sediment sizes. Rates of channel degradation are determined from Bagnold's (1977) stream power equation. Sediment size is estimated from the primary particle size distribution (Foster and others, 1980) for the soils. Stream power also is accounted for in the sediment routing routine, and is used for calculation of re-entrainment of loose and deposited material in the system until all of the material has been removed.

The SWAT model has interface with GRASS GIS system. The model uses spatially distributed parameters of elevation, land use, soil types, and groundwater table. The interface creates a number of input files for the basin and subbasins, including the subbasin routing structure file. The SWAT-GIS linkage incorporates advanced visualization tools capable of statistical analysis of output data.

2.3 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.

2.3.1 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.

2.3.2 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.

2.3.3 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:

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

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

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

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

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

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

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

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

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

b) Soil water balance module

Soil water balance equation is a mathematical statement of law of conservation of mass as applied to the hydrologic cycle. It states that in a specified period of time, all water entering a specified volume must either go into storage within its boundaries, be consumed therein, or be exported therefrom either on surface or underground. Soil water balance approach allows a basin planner to compute a continuous record of soil moisture, actual evapo-transpiration, ground water recharge, and surface runoff. The storage volume in the basin soil cover provides an effective storage of water in a river basin. The model accounts for the water content in the basin soil cover by simulating the moisture status in the soil at all the grids and on all days of simulation period. Figure-2.2 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.

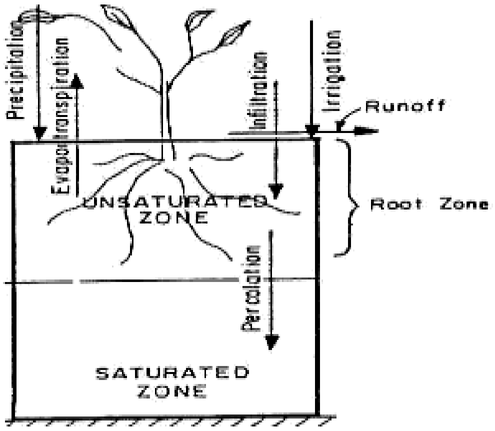


Figure – 2.2: Schematic sketch of soil water balance components

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 – 2.3) of surface area 'A' sq. m and soil depth 'H' meter.

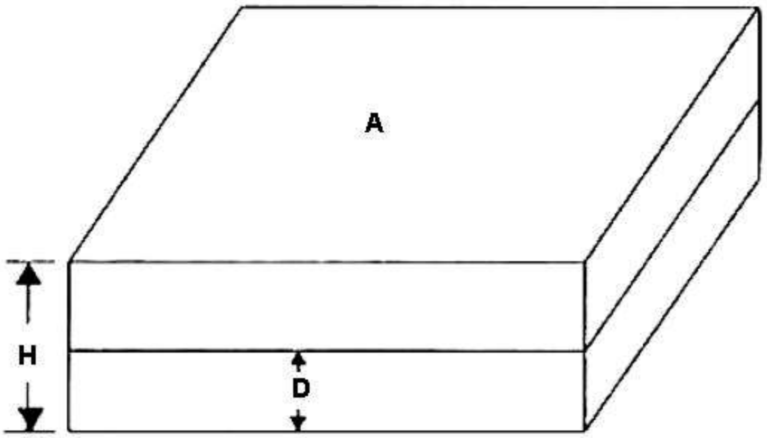


Figure – 2.3: A grid representing soil reservoir

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:

$$\begin{aligned} WDS &= 10 \,.\, w_s .\, G_a \,.\, H \\ &= 10.\frac{W_{water}}{W_{solid}}.\frac{W_{solid}}{V}.H \\ &= 10.\frac{W_{water}}{V}.H \;=\; 10.\frac{V_{water}}{V}.H \\ &= 10.\ \eta.\ H \end{aligned} \qquad ...(2.12)$$

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

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

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

where 'w_{fc}' is soil water content at field capacity and 'w_{pwp}' is water content at permanent wilting point, both expressed as % on dry weight basis.

In addition, upper limit of water depth (UL) is defined to represent maximum water depth that can be stored in a grid before generating overland flow. UL is represented as:

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

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 – 2.4.

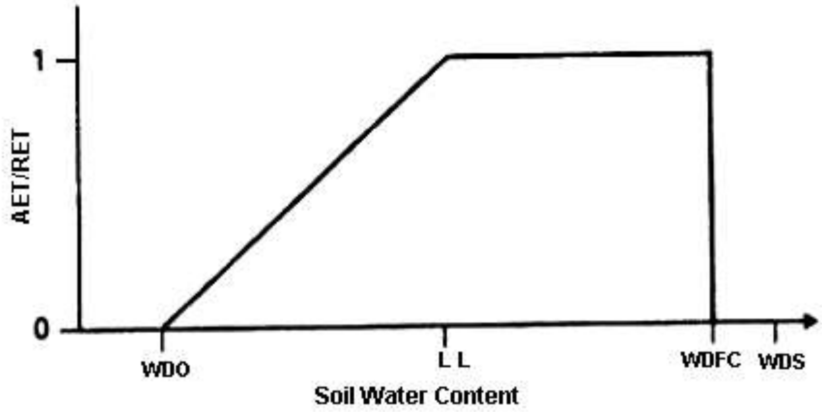


Figure – 2.4: Variation of actual crop evapo-transpiration with soil water content

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 – 2.5.

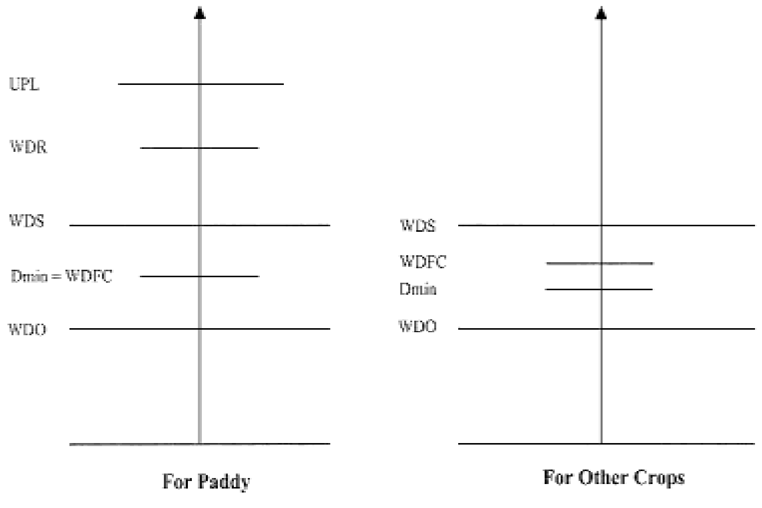


Figure-2.5: Definition sketch of specific equivalent water depths

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:

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

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:

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

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

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

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

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

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

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

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

d) Overland flow movement module

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

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

While moving the flow from higher to lower elevations, if a downstream grid happens to be a water grid (water surface of a reservoir), then the overland flow (converted from depth to volume units) is added to reservoir storage as “Peripheral Flow”. If the downstream grid happens to be a river grid, then 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-2.6.

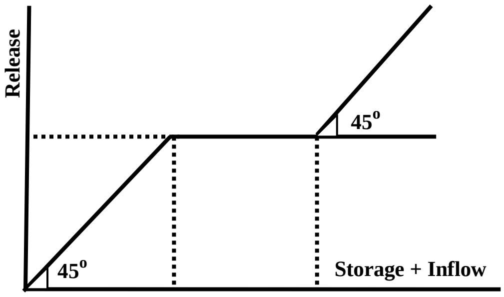


Figure-2.6: Standard linear operating policy

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:

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

where $Stor_t$ is total storage considering only inflows, $Stor_{t-1}$ is initial storage at beginning of tth 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:

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

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:

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

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

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

h) Base flow computation module

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

For a downstream gauging station having upstream gauging site also, the groundwater storage above the bed level in its free catchment area is computed. Next, for each upstream sub-basin, groundwater storage in between 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.

2.3.4 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:

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

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.

2.3.5 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:

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

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

2.3.5 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.

2.3.5 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 TAPI RIVER BASIN

3.1 General

The river basin simulation model developed in this study has been applied to the Tapi River basin to check for its linkages, computational algorithm, and performance analysis. Spatial, attribute, and dynamic data has been collected for the Tapi basin. Fifteen spatial data layers have been generated in ILWIS GIS system using remote sensing analysis and GIS analysis. The basin DEM and other topographic attributes have been obtained from SRTM data. Multi-temporal NOAA AVHRR data (1 km resolution) has been used determining the cropping pattern and delineating the irrigable command areas of different reservoirs. Landsat data of the basin has been used for delineating different 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 of a few years of record was obtained from CWC. Average evapo-transpiration depths have been worked out through CROPWAT model by using the average meteorological parameters.

It needs to be mentioned here that database requirement of the model is quite extensive. Since this study was mainly concerned with the model development and its testing for a river basin, individual efforts have been made by the study team to gather the information for the Tapi basin as accurately. 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 database development for the Tapi basin. After a brief introduction of the Tapi basin, various methods and resources employed to generate various data layers and obtain various attribute data are presented.

3.2 The Tapi River Basin

The Tapi River is the second largest west flowing river of India with its catchment area lying in the States of Madhya Pradesh, Maharashtra and Gujarat States. The river originates in the highlands of the Satpura hills near Multai town in Betul district of Madhya Pradesh and finds its outlet in the Arabian Sea after traversing a total length of 724 km. For first 282 km, the river flows in Madhya Pradesh, for next 228 km, it flows in Maharashtra and for the remaining 214 km, it flows in Gujarat.

The Tapi basin is the northern-most basin of the Deccan Plateau and lies between East Longitude 72° 38' to 78° 17' and North Latitude 20° 05' to 22° 00'. The Satpura range forms its northern boundary, Mahadeo hills form its eastern boundary and the Ajanta and Satmala hills form its southern extremity. Bounded on the three sides by the hill ranges, the Tapi River along with its tributaries flows over the plains of Vidarbha, Khandesh, and Gujarat. The total catchment area of Tapi basin up to its confluence with Arabian Sea is 65,145 sq. km whereas its catchment area up to Ukai dam is 62,225 sq. km. Nearly 80% of the basin lies in State of Maharashtra. An Index map of Tapi basin is presented in Figure – 3.1. The map also shows locations of various projects and gauging sites in the basin.

3.2.1 Main Tributaries of Tapi River

The Tapi River receives several tributaries on both the banks. There are 14 major tributaries having a length more than 50 km. On the right bank, 4 tributaries, namely Waki, Aner (length 94 km, drainage area 1399 sq. km), Arunawati (length 53 km, drainage area 798 sq. km), and Gomai (length 58 km, drainage area 1311 sq. km) have their origin in Satpura ranges and flow generally in South-West direction. They are comparatively of shorter length and individually drain small areas as they descend down the steep slopes of the Satpuras. On the left bank, important tributaries, namely Burai (length 87 km, drainage area 1127 sq. km), Panjhara (length 138 km, drainage area 2849 sq. km), Bori (length 130 km, drainage area 2429 sq. km), Girna (length 265 km, drainage area 10249 sq. km), Waghur (length 96 km, drainage area 2525 sq. km), and Purna (length 274 km, drainage area 18580 sq. km) drain into the main Tapi River. The left bank tributaries rise in Gawaligarh hills, Ajanta hills, the Western Ghats, and the Satmalas. These rivers are of comparatively longer length with fairly large individual drainage areas. Major tributaries of Tapi basin are shown in Figure – 3.2.

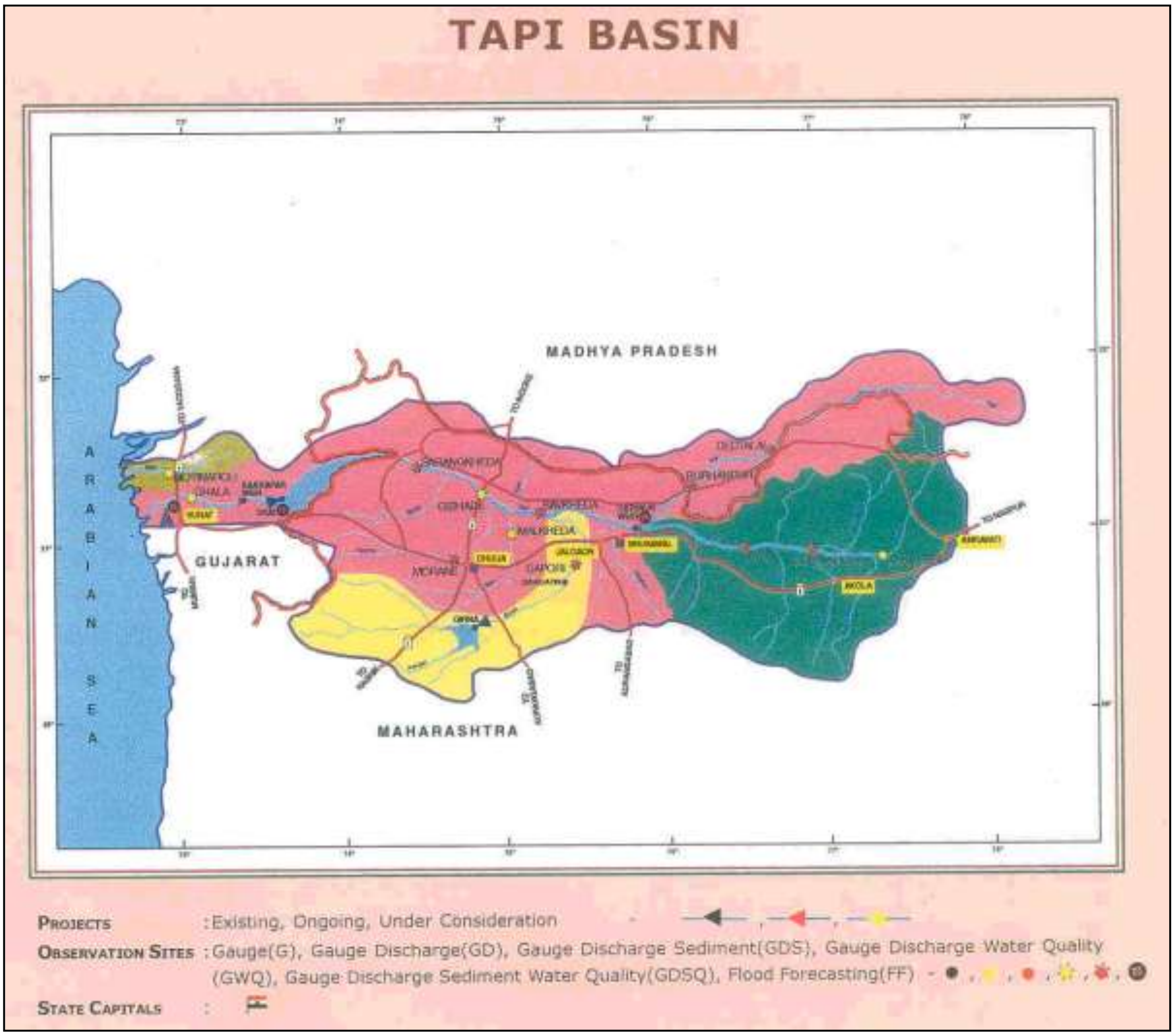


Figure-3.1: Index map of Tapi River Basin

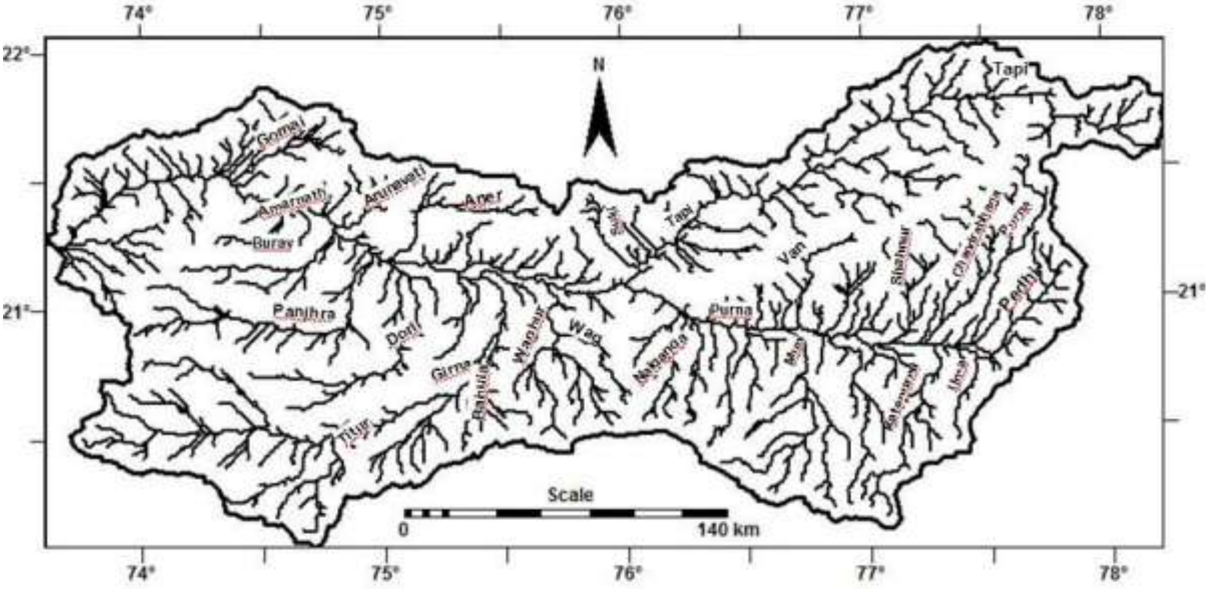


Figure – 3.2: Major tributaries of Tapi River

3.2.2 Topography, Geology, and Soils of Tapi Basin

The Tapi basin is bounded on the north by the Satpura range, on the east by the Mahadeo hills, and on the south by the Ajanta and Satmala ranges. The basin has elongated shape with a maximum length of 587 km from east to west and a maximum width of 210 km from north to south. The Tapi basin has two well-defined physical regions, viz. the hilly regions and the plains. The hilly regions cover the Satpura, the Satmala, the Mahadeo, the Ajanta and the Gawaligarh hills and are well forested. The plains cover Khandesh plains which are broad and fertile areas suitable for cultivation. The shadow map of the Tapi basin showing the basin boundary and the drainage network is shown in Figure – 3.3.

The basin in Madhya Pradesh is mostly covered with Deccan trap lava flows. Other formations found in the basin are alluvium, lower Gondwana, Cuddapah system, Bijawar series, and Granite Gneiss. Most of the area of Tapi basin falling within Maharashtra State is full of cuts & valleys. Lands on the right side of the river lying on southern slopes of Satpura hills consist of black soils. The soil cover is deep and rock is found at greater depths. Lands on the left side of the river on northern slopes of Sahyadri consist mainly of dykes & red murrum soil and are rocky in most part.

The soils in the Tapi basin can be broadly classified into 3 groups, viz. 1) coarse shallow soils, 2) medium black soils, and 3) deep black soils. Coarse shallow soils have developed from the basaltic Deccan traps and have depth generally between 25 to 50 cm and seldom more. Their texture from surface to sub-surface varies from silt-loam to clay. Medium black soils have developed from Deccan traps and cover the largest area of the basin. Their depth is generally between 50 cm to 1 m. Deep black soils are found along the Purna River and in the middle & lower reaches of Tapi River. These soils have originated primarily from decomposition of trap rocks of hilly ranges and their depth varies from 1 to 6 m.

3.2.3 Rainfall and Climate of Tapi Basin

Annual average rainfall in Tapi basin is 830 mm and it is in medium rainfall zone. The south-west monsoon sets in by the middle of June and withdraws by mid-October. About 90% of the total rainfall is received during the monsoon months, of which 50% is received during July and August. There are 70 raingauge stations in/around the basin up to Ukai dam.

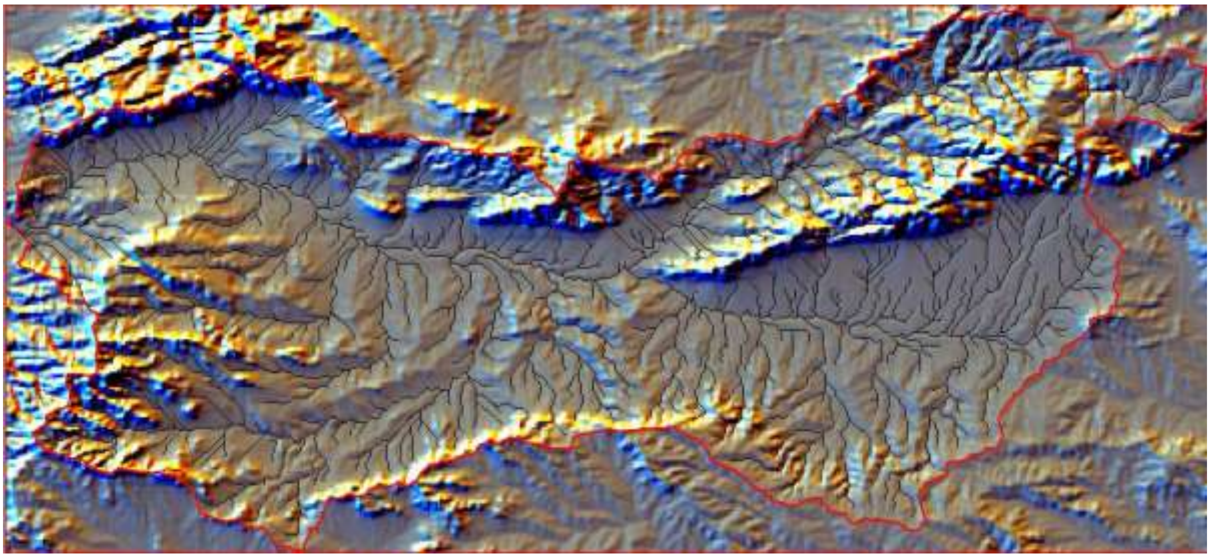


Figure – 3.3: Shadow map of Tapi basin showing the topography & drainage

The climate of the basin is characterized by hot dry summer and winter. Owing to topographical characteristics, the climate is variable. In winter, the minimum temperature varies from 10°C to 14.5°C. May is the hottest month with temperature varying from 38°C to 48°C. The Purna sub-catchment of the Tapi basin is one of the hottest regions of India. Eight IMD observatories at Betul, Amrawati, Akola, Khandwa, Buldhana, Jalgaon, Malegaon and Surat are located in and around the basin.

3.2.4 Land Use, Agriculture, and Population in Tapi Basin

Major part of the land use in Tapi basin is covered by the forests (more than 20%) and the cultivated area (around 60%). The important crops grown in the basin are cotton, jowar, bajra, oilseeds, wheat, paddy, tuar, black gram, fodder crops, vegetable, fruit, and sugarcane. The major land use of the basin in the year 1995-96, derived by proportionately reducing the district-wise statistics in the ratio of the area falling within Tapi basin, is presented in Table – 3.1.

Table – 3.1
Major land uses in Tapi basin in the year 1995-96

Land use category	Area (sq. km)
Forest area	14788.72
Barren/Uncultivable area	2737.97
Non-agricultural area	2002.84
Cultivable waste land	719.21
Permanent pasture	2312.33
Miscellaneous crops/trees	118.43
Fallow land	1781.46
Net sown area	37765.07
Net irrigated area	4335.02

The population of Tapi basin, as per the 1991 census, is 12.576 million of which, the rural population is 9.132 million and the urban population is 3.444 million [NWDA Report (WB-194), 2002]. The basin population in the NWDA report was derived from the district-wise population census of year 1991 on proportionate area basis. The density of population in the year 1991 in Madhya Pradesh, Maharashtra and Gujarat is 128 per sq. km, 250 per sq. km, and 204 per sq. km respectively. The livestock population in basin is 7.0 million which is also estimated on proportionate area basis.

3.2.5 Water Resources Development in Tapi Basin

The utilizable water of Tapi River at Ukai dam has been estimated by Central Water Commission (CWC) to be 14500 MCM (Million Cubic Meter). According to the agreements among different states constituting the Tapi basin, upstream utilization by riparian States of Maharashtra and Madhya Pradesh will be 5420 MCM and 1980 MCM respectively. There is no import of water to the Tapi basin. However, water is exported from the Lower Tapi basin (from Ukai dam and Kakrapar weir). In the proposed Par-Tapi-Narmada interlinking scheme, it is planned to transfer 1554 MCM from the Ukai dam for meeting the demands in water deficit areas in North Gujarat.

There are 12 G&D sites maintained by CWC in Tapi basin, viz. Dedtalai, Burhanpur, Lakhpuri, Gopalkheda, Yerli, Dapuri, Savkheda, Malkheda, Morane, Gidhade & Sarangkheda located upstream of Ukai dam and Ghala G&D site located downstream of the Ukai dam. Kathor G & D site, located downstream of Ghala is maintained by Government of Gujarat.

There are 5 major, 27 medium and 364 minor irrigation projects in the basin with annual irrigation of 3,57,959 ha utilizing 2717 MCM of water. Most of these projects are located in Maharashtra. Construction of 3 major, 24 medium and 123 minor projects is going on in the basin while 3 major, 4 medium and 197 minor projects are proposed to be constructed in future in the Tapi basin. Hathnur dam, Kakrapar weir, Ukai dam, Girna dam, and Dahigaon weir are some of the important hydraulic structures in the Tapi basin. Important existing major and medium hydraulic structures along with their capacities are presented in Table - 3.2. Information about these projects have been drawn from the Hydrological Year Book of the Tapi Basin (1998-99), published by the CWC. Information about the on-going major, medium and minor projects is obtained from the Annexure – 6.4 of the NWDA (2002) report. A district-wise list of on-going projects in the Tapi basin along with their design utilisation is presented in Table – 3.3.

Table – 3.2
Major/Medium existing projects in Tapi basin

Name of project	River	Status	Gross storage (MCM)	Live storage (MCM)	Utilisation
Upper Tapi Basin (up to Hathnur Dam)					
Sonkhedi Tank	Local Nala	Medium	5.45	4.59	Irrigation
Chandora	Tapi	Medium	18.2	16.48	Irrigation
Kate Purna	Kate Purna	Major	97.67	86.35	Irrigation/Domestic
Nal ganga	Nal ganga	Major	76.2	69.32	Irrigation/Domestic
Uma	Uma	Medium	14	11.68	Irrigation/Domestic
Nirguna	Nirguna	Medium	32.29	28.85	Irrigation/Domestic
Morna	Morna	Medium	44.74	41.46	Irrigation/Domestic
Gyan ganga	Gyan ganga	Medium	36.26	33.93	Irrigation/Domestic
Mos	Mos	Medium	17.5	15.14	Irrigation/Domestic
Paltag	Vishv ganga	Medium	9.09	7.51	Irrigation/Domestic
Man	Man	Medium	39.76	36.83	Irrigation/Domestic
Thoran	Tributary of Purna	Medium	8.48	7.9	Irrigation/Domestic
Hathnur	Tapi	Medium	388	255	Irrigation
Middle Tapi Basin (up to Gidhade Gauging Site)					
Girna	Girna	Medium	608.45	523.55	Irrigation
Dahigaon	Girna	Medium	-	-	Irrigation
Manyad	Manyad	Medium	53.95	40.27	Irrigation
Bori	Bori	Medium	40.3	25.15	Irrigation
Suki	Suki	Medium	50.16	39.85	Irrigation
Abhora	Boked Nalla	Medium	7.44	6.02	Irrigation
Boker Bari	Boker Bari	Medium	7.09	6.54	Irrigation
Agnawati	Agnawati	Medium	3.74	2.76	Irrigation
Titur	Titur	Medium	-	-	Irrigation
Tondapur	Khadki Nalla	Medium	4.63	4.64	Irrigation/Domestic
Aner	Aner	Medium	103.23	56.38	Irrigation
Karwand	Arunawati	Medium	33.84	31.15	Irrigation
Panjhra	Panjhra	Medium	43.41	35.63	Irrigation
Malangaon	Kan	Medium	13.02	11.35	Irrigation
Kanholi	Kanholi	Medium	11.79	8.45	Irrigation
Burai	Burai	Medium	21.33	14.21	Irrigation
Arunawati	Arunawati	Medium	27.78	14.97	Irrigation
Rangawali	Rangawali	Medium	15.02	12.89	Irrigation
Nagasakya	Panzar	Medium	15.62	11.24	Irrigation
Haran bari	Mausam	Medium	34.78	27	Irrigation
Lower Tapi Basin (D/s of Gidhade gauging site)					
Ukai	Tapi	Major	8510	7092	Irrigation & Power
Kakrapar	Tapi	Major	51.51	36.57	Irrigation/Domestic
Lakhigav	Dhakani	Medium	38.8	37.41	Irrigation
Ver	Ver	Medium	4.9	4.61	Irrigation

Table – 3.3
Major/Medium/Minor on-going projects in Tapi basin

Name of project	District	CCA (Ha)	Design irrigation (Ha)	Design utilization (MCM)
Maharashtra State (Major projects)				
Wan	Akola	22525	19177	84.4
Waghur	Jalgaon	29748	23580	307.0
Punand	Nasik	17841	10850	46.0
Maharashtra State (Medium projects)				
Chandrabhaga	Amrawati	7013	6732	51.54
Purna	Amrawati	7843	9815	48.99
Torna	Buldhana	1831	1428	7.36
Utawali	Buldhana	4650	5394	28.89
Bahula	Jalgaon	5487	4654	16.0
Gul	Jalgaon	3220	2630	16.0
Anjani	Jalgaon	3567	3670	16.0
Hiwara	Jalgaon	2923	2566	10.0
Mor	Jalgaon	3113	2160	8.0
Mangrul	Jalgaon	2404	2446	6.0
Lower Panzara	Dhule	9980	6810	99.0
Sulwade	Dhule	7560	7560	75.05
Wadi Shewadi	Dhule	7851	7180	35.0
Amrawati	Dhule	4005	3870	26.0
Sonwad	Dhule	3302	3450	22.0
Jamkhedi	Dhule	6270	4130	19.0
Shivan	Dhule	3547	2670	26.0
Dehali	Dhule	3706	3480	25.0
Prakasha	Dhule	9840	8860	82.98
Nagan	Dhule	3427	3000	27.0
Dara	Dhule	3523	3450	17.0
Kordi	Dhule	4032	3660	17.0
Sarangkheda	Dhule	9742	8768	79.01
Maharashtra State (Minor projects)				
5 Nos.	Amrawati	2123	1429	9.11
16 Nos.	Akola	9192	8037	49.32
42 Nos.	Jalgaon	14538	12880	102.0
50 Nos.	Dhule	23463	18879	124.3
4 Nos.	Nasik	1770	1348	7.0
Madhya Pradesh (Major projects)				
Nil	-			-
Madhya Pradesh (Medium projects)				
Nil	-			-
Madhya Pradesh (Minor projects)				
6 Nos.	Khandwa	-	1576	7.7
Total				1495.75

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 Tapi 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 Tapi river basin (around 62,500 sq. km), the grid size of analysis has been taken as 1 km. All the data layers have been generated with "Polyconic" projection, ellipsoid "Everest 1956", datum "Indian (India, Nepal) and origin coordinates as 73 E longitude and 20 N latitude. The whole basin up to Ukai dam is covered in 220 rows and 482 columns. For the remote sensing analysis (Landsat TM and NOAA AVHRR), ERDAS Image Analysis System has been used. 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 Tapi River basin have been generated by using the "DEM Hydro-processing" module of ILWIS. The SRTM data for the Tapi 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 Tapi basin up to Ukai dam has been considered. So, the basin area corresponding to the outlet (coordinates of the Ukai dam) has been obtained. The basin boundary map of Tapi basin up to Ukai dam is presented in Figure – 3.4. Digital elevation map of the basin is shown in Figure – 3.5 and the slope map of the basin is presented in Figure – 3.6. The drainage network map (derived from GIS analysis of DEM) is depicted in Figure – 3.7. This figure also shows the drainage map digitized from SOI toposheets and the close matching of the two maps. The sub-basin map corresponding to different gauging stations is depicted in Figure – 3.8. The flow direction map is presented in Figure – 3.9.

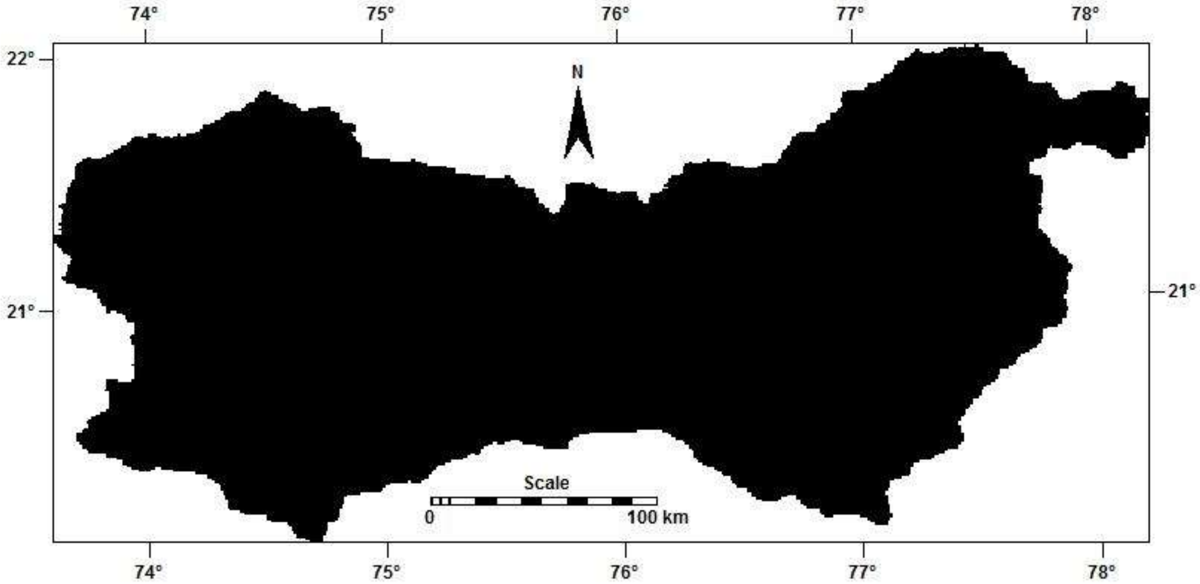


Figure-3.4: Tapi River basin up to Ukai dam obtained from GIS analysis

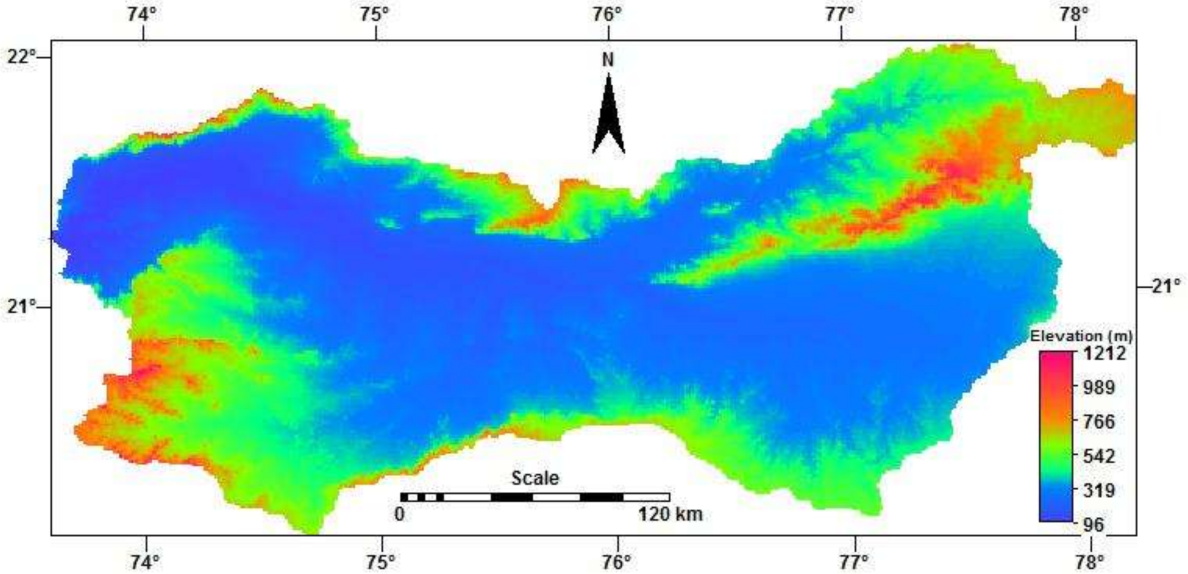


Figure-3.5: Digital elevation map of Tapi basin (obtained from SRTM)

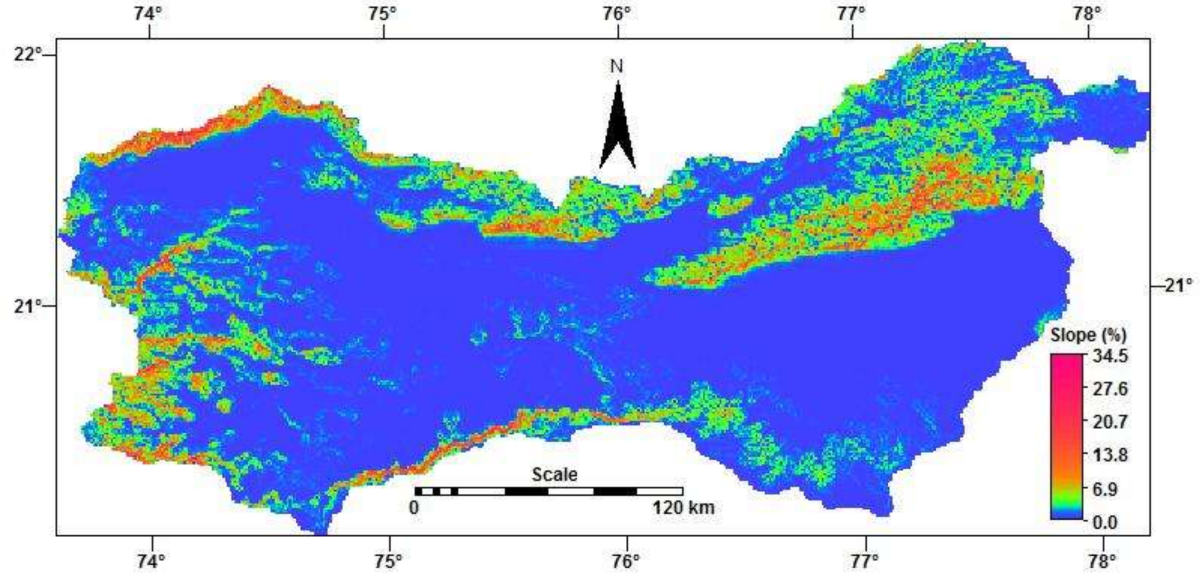


Figure-3.6: Slope map of Tapi River basin obtained from GIS analysis

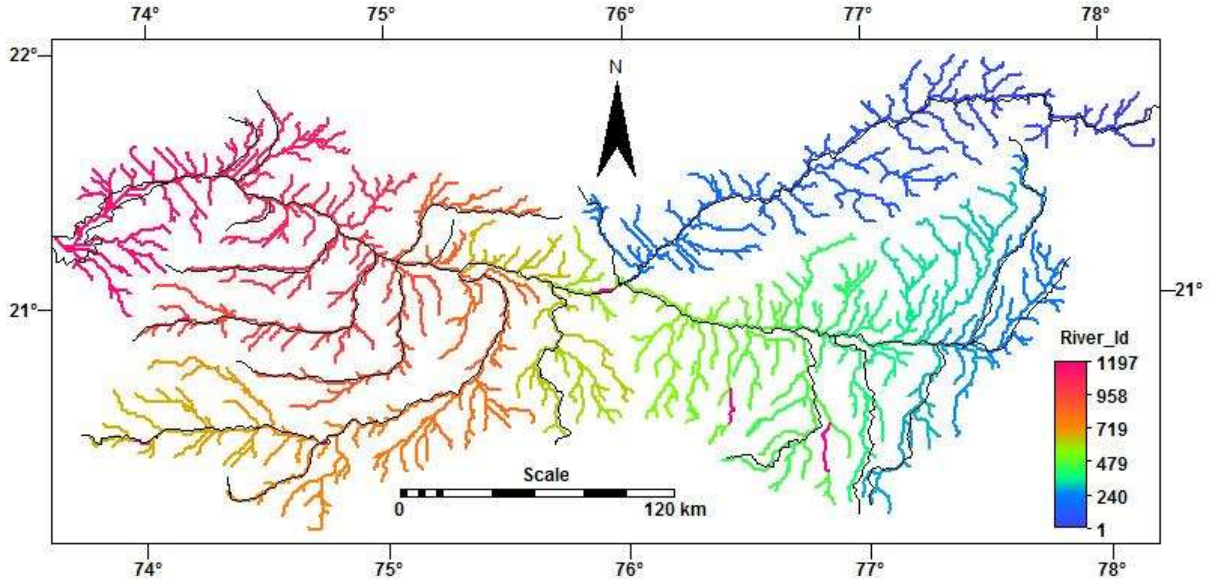


Figure-3.7: River network in Tapi River basin obtained from GIS analysis

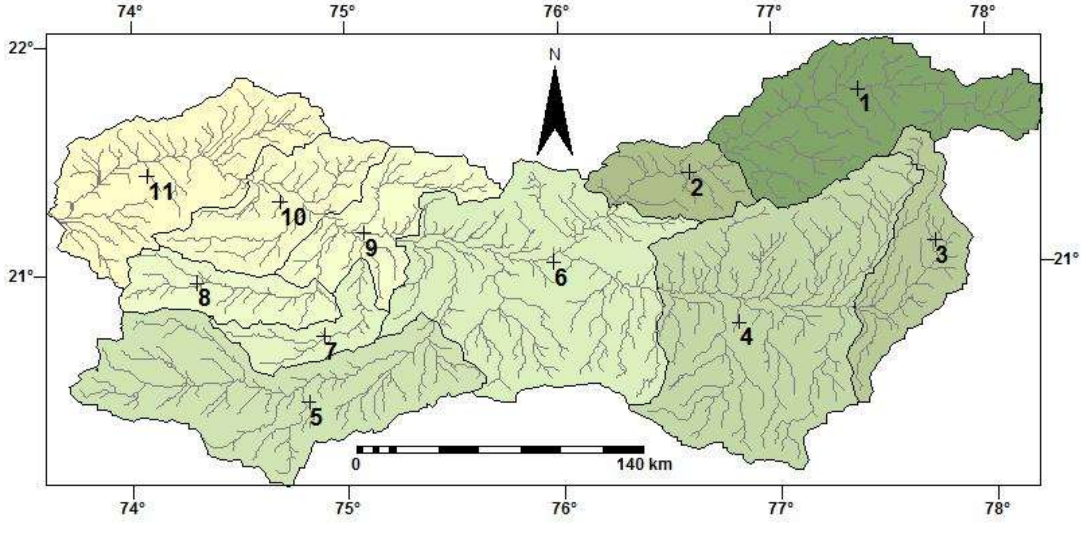


Figure-3.8: Sub-basin boundaries in Tapi River basin obtained from GIS analysis

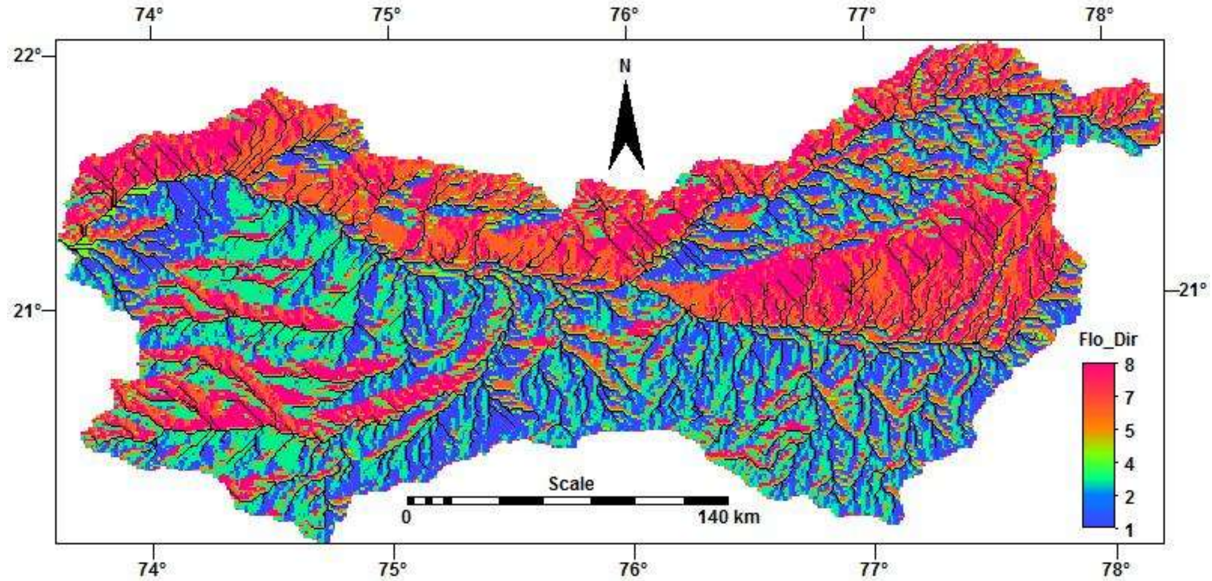


Figure-3.9: Flow direction map with drainage of Tapi basin derived from GIS analysis

In the sub-basin map, the gauging sites corresponding to different sub-basins (with numeric identity) are: 1 – Dedtalai, 2 – Burhanpur, 3 – Lakhpuri, 4 – Yerli, 5 – Dapuri, 6 – Savkheda, 7 – Malkheda, 8 – Morane, 9 – Gidhade, 10 – Sarangkheda, and 11 – Ukai dam. 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 55 stations within the basin are available for the period from 1992 – 96 and the same has been utilized. Thiessen polygon map of rainfall stations is depicted in Figure – 3.10.

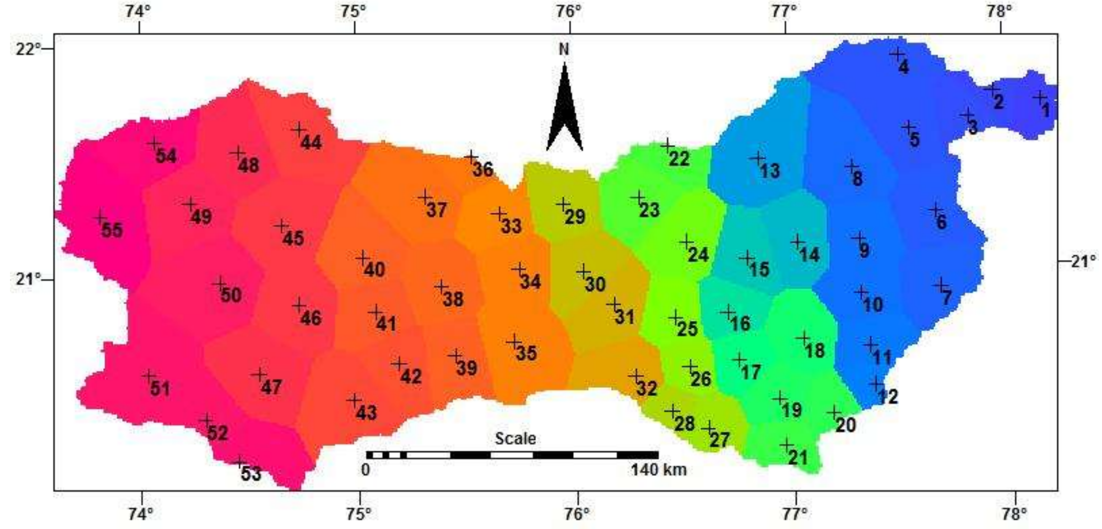


Figure – 3.10: Thiessen polygon of rainfall stations in Tapi basin

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

Table – 3.4
Numeric identity of different rainfall stations in Tapi basin

Numeric Identity	Rainfall Station	Numeric Identity	Rainfall Station	Numeric Identity	Rainfall Station
1	Multai	20	Mangrulpur	39	Pachora
2	Betul	21	Sirpur	40	Amalner
3	Atner	22	Khandwa	41	Parola
4	Chicholi	23	Burhanpur	42	Bhadgaon
5	Bhaindeshi	24	Jalgaon	43	Chalisgaon
6	Chandur Bazar	25	Nandura	44	Pansemal
7	Amrawati	26	Khamgaon	45	Sindkheda
8	Chikhalda	27	Mekhar	46	Dhulia
9	Anjangaon	28	Chikhili	47	Malegaon
10	Daryapur	29	Raver	48	Shahada
11	Murtzapur	30	Edalabad	49	Nandurbar
12	Karanjia	31	Malakpur	50	Sakri
13	Dharni	32	Buldana	51	Kalvan
14	Akot	33	Yaval	52	Chandor
15	Telhera	34	Bhusaval	53	Yeola
16	Shegaon	35	Jamner	54	Taloda
17	Balapur	36	Khargaon	55	Navapur
18	Akola	37	Chopada	-	-
19	Patur	38	Erandol	-	-

Monthly long-term average meteorological parameters (maximum and minimum temperature, humidity, wind speed, and cloudiness) are available for eight stations in/around the Tapi basin. Thiessen polygon map for the ET stations is depicted in Figure – 3.11.

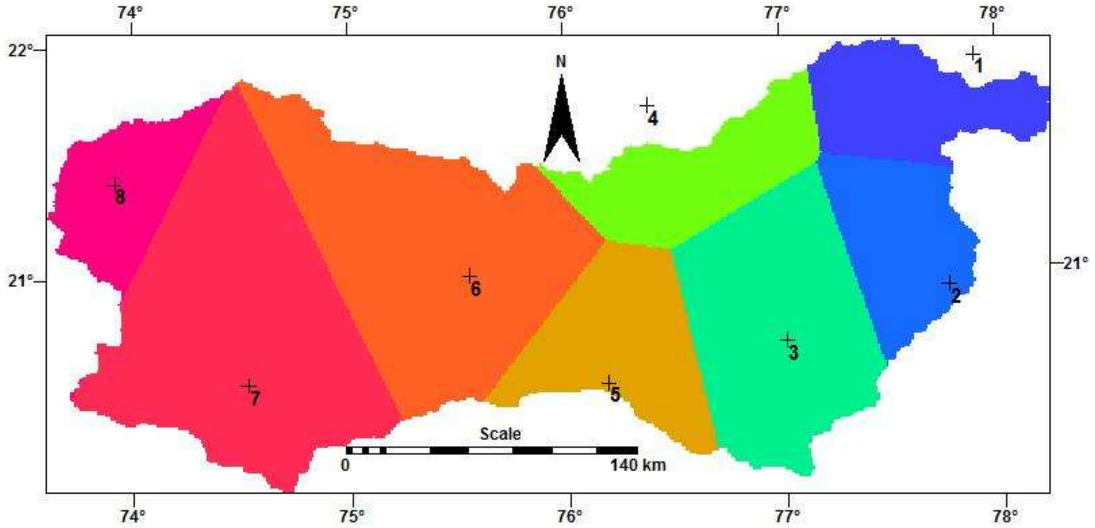


Figure – 3.11: Thiessen polygon map of ET stations in Tapi basin

Names of various ET stations corresponding to their numeric identity are: 1 – Betul, 2 – Amrawati, 3 – Akola, 4 – Khandwa, 5 – Buldhana, 6 – Jalgaon, 7 – Malegaon, and 8 – Surat.

c) District, City, and soil map

Maps showing the boundaries of different districts and the city layout have been digitized from the SOI toposheets at 1:250,000 scale. The basin boundary is covered in toposheet nos. 46 G, 46 H, 46 L, 46 O, 46 P, 55 C, 55 D, 55 G, 55 H, and 55 K. The district boundary map is presented in Figure – 3.12.

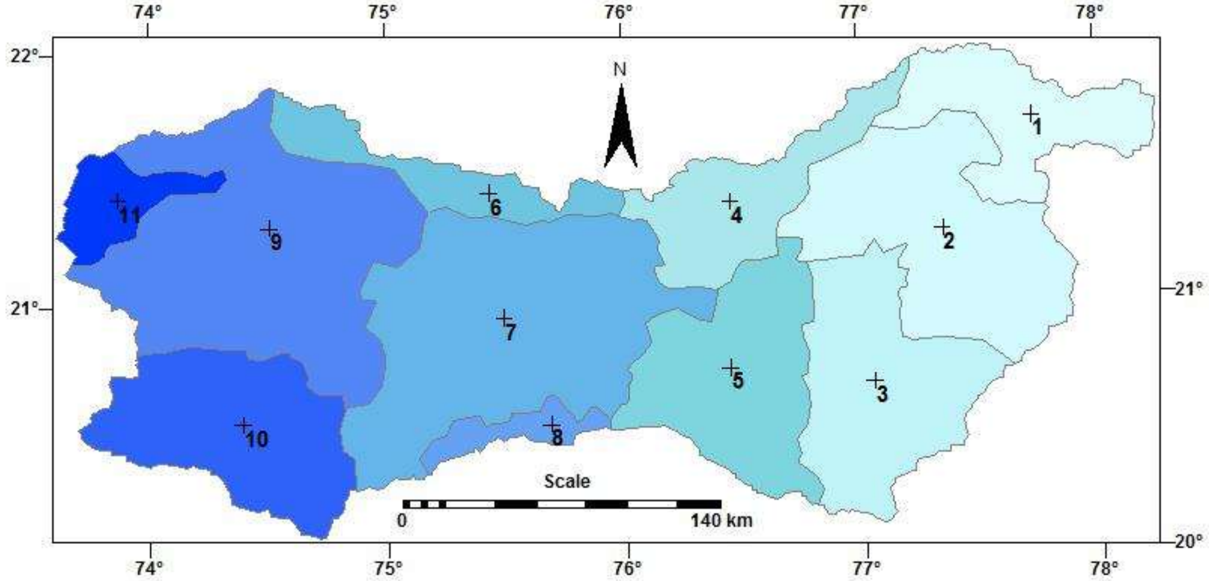


Figure – 3.12: District boundary map of the Tapi River basin

Names of various districts corresponding to their numeric identity are: 1 – Betul, 2 – Amrawati, 3 – Akola, 4 – Khandwa, 5 – Buldhana, 6 – Khargaon, 7 – Jalgaon, 8 – Aurangabad, 9 – Dhule, 10 – Nasik, and 11 - Surat. A total of 191 cities (urban area) in the basin have been delineated from the SOI toposheets and satellite data of Landsat TM sensor. The boundaries of cities digitized from toposheets have been superimposed on the satellite image to confirm the extent of city. Based on the tone of urban area in remote sensing data (taken in between the years 1989 to 1993), the boundaries of the cities (mapped from SOI toposheets prepared in 1970s) have been expanded. The names of the 132 cities, as obtained from the SOI toposheets are given in Table – 3.6. The map showing layout of various cities is presented in Figure – 3.13. Names of various cities corresponding to their numeric identity are presented in Table – 3.5.

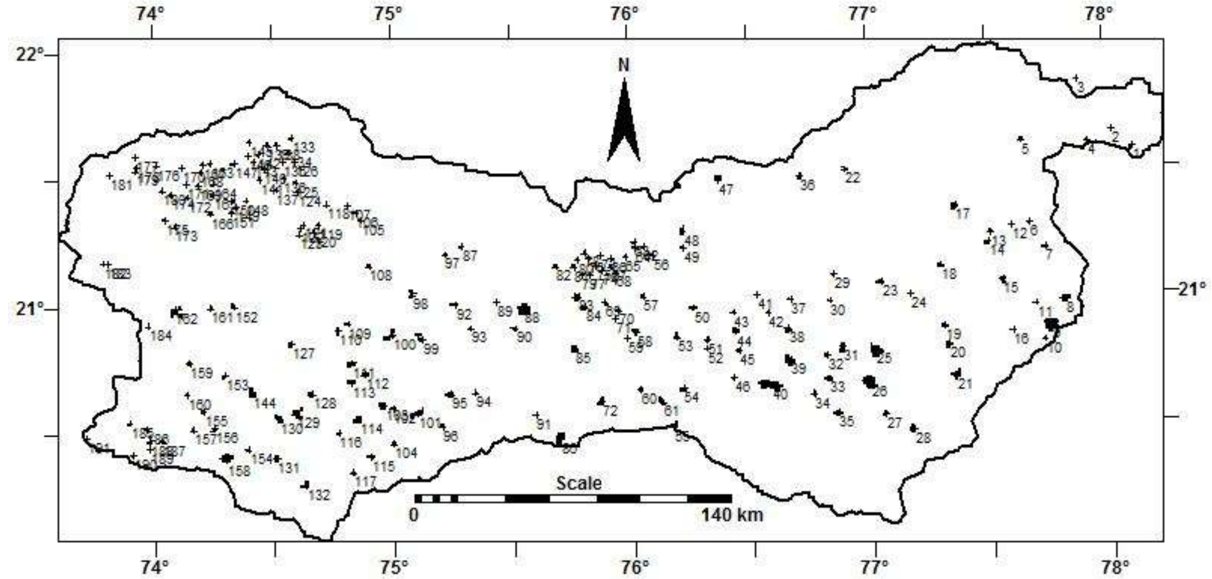


Figure – 3.13: Map showing layout of different cities in Tapi basin

Table – 3.5
Numeric identity of different cities in Tapi basin

Num_Id	City	Num_Id	City	Num_Id	City	Num_Id	City
1	Betul	34	Telhara	67	Pachora	100	Nampur
2	Atner	35	Hiwarkheda	68	Bhadgaon	101	Khakurdi
3	Bhainsdehi	36	Nalgaon	69	Chalisgaon	102	Satana
4	Chikalda	37	Malakpur	70	Jolchakra	103	Thengoda
5	Baratwada	38	Nandura	71	Nagar Devla	104	Virgaon
6	Karasgaon	39	Wadner	72	Kajgaon	105	Kalvan
7	Sirasgaon	40	Chandur	73	Chopda	106	Devla
8	Achalpur	41	Pimpalgaon	74	Chahardi	107	Manmad
9	Chandur Bazar	42	Kurha	75	Amalner	108	Umbrane
10	Nandgaon-1	43	Yerly	76	Dharangaon	109	Saundane
11	Walgaon	44	Shegaon	77	Poldhi	110	Nimgaon
12	Assegaon	45	Manasgaon	78	Jalgaon	111	Nandgaon
13	Anjangaon	46	Madakhed	79	Yaval	112	Hirapur
14	Akot	47	Ural	80	Bhusawal	113	Naydongri
15	Wadner Gangal	48	Hatrun	81	Savda	114	Nanduri
16	Daryapur	49	Gandhigram	82	Pimpalner	115	Gopapur
17	Lakhpuri	50	Wadegaon	83	Taharabad	116	Budruk
18	Badnera	51	Balapur	84	Sakri	117	Abhona
19	Amravati	52	Paras	85	Kasare	118	Shinde
20	Bhatkuli	53	Khamgaon	86	Kusumbe	119	Mohpada
21	Murtajapur	54	Pipalgaon Raja	87	Dhule	120	Borgaon
22	Akola	55	Buldhana	88	Nyahalode	121	Kanashi
23	Barsi Takli	56	Rohankhed	89	Bor Vihir	122	Bhandne
24	Mahan	57	Dhamangaon	90	Shirud	123	Warse
25	Dharni	58	Motala	91	Borkund	124	Dighar
26	Paretha	59	Parola	92	Pilkhod	125	Dekale
27	Nepanagar	60	Bahadurpur	93	Mehumbare	126	Chankapur
28	Burhanpur	61	Randol	94	Jamda	127	Sagbara
29	Raver	62	Shirsoli	95	Malegaon	128	Navapur
30	Shahpur	63	Jamner	96	Jhodge	129	Chinchpada
31	Edalabad	64	Ajanta	97	Arvi	130	Multai
32	Jalgaon-1	65	Fatehpur	98	Chikhalvahal	131	Bisnur
33	Sangrampur	66	Soygaon	99	Brahmangaon	132	Masod

The soil map for the Tapi basin is obtained from the National Bureau of Soil Survey and Land Use Planning (NBSSLUP). Different soil classes map have been merged to form four hydrological soil classes: A (High infiltration and low runoff potential), B (moderate infiltration rate), C (slow infiltration rate), and D (very slow infiltration rate and high runoff potential). Soils with texture sandy/loamy sand/sandy loam have been considered as class A (num_id 1), with texture silt loam/loam as class B (num_id 2), with texture sandy clay loam as class C (num_id 3), and with texture clay loam/silty clay loam/sandy clay/silty clay/clay as class D (num_id 4). The soil map of Tapi basin with these classes is shown in Figure – 3.14.

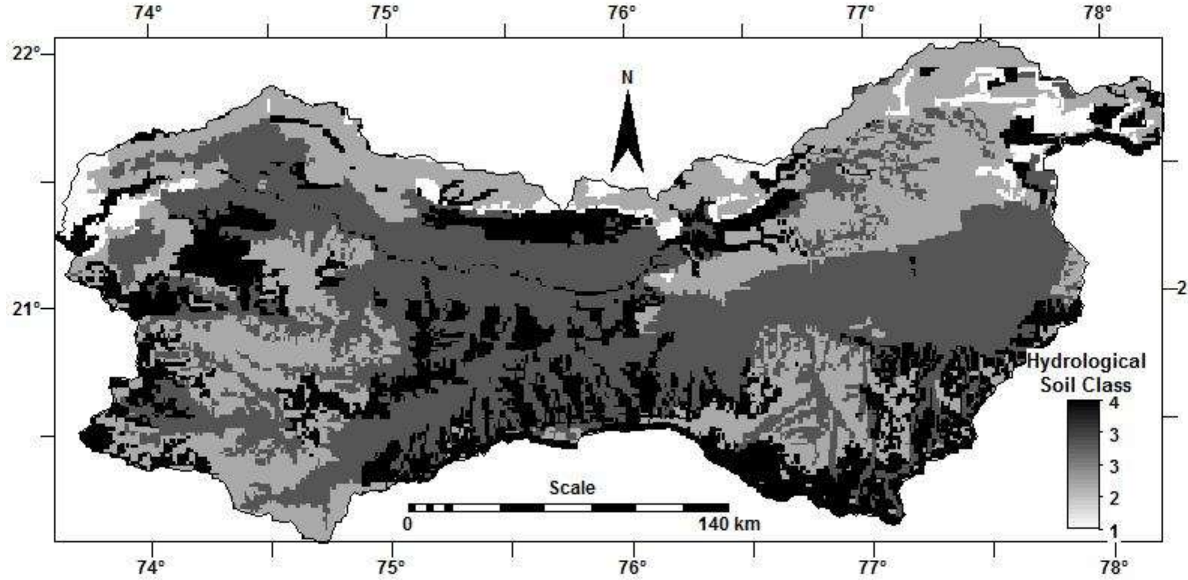


Figure – 3.14: Hydrological soil map of Tapi River basin

d) Reservoir waterspread map

Reservoirs and diversion weirs/barrages are important component of a river basin that change the spatial and temporal water availability. Location of different reservoirs in the Tapi basin was not available. So, the same have been ascertained from remote sensing data. 10 Landsat TM images for the Tapi basin (freely available at internet) with given specifications (Path/ Row/DOP) have been downloaded: 144/45/05.11.89; 144/46/05.11.89; 145/45/06.10.93; 145/46/04.11.92; 146/45/18.10.89; 146/46/18.10.89; 147/45/09.10.89; 147/46/25.10.89; 148/45/19.10.90; 148/46/19.10.90. These images (B2, B3, and B4) have been imported in ERDAS IMAGINE system and geo-referenced by specifying corner coordinates. Then images have been stitched and a composite remote sensing image of the Tapi basin has been obtained. The composite remote sensing image for the Tapi basin as obtained from Landsat TM data is shown in Figure – 3.15.

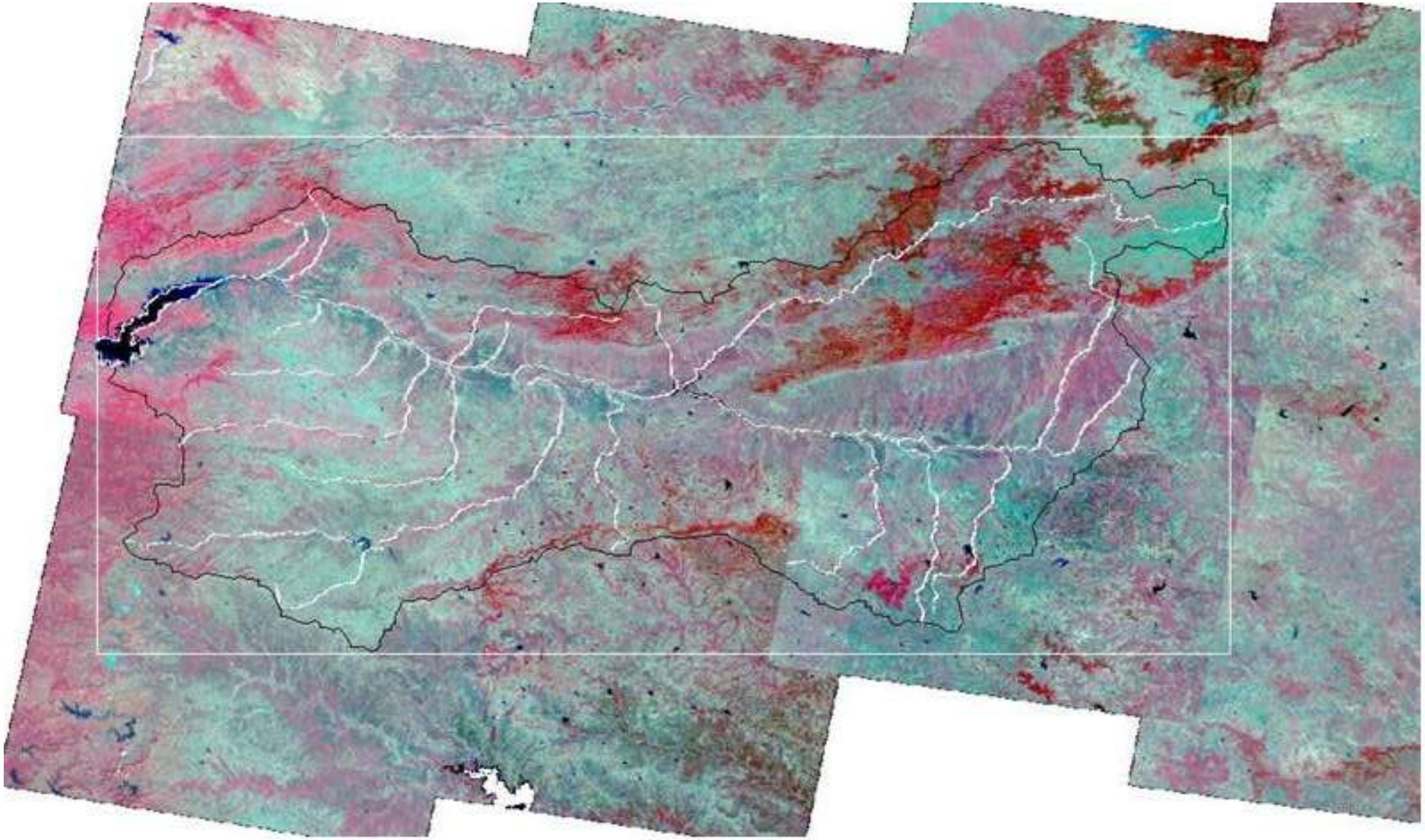


Figure – 3.15: Composite Landsat TM image of Tapi River basin showing basin boundary and main

From the composite image, water spread area of different water bodies has been worked out by comparative analysis of water pixels in different bands [B2(Green), B3(Red), and B4(NIR)]. For a water pixel, B4 was found to have zero value. In addition, the condition [(B3+0.1)/(B2+0.1) < 1.2] has been used to decipher a pixel as water pixel. Classified water pixels, so obtained have been clumped and a clump area exceeding 0.75 sq. km has been taken as a water body. Figure – 3.16 shows water bodies superimposed on the remote sensing composite.

The water body image has been exported from ERDAS system and imported in ILWIS system. Since all the basin analysis is being carried out at 1 km grid size, the image of water bodies has been resampled to 1 km size grid. There are 78 water bodies identified in the Tapi basin from remote sensing analysis. Based on the coordinates of 32 (major and medium) reservoirs available in the Water Year books of CWC, the corresponding water spread areas have been identified. For the other water bodies, names such as Misc1, Misc2 . . . have been mentioned. The finalized waterspread image of different reservoirs in the Tapi basin is shown in Figure – 3.17. The names of reservoirs corresponding to various numeric_ids is specified in Table – 3.6. Ukai dam has been given numeric_id of 78.

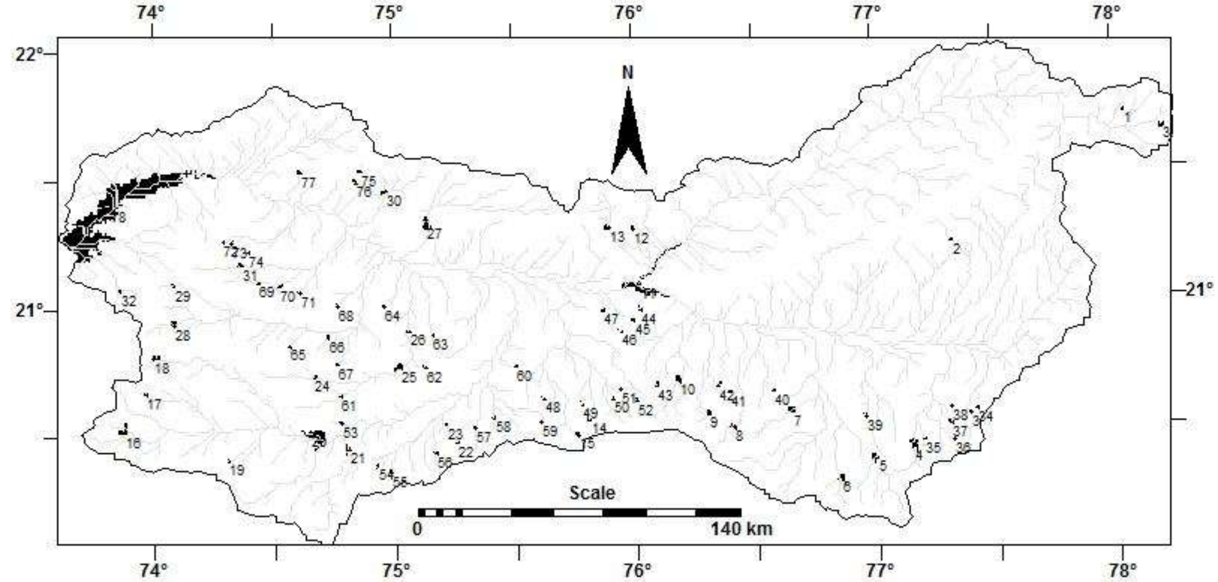


Figure – 3.17: Location of different reservoirs in the Tapi River basin

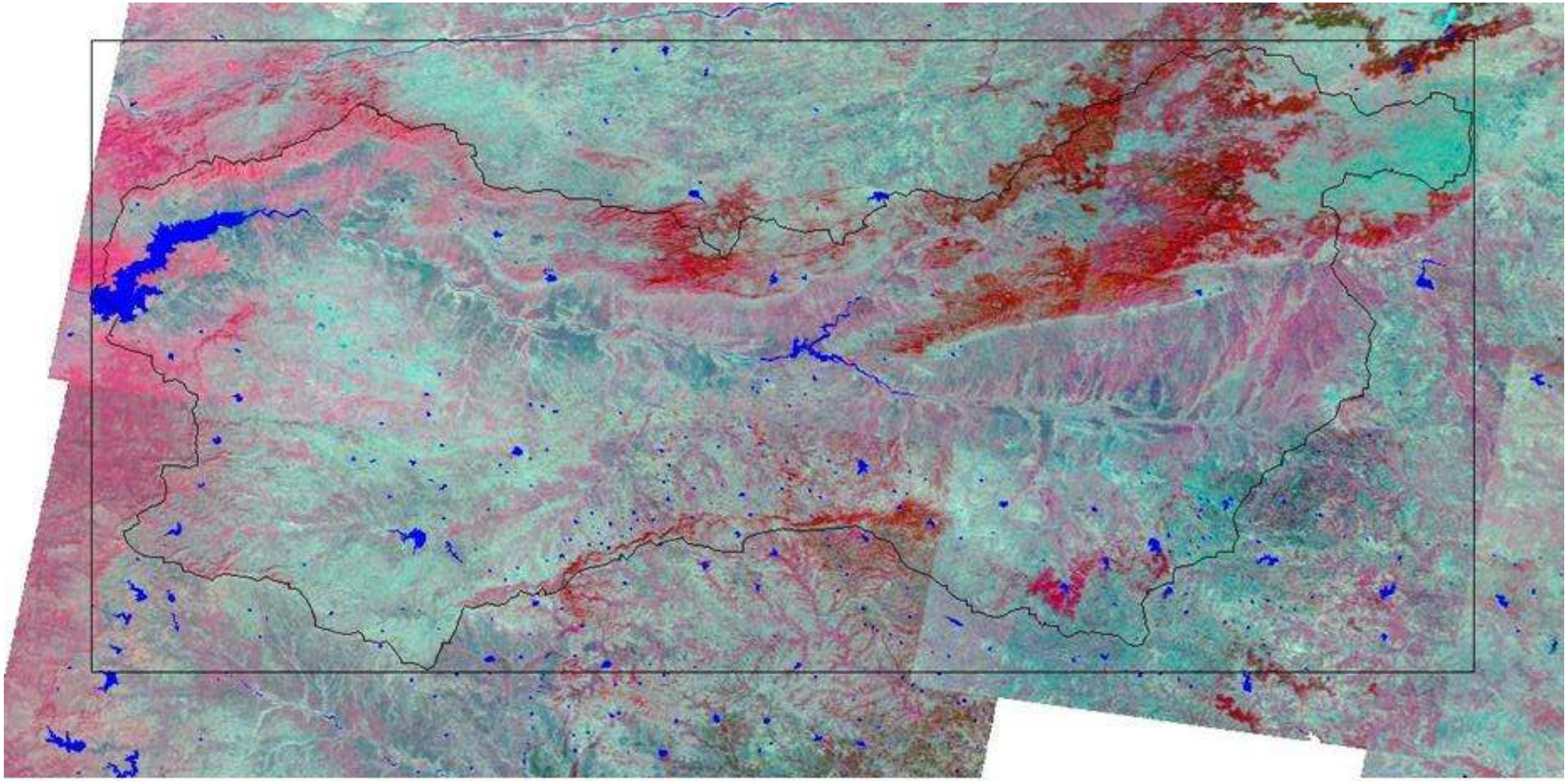


Figure – 3.16: Water bodies (Blue) obtained by digital analysis superimposed on RS image

Table – 3.6
Numeric identity of different reservoirs in Tapi basin

Num_Id	Reservoir	Num_Id	Reservoir	Num_Id	Reservoir	Num_Id	Reservoir
1	Sonkhedi	9	Paltag	17	Kelzar	25	Bori
2	Shahanur	10	Nalganga	18	Haran Bari	26	Bokar Bari
3	Uma	11	Hathnur	19	Nagya Sakya	27	Aner
4	Katepurna	12	Abhora	20	Girna	28	Panzara
5	Morne	13	Sukhi	21	Manyad	29	Malangaon
6	Nirguna	14	Tondapur	22	Gadad Gad	30	Karwand
7	Mhas	15	Ajanta Andheri	23	Agnawati	31	Burai
8	Gyan Ganga	16	Chankapur	24	Kanholi	32	Rangawli

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 Tapi basin, Land use map has been obtained from the Global Land Use Facility at the internet. The land use map for the whole globe (developed on a continent-by-continent basis) is available with Lambert Azimuthal Equal Area projection, have 1 - km spatial resolution, and are based on 1 - km AVHRR data spanning April 1992 through March 1993. Version 2.0 of the land use map (updated from version 1.2) has been downloaded for the eurasia region.

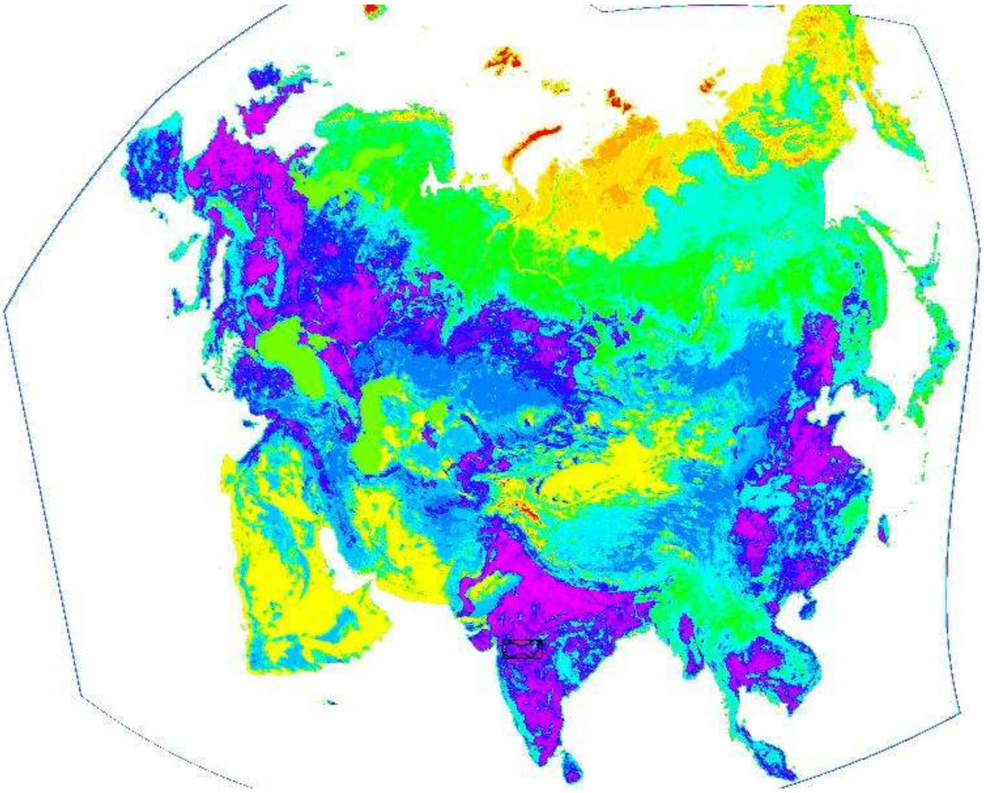


Figure – 3.18: USGS landuse/land cover map for Eurasia overlaid with Tapi Basin

- The Eurasia land cover data can be downloaded at the World Wide Web site: (http://LPDAAC.usgs.gov/glcc/ea_int.html). The data has been downloaded for the Lambert Azimuthal Equal Area projection optimized for Asia. The image has 12,000 rows and 13,000 columns, pixel size 1000 m, longitude of origin 100° E, latitude of origin 45° N. The X-Y corner coordinates are also specified. Using these coordinates and projection parameters, the image has been geo-referenced (shown in Figure – 3.18). Various landuse/land cover categories specified by the image include:
    i) Urban and Built-Up Land
    ii) Dryland Cropland and Pasture
    iii) Irrigated Cropland and Pasture
    iv) Mixed Dryland/Irrigated Cropland and Pasture
    v) Cropland/Grassland Mosaic
    vi) Cropland/Woodland Mosaic
    vii) Grassland
    viii) Shrubland
    ix) Mixed Shrubland/Grassland
    x) Savanna
    xi) Deciduous Broadleaf Forest
    xii) Deciduous Needleleaf Forest
    xiii) Evergreen Broadleaf Forest
    xiv) Evergreen Needleleaf Forest
    xv) Mixed Forest
    xvi) Water Bodies
    xvii) Herbaceous Wetland
    xviii) Wooded Wetland
    xix) Barren or Sparsely Vegetated
    xx) Herbaceous Tundra
    xxi) Wooded Tundra
    xxii) Mixed Tundra
    xxiii) Bare Ground Tundra
    xxiv) Snow or Ice

In the present case, six land use/land cover categories have been defined: urban land, rainfed agriculture, irrigated agriculture, forest, barren land, and water body. Category (i) has been taken as urban land, category (ii) as rainfed agriculture, categories (iii & iv) as irrigated agriculture, categories (v, vi, vii, viii, ix, x, and xix) as barren land, categories (xi, xii, xiii, xiv, and xv) as forest, and category (xvi) as water body. Next the area of interest surrounding the Tapi basin has been extracted and control points have been specified by matching the common water bodies in the USGS land use map and the Landsat TM image of the region. Then, the image has been imported in ILWIS and the image area within the basin has been separated. It is observed that the forest area and major waterspread areas (Ukai dam, Hathnur dam, Girna dam) have been correctly specified in the landuse map. Further, irrigated agriculture areas have been observed in the downstream/ surroundings of most of the hydraulic structures. These observations corroborate the authenticity of the land use map. However, a few corrections have been made to the land use map. Urban areas and water spread areas, derived separately using toposheets and Landsat TM image, have been specified in the land use map. The land use map of Tapi basin is shown in Figure – 3.19.

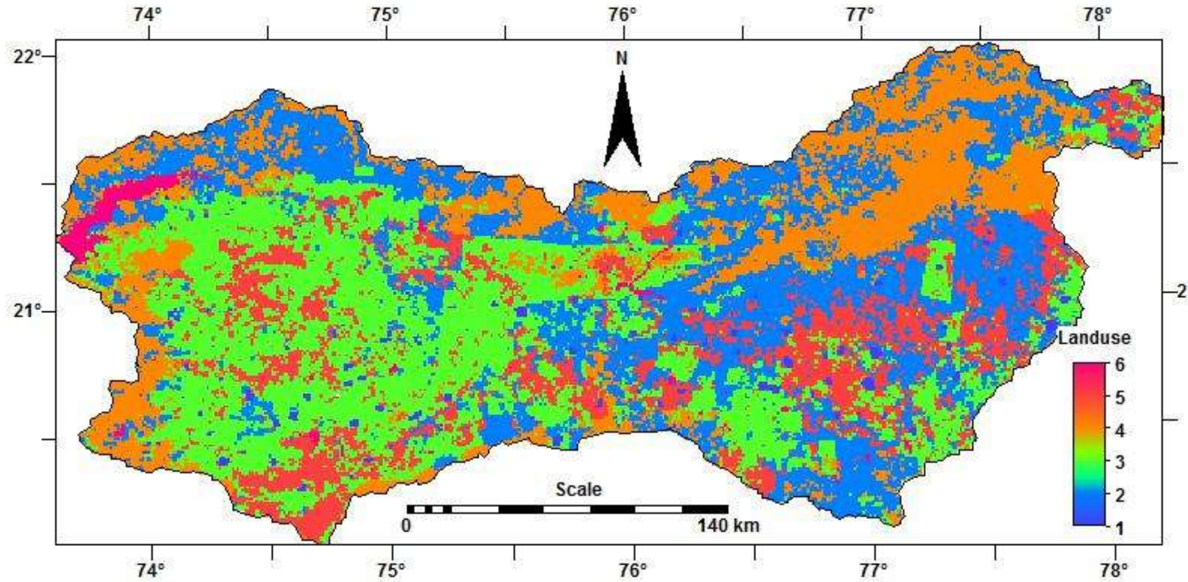


Figure – 3.19: Landuse map of the Tapi River basin

Names of various land use categories corresponding to their numeric identity are: 1– Urban area, 2– Rainfed agriculture, 3– Irrigated agriculture, 4– Forest, 5– Barren land, and 6– Water body.

e) Kharif and Rabi crop maps

Irrigation demands account for nearly 70 – 80% of the freshwater demands. So, it is important to correctly assess these demands in a river basin for planning and management. Water demands of crops vary with the type of crop and its growth stage. The root depth, planting date and duration also varies as per crop types. To account for all these factors in the assessment of irrigation demands, crop maps for different seasons are used by the basin simulation model. Remote sensing data in combination with the field observations can be used to decipher the spatial and temporal cropping pattern in a river basin. In the present study, multi-temporal satellite data (NOAA AVHRR) and the ancillary information about acreage of various crops in the Tapi basin up to Ukai dam have been used to map the crops in the basin in Kharif and Rabi season.

Images of NOAA/AVHRR at daily time step are available for the whole globe at the internet and the same for Tapi basin have been downloaded for Kharif and Rabi season months. Satisfactory images for the months of October, November, December, February, March, and April have been obtained. In the month of October, most of the Kharif crops are in their maturity stage and show prominent vegetation signatures. In November, except cotton, most of the Kharif crops are harvested. In December, the Rabi crops are grown which mature by March/April. So good vegetation signatures for Rabi crops are expected in the months of February, March, and April. The acreage of different crops in the Tapi basin (obtained from NWDA report) up to Ukai dam is given in Table – 3.7.

Table – 3.7
Acreage of different crops in Tapi basin up to Ukai dam

Crop	Area (ha)	Crop	Area (ha)	Crop	Area (ha)
Kharif Crops					
Rice	94655	Kodara	3732	Vegetable	19231
Jowar	849488	Banti	3296	Cotton	995434
Bajra	384000	Bhaldi	2113	Foddar	22403
Maize	65046	Sugarcane	81577	Oilseeds	293283
Ragi	26913	Fruits	96409	Edible crops	283148
Rabi Crops					
Wheat	196023	Black Gram	185409	Oilseeds	293283
Gram	215965	Other Pulses	67664	Edible crops	283148
Green Gram	256091	Vegetable	19231	Fruit	96409
Tur	239381	Foddar	22403	Sugarcane	81577

The images were imported in ERDAS IMAGINE and geo-referenced using corner coordinates and the control points from the drainage network. The images for October, November/December are shown in Figure – 3.20 and for February/March/April are shown in Figure – 3.21.

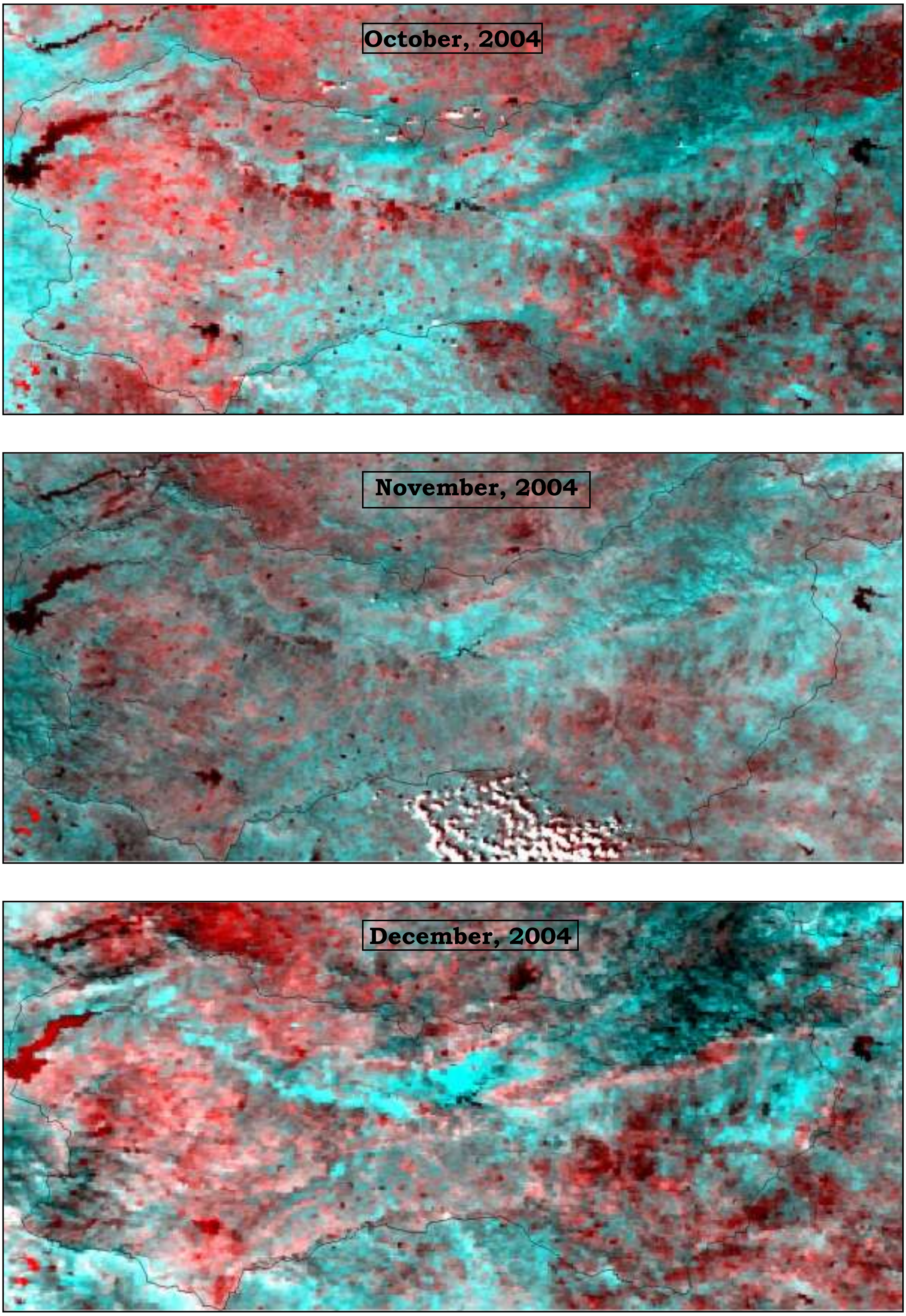


Figure – 3.20: NOAA-AVHRR color composites (1,2,2) of Tapi basin for different months

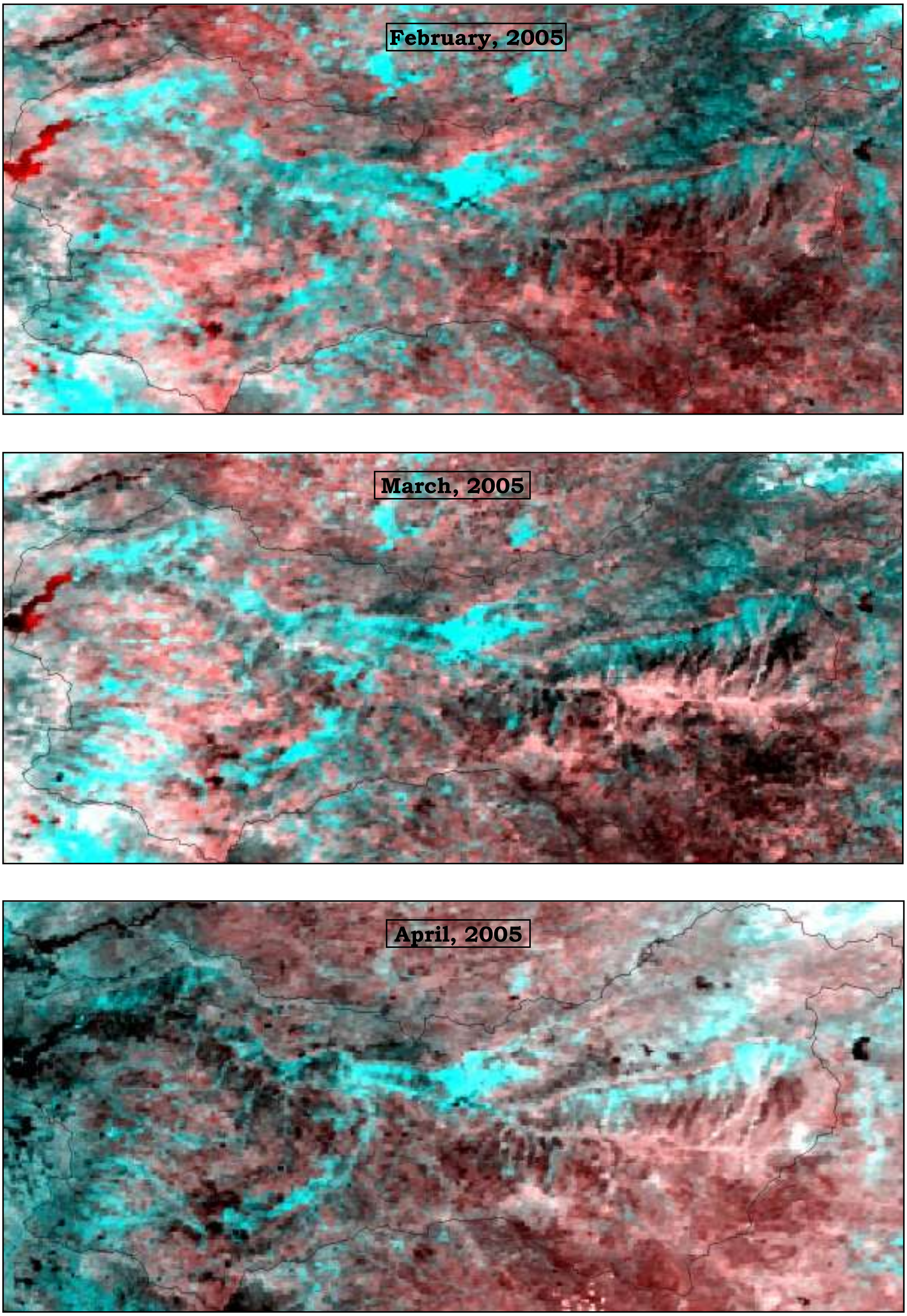


Figure – 3.21: NOAA-AVHRR color composite (1,2,2) for Tapi basin in different months

For estimation of spatial cropping pattern in the Kharif season, October and November images have been utilized. For Rabi season cropping pattern, images of February and March have been utilized. For the Kharif season, crops have been grouped in nine different types. These types along with their numeric identity are: 1- Rice, 2- Jowar (also includes Bajra, Maize, Ragi, Kodara, Banti, and Bhaldi), 3- Oilseeds, 4-Sugarcane, 5- Cotton, 6- Foddar, 7- Fruit, 8- Vegetable, and 9- Edible crops (condiments, edible crops etc.). For Rabi season also, crops have been grouped in eight different types. These types along with their numeric identity are: 10- Wheat, 11- Gram (also includes Green gram, Tur, and Black gram), 12- Oilseeds, 13- Foddar, 14- Edible crops (condiments, edible crops etc.), and 15- Vegetable. Sugarcane, fruit have been taken as perennial crops.

In the month of October, all Kharif crops are found in the field with enhanced vegetation signatures. For the October image, Vegetation index (VI) map (B2/B1) has been prepared and the forest area has been separated out. In the rest of the area, the cutoff limit of VI has been determined such that the area above the limit corresponds to the acreage of Kharif crops. The cutoff limit of VI for October image comes out to be 8. Using density slicing of VI of October image, rice (VI > 13.6), jowar (VI - 9.2 to 12), oilseeds (VI - 12.1 to 13.3), fodder (VI - 13.4 to 13.6), and edible crops (VI - 8 to 9.1) have been identified. Since sugarcane, cotton, fruit, and vegetable crops of Kharif season remain in the field in November, the same have been identified from the VI image of November (after separating out forest area). The cutoff VI comes out to be 7.1.

Since all the Rabi crops generally remain in the filed in February/March, the images of February and March have been utilized for identifying these crops. VI images of February and March have been derived and forest area has been separated out. The VI threshold for the rabi crops comes out to be 3.7 for February and 2.9 for March. Using density slicing of VI of March image, wheat (VI > 6.7), fodder (VI – 6.55 to 6.69), oilseeds (VI – 5.05 to 6.54), gram (VI – 3.25 to 5.04), and misc. edible crops (VI – 2.9 to 3.24) have been identified. Fruit, vegetable, and sugarcane have been taken at the same locations as they have been in the Kharif season. The acreage of different crops identified with remote sensing is presented in Table – 3.8. The crop image of Kharif is presented in Figure – 3.22 and the crop image for Rabi is presented in Figure – 3.23.

Table – 3.8
Acreage of crops as identified from remote sensing analysis

Crop_id	Area (ha)	Crop_id	Area (ha)	Crop_id	Area (ha)
Kharif Crops					
1	94300	4	77700	7	94100
2	1316700	5	1053600	8	57100
3	283600	6	21800	9	235700
Rabi Crops					
10	201600	12	293400	14	291300
11	1044000	13	18200	15	57100

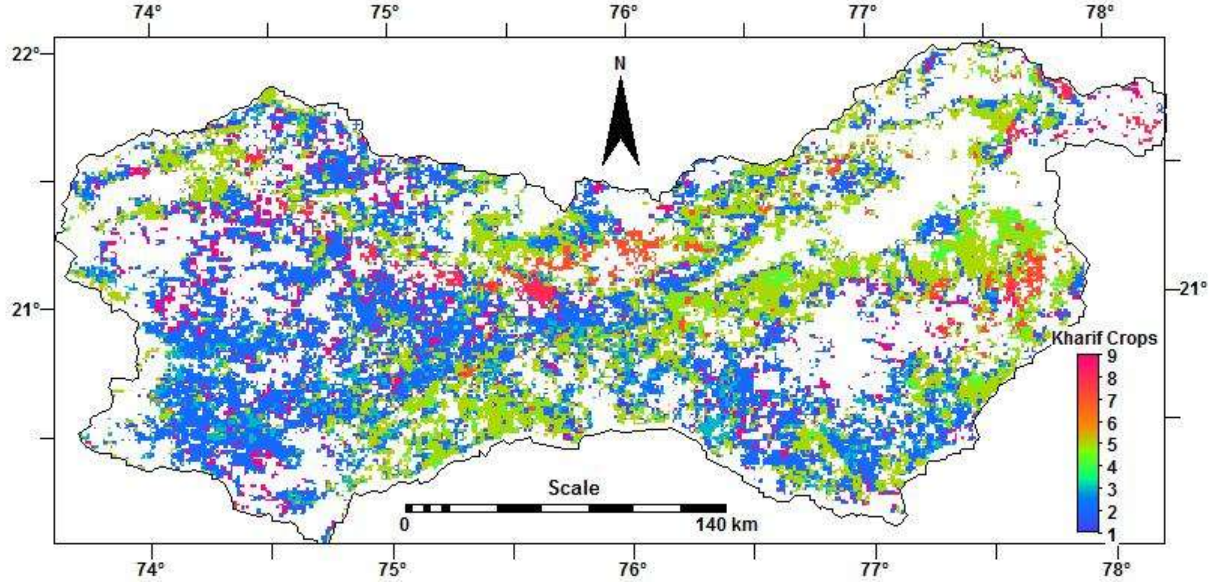


Figure – 3.22: Kharif crop map for the Tapi River basin

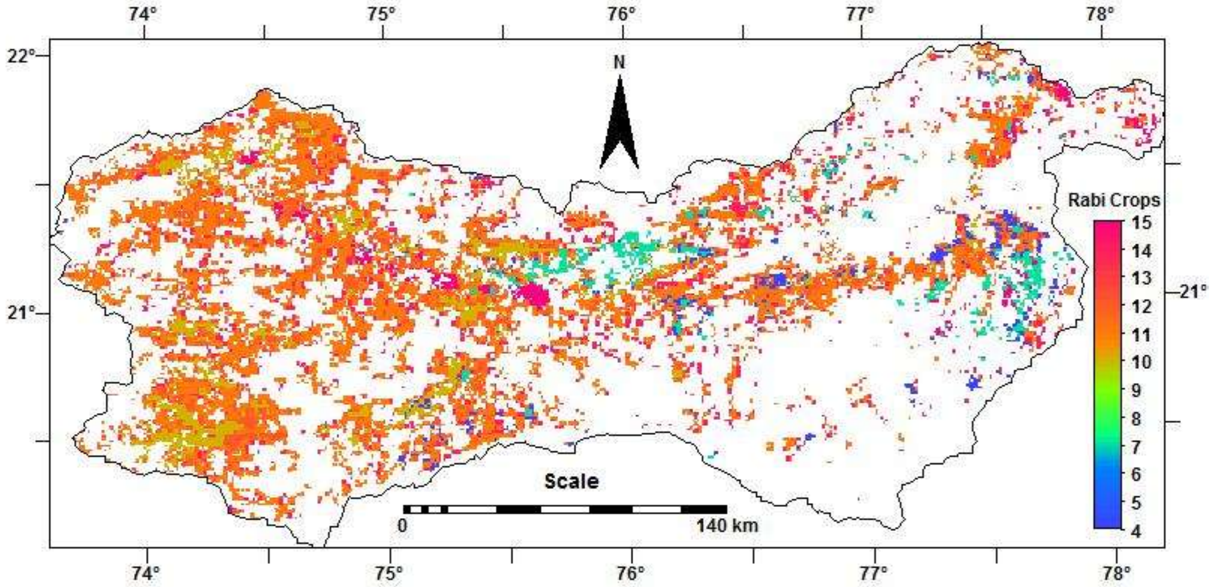


Figure – 3.23: Rabi crop map for the Tapi River basin

In the present study, an approximate method has been used to identify the cropping pattern in the Tapi River basin from the satellite data. In actual application of the simulation model to a river basin, authentic cropping pattern maps for different seasons can be obtained either from the State Remote Sensing Department or River Basin Authority. The properties of the crops prevalent in the region can be obtained from the State Agriculture Department.

f) Irrigable command area map

Irrigable command area map helps in identifying that portion of the basin that can be supplied with irrigation water from surface water through diversion from a reservoir or barrage. This information is then used in estimating the irrigation demands from a reservoir/barrage. Irrigation command areas of individual reservoirs/barrages are generally available with the project authorities and can be incorporated in the present model by digitizing their boundaries. In the present study, the command boundaries of different projects have been derived using:

i) vegetation signatures in October, March, and April NOAA satellite images,
ii) irrigated agriculture area information from the land use map,
iii) proximity to the reservoir/barrage and possible flow direction, and
iv) culturable command areas of some projects (32) in the basin.

A number of trial and error command boundaries of different projects using above (i, ii, and iii) spatial information have been delineated and the CCA of each project has been compared with the specified CCA for that project. The boundaries have been modified so as to match the computed and specified CCA information. The command boundaries of different projects overlaid on the October, March, and April scene is shown in Figure – 3.23. The command boundaries along with their associated projects are presented in Figure – 3.24.

The computed and specified CCA of 32 projects is given in Table – 3.9. In the present case, it was difficult to contact so many project authorities and get the command area boundaries. So, alternative methods of command area delineation have been resorted to. From the figure – 3.23, it is obvious that the prominent vegetation signatures in March/April have been covered under command areas.

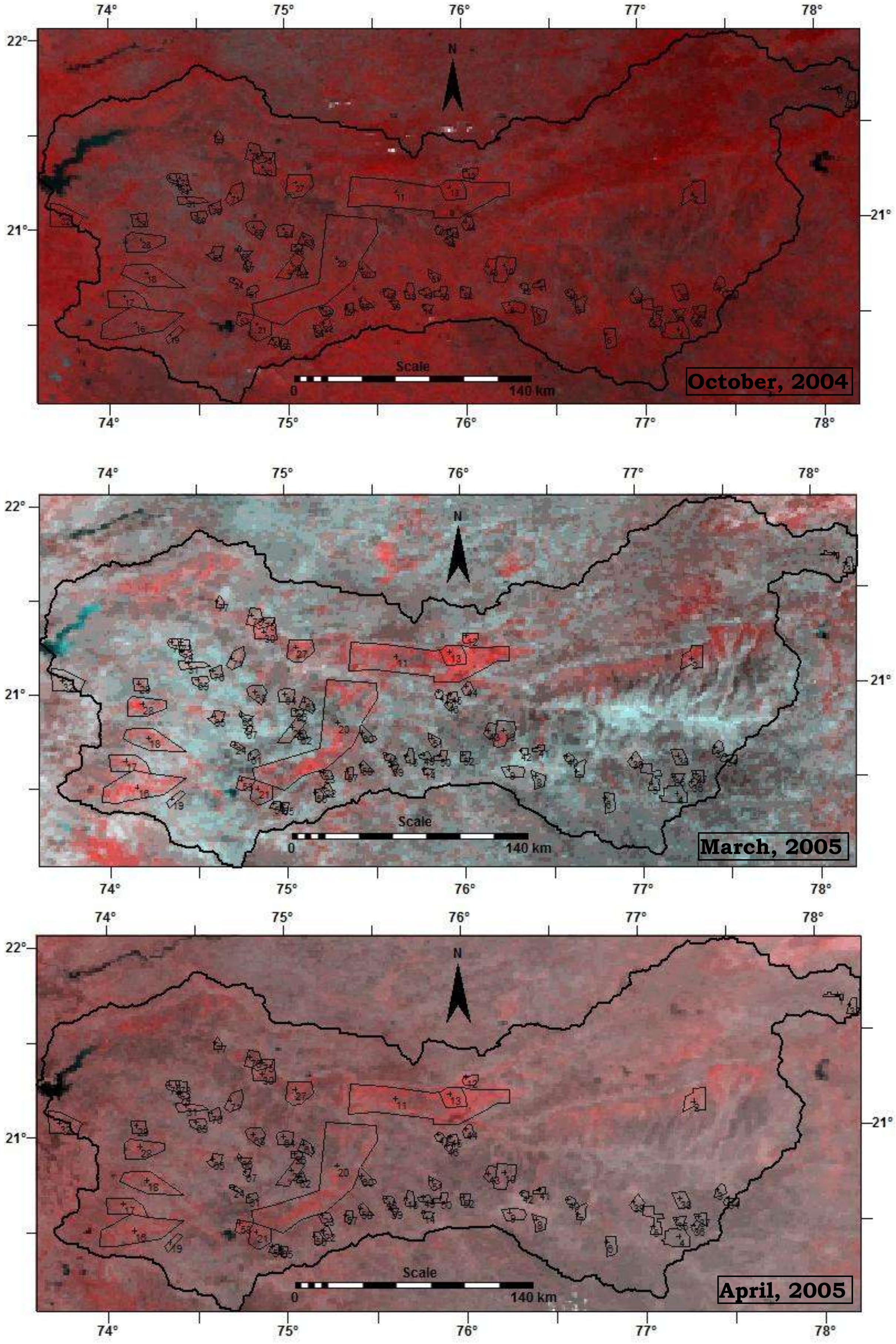


Figure – 3.23: Command area boundaries of projects overlaid on remote sensing images

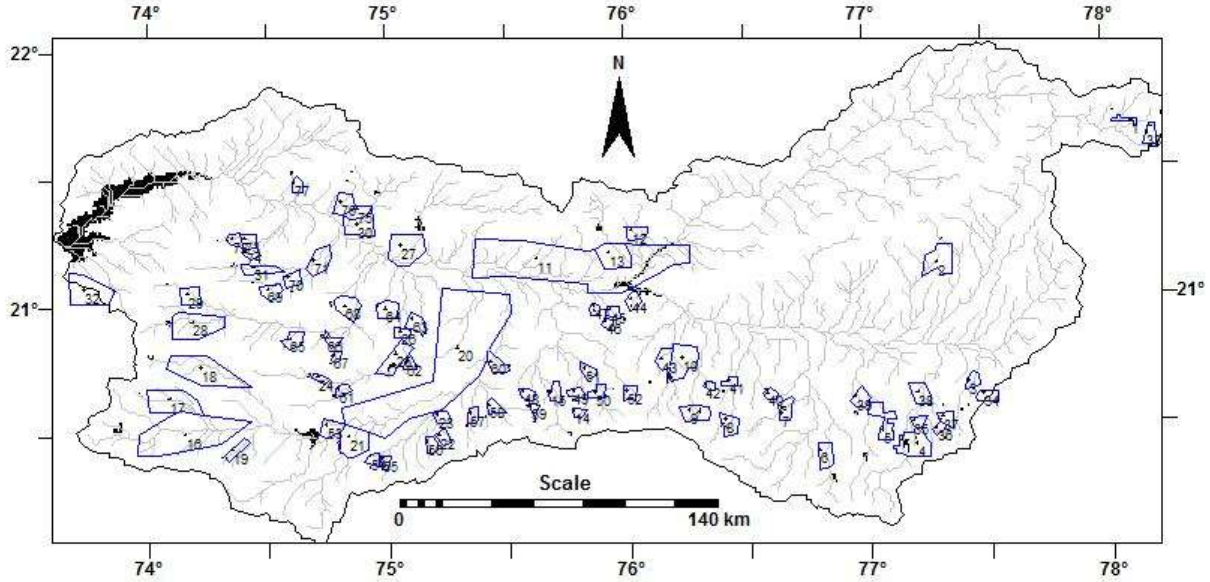


Figure – 3.24: Different projects and layout of their command areas in Tapi basin

Table – 3.9
Computed and actual CCA of command areas of projects in Tapi basin

Numeric_id	Name of Structure	Computed CCA (ha)	Actual CCA (ha)
1	Sonkhedi	1200	943
2	Shahanur	9700	9330
3	Uma	2700	3007
4	Katepurna	10200	11187
5	Morne	6800	6532
6	Nirguna	5700	6377
7	Mhas	3600	4234
8	Gyan Gange	5100	5463
9	Paltag	4600	3032
10	Nalganga	10700	9165
11	Hathnur	78000	47350
12	Abhora	2200	1403
13	Sukhi	4000	8647
14	Tondapur	700	1597
15	Ajanta Andheri	1600	1972
16	Chankapur	43500	19173
17	Kelzar	15600	4536
18	Haran Bari	19200	12340
19	Nagya Sakya	3400	2893
20	Girna	141600	101639
21	Manyad	7400	6508
22	Gadad Gad	2900	1296
23	Agnawati	1500	950
24	Kanholi	1500	1704
25	Bori	7500	6504
26	Bokar Bari	1900	1720
27	Aner	12800	7045
28	Panzara	19000	12186
29	Malangaon	4100	2674
30	Karwand	7700	7125
31	Burai	4300	3391
32	Rangawli	3800	5130

g) Groundwater depth map

Groundwater depth map is used by the simulation model to compute the baseflow at gauging stations, to find the maximum recharge in a grid, and for estimation of groundwater potential in a grid. The model assumes that revised groundwater depth map is provided for each month. Therefore, pumping and recharge are computed by the model during a month and revised groundwater surface is generated by using a groundwater model. In the present study, groundwater depths for around 142 locations in the Tapi basin have been obtained from CGWB, Nagpur. The groundwater depth is subtracted from the digital elevation at the grid to give the water table elevation. Then, the point values of groundwater elevation at 142 points have been interpolated using kriging to give the spatial groundwater surface. Water table depth is obtained by subtracting groundwater surface from the digital elevation map. The groundwater depth map for May, 1992 for the Tapi basin is shown in Figure – 3.25.

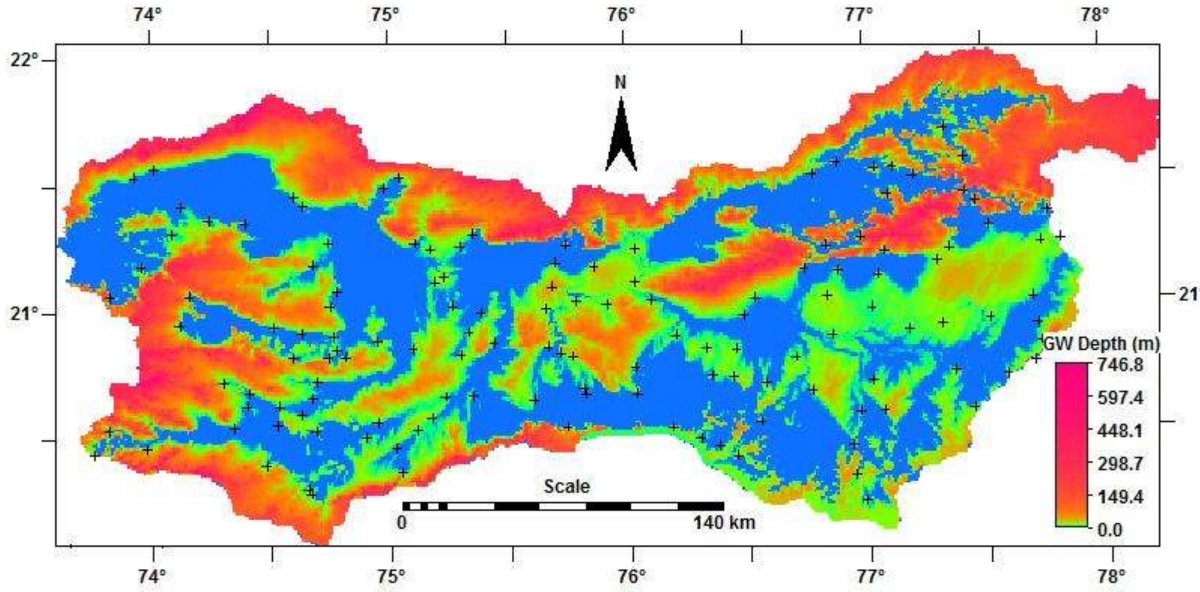


Figure – 3.25: Groundwater depth map for Tapi basin in May, 1992

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 Tapi basin, these have been obtained from different sources and are discussed in the following:

a) Crop attributes

Different crops have different characteristics, such as crop factors at different growth stages, maximum root depth, time to reach maximum root depth, starting week of crop, crop duration, standing water requirement (if any), and the fraction of the available water without affecting the yield of the crop. Starting week of crop, crop period, and crop factors as applicable to crops in the region at different growth stages have been obtained from the Design Circular No. 25 of M.P. Irrigation Department. Root depth characteristics and the fraction of available water for different crops have been obtained from the FAO – IDP 24 (1977).

Palewa depth of 150 mm for rice crop and 50 mm for other crops have been assumed. Land preparation time has been taken as one week. Bund height of 150 mm has been kept for the rice crop for maintaining standing water while for other crops, it is taken as zero. Standing water depth for rice crop has been taken as 100 mm. Since ponding conditions exist in the rice field, percolation rate of 16 mm/day has been taken in the first week which reduces to 3 mm/day in 4 weeks after the formation of hard pan at the top of soil (CWC, 1995). For other crops, percolation rate depends on the water depth available for recharge, hydraulic conductivity of soil and groundwater depth. Crop factors for forest have been considered same as that for fruit. Effective root depth for forest is taken as 2 m. Various characteristics of crops and weekly crop factors, as used in this study, are presented in Table – 3.10.

b) Soil attributes

For SCS application, soils in the Tapi River basin has been divided in four hydrological groups. The properties of different groups of soils used in this study are presented in Table – 3.11.

Table – 3.11
Soil properties used in the study

Soil Group	Specific gravity	Porosity	Field capacity (%)	Permanent wilting point (%)	Hydraulic Conductivity (m/day)
A	2.7	0.42	17.5	7.5	10
B	2.67	0.45	19.2	10.1	1
C	2.63	0.43	21.9	12.4	0.08
D	2.58	0.42	23.6	14.3	0.01

Table – 3.10
Characteristics of crops used in Tapi River Basin

Crop characteristic	Rice	Jowar	Oilseed - Kharif	Sugarcane	Cotton	Foddar - Kharif	Fruit	Veg – Kharif	Eatable - Kharif	Wheat	Gram	Oilseed - Rabi	Foddar - Rabi	Eatable - Rabi	Veg - Rabi
Fraction of available soil water	1.00	0.55	0.55	0.65	0.55	0.55	0.55	0.55	0.6	0.55	0.55	0.55	0.55	0.25	0.55
Maximum root depth (mm)	600	1000	1000	1500	1200	1000	2000	900	1200	1000	1000	1000	1000	600	900
Time to maximum root depth (weeks)	9	6	6	15	6	6	10	6	9	9	9	9	6	9	6
Required water depth for initial land preparation (mm)	150	50	50	50	50	50	50	50	50	50	50	50	50	50	50
Time of initial land preparation (weeks)	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Starting week (calendar week)	27	25	25	45	25	25	49	25	25	49	49	49	49	49	49
Period of crop (weeks)	17	16	17	51	24	16	52	14	15	18	16	18	16	17	14
Standing water depth required (mm)	100	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Time of standing water requirement (weeks)	15	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Bund height (mm)	150	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Crop Factors															
Week-1				0.61			0.65			0.80	0.83	0.50	0.83	0.72	0.67
Week-2				0.61			0.65			0.80	0.83	0.50	0.83	0.72	0.67
Week-3				0.64			0.65			1.08	1.05	1.09	1.07	1.00	1.00
Week-4				0.64			0.65			1.08	1.05	1.09	1.07	1.00	1.00
Week-5				0.66			0.65			1.10	1.05	1.10	1.10	1.15	1.00
Week-6				0.66			0.65			1.10	1.05	1.10	1.10	1.15	1.00
Week-7				0.70			0.65			1.10	0.96	1.10	1.10	1.15	1.00
Week-8				0.70			0.65			1.10	0.96	1.10	1.10	1.15	1.00
Week-9				0.75			0.65			1.07	0.68	1.09	1.02	1.11	0.94
Week-10				0.75			0.65			1.07	0.68	1.09	1.02	1.11	0.94
Week-11				0.81			0.65			0.87	0.42	0.93	0.71	0.86	
Week-12				0.81			0.66			0.87	0.42	0.93	0.71	0.86	
Week-13				0.87			0.66			0.50		0.52		0.86	
Week-14				0.87			0.69			0.50		0.52			
Week-15				0.92			0.69								
Week-16				0.92			0.70								

Crop factor for a week	Rice	Jowar	Oilseed - Kharif	Sugarcane	Cotton	Foddar - Kharif	Fruit	Veg – Kharif	Eatable - Kharif	Wheat	Gram	Oilseed - Rabi	Foddar - Rabi	Eatable - Rabi	Veg - Rabi
Week-17				0.96			0.70								
Week-18				0.96			0.71								
Week-19				1.00			0.71								
Week-20				1.00			0.72								
Week-21				1.05			0.72								
Week-22				1.05			0.72								
Week-23				1.09			0.73								
Week-24				1.09			0.73								
Week-25		0.48	0.31	1.10	0.29	0.48	0.74	0.39	0.49						
Week-26		0.48	0.31	1.10	0.29	0.48	0.74	0.39	0.49						
Week-27	1.06	0.59	0.48	1.10	0.37	0.54	0.75	0.46	0.59						
Week-28	1.06	0.59	0.48	1.10	0.37	0.54	0.75	0.46	0.59						
Week-29	1.10	0.82	0.50	1.10	0.48	0.77	0.74	0.69	0.91						
Week-30	1.10	0.82	0.50	1.10	0.48	0.77	0.74	0.69	0.91						
Week-31	1.10	1.02	1.09	1.10	0.77	0.99	0.73	1.00	1.10						
Week-32	1.10	1.02	1.09	1.10	0.77	0.99	0.73	1.00	1.10						
Week-33	1.12	1.05	1.10	1.10	0.99	1.05	0.73	1.00	1.10						
Week-34	1.12	1.05	1.10	1.06	0.99	1.05	0.72	1.00	1.10						
Week-35	1.15	1.05	1.10	1.06	1.08	1.05	0.72	1.00	1.01						
Week-36	1.15	1.05	1.10	1.02	1.08	1.05	0.70	1.00	1.01						
Week-37	1.15	0.92	1.09	1.02	1.10	1.04	0.70	0.92	0.71						
Week-38	1.15	0.92	1.09	1.00	1.10	1.04	0.70	0.92	0.71						
Week-39	1.04	0.63	0.93	1.00	1.10	0.98	0.70		0.71						
Week-40	1.04	0.63	0.93	0.98	1.10	0.98	0.70								
Week-41	0.98		0.52	0.98	1.09		0.70								
Week-42	0.98			0.51	1.09		0.69								
Week-43	0.98			0.51	1.01		0.69								
Week-44					1.01		0.67								
Week-45				0.53	0.85		0.67								
Week-46				0.53	0.85		0.65								
Week-47				0.55	0.71		0.65								
Week-48				0.55	0.71		0.65								
Week-49				0.57			0.65			0.31	0.23	0.31	0.28	0.34	0.29
Week-50				0.57			0.65			0.31	0.23	0.31	0.28	0.34	0.29
Week-51				0.59			0.65			0.42	0.29	0.48	0.47	0.42	0.37
Week-52				0.59			0.65			0.42	0.29	0.48	0.47	0.42	0.37

c) Domestic and Industrial (D&I) demand 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 lpcd (litre per capita per day), 90, and 60 respectively. The data used for various variables used for computing D & I demands is presented in Table – 3.12.

d) City attributes

City attribute includes identity of city, district in which it is located, and the hydraulic structure from which it receives water supply. In the present case, it was not known which cities are connected to reservoirs for water supply. Therefore, proximity concept is used and a city located on the downstream or very close to a reservoir is assumed to get its water supply from the reservoir. City attributes for 132 cities is mentioned in Table – 3.13.

Table – 3.13
City attributes in the Tapi River basin

City_id	Dist_id	Resr_id	City_id	Dist_id	Resr_id	City_id	Dist_id	Resr_id	City_id	Dist_id	Resr_id
1	1	0	34	5	7	67	7	0	100	7	0
2	1	0	35	3	0	68	7	11	101	7	0
3	1	0	36	4	0	69	7	0	102	7	0
4	1	0	37	5	0	70	7	45	103	7	0
5	1	0	38	5	0	71	7	46	104	7	0
6	2	0	39	5	0	72	7	0	105	9	30
7	2	0	40	5	40	73	7	0	106	9	0
8	2	0	41	5	0	74	7	0	107	9	0
9	2	0	42	5	0	75	7	0	108	9	0
10	2	0	43	5	0	76	7	0	109	9	0
11	2	0	44	5	0	77	7	0	110	9	66
12	2	0	45	5	0	78	7	0	111	9	0
13	2	0	46	5	41	79	7	0	112	9	0
14	2	0	47	4	0	80	7	0	113	9	24
15	2	0	48	4	0	81	7	0	114	7	20
16	2	0	49	4	0	82	7	0	115	7	0
17	2	0	50	7	0	83	7	0	116	10	20
18	2	0	51	5	0	84	7	0	117	10	0
19	2	0	52	5	0	85	7	0	118	9	0
20	3	0	53	5	10	86	8	0	119	9	0
21	3	0	54	5	0	87	7	0	120	9	0
22	2	0	55	5	0	88	7	0	121	9	0
23	3	0	56	7	11	89	7	0	122	9	0
24	2	0	57	7	11	90	7	0	123	9	0
25	3	0	58	7	0	91	8	59	124	9	0
26	3	0	59	7	0	92	7	0	125	9	77
27	3	0	60	5	0	93	7	0	126	9	0
28	3	4	61	5	0	94	7	0	127	9	65
29	3	0	62	7	0	95	7	0	128	10	0
30	3	0	63	7	0	96	7	23	129	10	0
31	3	0	64	7	0	97	7	0	130	10	0
32	3	0	65	7	13	98	7	0	131	10	0

Table – 3.12

Domestic and Industrial Demand Details of Different Districts Used in the Study

District	Population		District Area	Forest Area	Water-spread Area	Urban Area	Area within Basin	Urban Population (%)	Urban demand (lpcd)	Rural demand (lpcd)	Cattle demand (lpcd)	Surface water use (%)	Consump-tive use factor	Drainage in surface water (%)
	Human	Cattle												
Betul	480667	345965	10078	3956	14	21	4069	18.62	140	90	60	30	0.8	10
Amrawati	1422608	672610	12217	3096	3	140	7798	32.59	140	90	60	45	0.8	10
Akola	1399475	758564	10560	649	67	208	6380	28.64	140	90	60	45	0.8	10
Khandwa	508859	303712	11183	5116	49	62	3823	27.53	140	90	60	18	0.8	10
Buldhana	1170096	677515	9671	1148	50	181	5996	20.57	140	90	60	45	0.8	10
Khargaon	274479	200964	13485	4309	0	5	2498	15.05	140	90	60	32	0.8	10
Jalgaon	3067755	1598641	11639	1567	110	209	11315	27.45	140	90	60	45	0.8	10
Aurangabad	214215	117428	10077	724	91	168	1000	32.75	140	90	60	45	0.8	10
Dhule	2006050	1282815	14380	5520	87	149	11350	20.5	140	90	60	45	0.8	10
Nasik	1514881	918603	15634	3335	113	301	6085	35.55	140	90	60	45	0.8	10
Surat	328321	79403	7762	1418	600	60	1672	50.56	140	90	60	100	0.8	10

e) River network attributes

There are 1197 river segments in Tapi 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 – 3.14
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	Id of 3rd seg
1	1	3	33	0			
2	2	0	0	1	1		
3	1	0	0	0			
4	1	0	0	0			
5	3	0	0	3	2	3	4
6	1	0	0	0			
7	1	0	0	0			
8	2	0	0	2	6	7	
9	4	0	0	2	5	8	
10	1	0	0	0			
11	5	0	0	2	9	10	
12	1	3	1	0			
13	2	0	0	1	12		
14	6	0	0	2	11	13	
15	1	0	0	0			
16	1	0	0	0			
17	2	0	0	2	15	16	
18	7	0	0	2	14	17	
19	1	0	0	0			
20	8	0	0	2	18	19	
21	1	0	0	0			
22	1	0	0	0			
23	2	0	0	2	21	22	
24	1	0	0	0			
25	3	0	0	2	23	24	
26	9	0	0	2	20	25	
27	1	0	0	0			
28	1	0	0	0			
29	2	0	0	2	27	28	
30	10	0	0	2	26	29	
:	:	:	:	:			
122	34	1	1	2	95	121	
123	1	0	0	0			
124	35	0	0	2	122	123	
:	:	:	:	:			
191	1	3	12	0			
192	2	0	0	1	191		
193	52	0	0	2	190	192	
:	:	:	:	:			
208	6	3	13	2	206	207	
209	7	0	0	1	208		
210	54	0	0	2	197	209	
:	:	:	:	:			

f) Hydraulic structure attributes

In addition to the Ukai dam, 77 reservoirs have been considered in the basin. Information of 32 reservoirs (water spread area at FRL, storage capacity, CCA etc.) have been available from the data year books of CWC for the basin. For other reservoirs, the same have been estimated by developing a relation between the unknown variable with water spread area. Since water spread areas for all the structures have been computed from the remote sensing image, various other variables have been roughly estimated by using the developed relationships.

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. The details of hydraulic structures used in the present study are given in Table – 3.15.

g) Gauging station attributes

Various sub-basins in a river basin are delineated on the basis of location of different gauging stations in the basin. Observed flow at each gauging site can be used to calibrate and validate the model parameters for the corresponding sub-basin. Various attributes for a gauging station

Table – 3.15
Details of Various Hydraulic Structures Used in the Study

Res_id	ET_Stn	Sb_Bas	Div_Cp (cumec)	Liv_Cp (MCM)	Ini_Cp (MCM)	SW_Eff (%)	GW_Eff (%)	PPA	Are_FRL (sq. km)	Minimum d/s Flow (cumec)											
										Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1	1	1	0	4.59	0.92	0.4	0.6	100	1.21	0.01	0.005	0	0	0	0.01	0.02	0.03	0.02	0.02	0.015	0.015
2	2	4	0	12.79	2.56	0.4	0.6	49	2.46	0.01	0.005	0	0	0	0.01	0.02	0.03	0.02	0.02	0.015	0.015
3	3	3	0	11.68	2.34	0.4	0.6	37	3.60	0.01	0.005	0	0	0	0.01	0.02	0.03	0.02	0.02	0.015	0.015
4	3	4	0	86.35	17.27	0.4	0.6	100	13.48	0.03	0.015	0	0	0	0.03	0.03	0.05	0.04	0.04	0.03	0.03
5	3	4	0	41.46	8.29	0.4	0.6	100	4.16	0.01	0.005	0	0	0	0.01	0.02	0.03	0.02	0.02	0.015	0.015
6	3	4	0	28.85	5.77	0.4	0.6	100	4.62	0.01	0.005	0	0	0	0.01	0.02	0.03	0.02	0.02	0.015	0.015
7	3	4	0	15.14	3.03	0.4	0.6	100	4.12	0.01	0.005	0	0	0	0.01	0.02	0.03	0.02	0.02	0.015	0.015
8	5	6	0	33.93	6.79	0.4	0.6	100	3.19	0.01	0.005	0	0	0	0.01	0.02	0.03	0.02	0.02	0.015	0.015
9	5	6	0	7.51	1.5	0.4	0.6	50	1.62	0.01	0.005	0	0	0	0.01	0.02	0.03	0.02	0.02	0.015	0.015
10	5	6	0	69.32	13.86	0.4	0.6	78	9.42	0.03	0.015	0	0	0	0.03	0.03	0.05	0.04	0.04	0.03	0.03
11	6	6	0	255	51	0.4	0.6	56	46.8	0.1	0.05	0	0	0	0.1	0.2	0.3	0.2	0.2	0.15	0.15
12	6	6	0	6.02	1.2	0.4	0.6	23	1.33	0.01	0.005	0	0	0	0.01	0.02	0.03	0.02	0.02	0.015	0.015
13	6	6	0	39.85	7.97	0.4	0.6	46	4.32	0.01	0.005	0	0	0	0.01	0.02	0.03	0.02	0.02	0.015	0.015
14	5	6	0	4.64	0.93	0.4	0.6	83	1.07	0.01	0.005	0	0	0	0.01	0.02	0.03	0.02	0.02	0.015	0.015
15	5	6	0	7.38	1.48	0.4	0.6	89	1.62	0.01	0.005	0	0	0	0.01	0.02	0.03	0.02	0.02	0.015	0.015
16	7	5	0	48.43	9.69	0.4	0.6	50	8.00	0.01	0.005	0	0	0	0.01	0.02	0.03	0.02	0.02	0.015	0.015
17	7	5	0	5.4	1.08	0.4	0.6	32	1.31	0.01	0.005	0	0	0	0.01	0.02	0.03	0.02	0.02	0.015	0.015
18	7	5	0	21.71	4.34	0.4	0.6	44	3.84	0.01	0.005	0	0	0	0.01	0.02	0.03	0.02	0.02	0.015	0.015
19	7	5	0	11.24	2.25	0.4	0.6	68	0.48	0.01	0.005	0	0	0	0.01	0.02	0.03	0.02	0.02	0.015	0.015
20	7	5	0	523.55	104.71	0.4	0.6	55	28.51	0.2	0.1	0	0	0	0.2	0.4	0.6	0.4	0.4	0.3	0.3
21	7	5	0	40.27	8.05	0.4	0.6	72	4.48	0.01	0.005	0	0	0	0.01	0.02	0.03	0.02	0.02	0.015	0.015
22	6	5	0	2.14	0.43	0.4	0.6	27	0.8	0.01	0.005	0	0	0	0.01	0.02	0.03	0.02	0.02	0.015	0.015
23	6	5	0	2.76	0.55	0.4	0.6	30	1.04	0.01	0.005	0	0	0	0.01	0.02	0.03	0.02	0.02	0.015	0.015
24	7	7	0	8.45	1.69	0.4	0.6	91	1.82	0.01	0.005	0	0	0	0.01	0.02	0.03	0.02	0.02	0.015	0.015
25	7	7	0	25.15	5.03	0.4	0.6	80	7.1	0.01	0.005	0	0	0	0.01	0.02	0.03	0.02	0.02	0.015	0.015
26	6	7	0	6.54	1.31	0.4	0.6	59	0.74	0.01	0.005	0	0	0	0.01	0.02	0.03	0.02	0.02	0.015	0.015
27	6	9	0	56.38	11.28	0.4	0.6	54	8.32	0.01	0.005	0	0	0	0.01	0.02	0.03	0.02	0.02	0.015	0.015
28	7	8	0	35.63	7.13	0.4	0.6	51	4.36	0.01	0.005	0	0	0	0.01	0.02	0.03	0.02	0.02	0.015	0.015
29	7	8	0	11.35	2.27	0.4	0.6	56	0.9	0.01	0.005	0	0	0	0.01	0.02	0.03	0.02	0.02	0.015	0.015
30	6	10	0	31.15	6.23	0.4	0.6	55	4.67	0.01	0.005	0	0	0	0.01	0.02	0.03	0.02	0.02	0.015	0.015
31	7	10	0	14.21	2.84	0.4	0.6	60	2.66	0.01	0.005	0	0	0	0.01	0.02	0.03	0.02	0.02	0.015	0.015
32	8	11	0	12.89	2.58	0.4	0.6	63	2.5	0.01	0.005	0	0	0	0.01	0.02	0.03	0.02	0.02	0.015	0.015
33	1	1	0	11.41	2.28	0.4	0.6	32	2.24	0.01	0.005	0	0	0	0.01	0.02	0.03	0.02	0.02	0.015	0.015
34	3	3	0	4.04	0.81	0.4	0.6	95	1.1	0.01	0.005	0	0	0	0.01	0.02	0.03	0.02	0.02	0.015	0.015
35	3	4	0	3.34	0.67	0.4	0.6	20	0.99	0.01	0.005	0	0	0	0.01	0.02	0.03	0.02	0.02	0.015	0.015
36	3	4	0	1.43	0.29	0.4	0.6	24	0.69	0.01	0.005	0	0	0	0.01	0.02	0.03	0.02	0.02	0.015	0.015
37	3	4	0	2.13	0.43	0.4	0.6	71	0.8	0.01	0.005	0	0	0	0.01	0.02	0.03	0.02	0.02	0.015	0.015
38	3	4	0	0.72	0.14	0.4	0.6	46	0.58	0.01	0.005	0	0	0	0.01	0.02	0.03	0.02	0.02	0.015	0.015
39	3	4	0	8.98	1.79	0.4	0.6	48	1.86	0.01	0.005	0	0	0	0.01	0.02	0.03	0.02	0.02	0.015	0.015

Res_id	ET_Stn	Sb_Bas	Div_Cp (cumec)	Liv_Cp (MCM)	Ini_Cp (MCM)	SW_Eff (%)	GW_Eff (%)	PPA	Ar_FRL (sq. km)	Minimum Flow (cumec)											
										Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
40	5	4	0	1.05	0.21	0.4	0.6	87	0.63	0.01	0.005	0	0	0	0.01	0.02	0.03	0.02	0.02	0.015	0.015
41	5	6	0	0.1	0.02	0.4	0.6	77	0.39	0.01	0.005	0	0	0	0.01	0.02	0.03	0.02	0.02	0.015	0.015
42	5	6	0	0.88	0.17	0.4	0.6	10	0.61	0.01	0.005	0	0	0	0.01	0.02	0.03	0.02	0.02	0.015	0.015
43	5	6	0	0.14	0.03	0.4	0.6	10	0.49	0.01	0.005	0	0	0	0.01	0.02	0.03	0.02	0.02	0.015	0.015
44	6	6	0	6.86	1.37	0.4	0.6	44	1.54	0.01	0.005	0	0	0	0.01	0.02	0.03	0.02	0.02	0.015	0.015
45	6	6	0	0.08	0.02	0.4	0.6	50	0.32	0.01	0.005	0	0	0	0.01	0.02	0.03	0.02	0.02	0.015	0.015
46	6	6	0	0.09	0.02	0.4	0.6	47	0.38	0.01	0.005	0	0	0	0.01	0.02	0.03	0.02	0.02	0.015	0.015
47	6	6	0	1.65	0.33	0.4	0.6	47	0.73	0.01	0.005	0	0	0	0.01	0.02	0.03	0.02	0.02	0.015	0.015
48	6	6	0	0.14	0.03	0.4	0.6	56	0.44	0.01	0.005	0	0	0	0.01	0.02	0.03	0.02	0.02	0.015	0.015
49	5	6	0	5.33	1.07	0.4	0.6	24	1.3	0.01	0.005	0	0	0	0.01	0.02	0.03	0.02	0.02	0.015	0.015
50	5	6	0	1.99	0.4	0.4	0.6	11	0.78	0.01	0.005	0	0	0	0.01	0.02	0.03	0.02	0.02	0.015	0.015
51	5	6	0	1.91	0.4	0.4	0.6	61	0.77	0.01	0.005	0	0	0	0.01	0.02	0.03	0.02	0.02	0.015	0.015
52	5	6	0	1.39	0.28	0.4	0.6	10	0.68	0.01	0.005	0	0	0	0.01	0.02	0.03	0.02	0.02	0.015	0.015
53	7	5	0	0.06	0.01	0.4	0.6	14	0.48	0.01	0.005	0	0	0	0.01	0.02	0.03	0.02	0.02	0.015	0.015
54	7	5	0	0.16	0.03	0.4	0.6	46	0.46	0.01	0.005	0	0	0	0.01	0.02	0.03	0.02	0.02	0.015	0.015
55	7	5	0	0.1	0.02	0.4	0.6	49	0.39	0.01	0.005	0	0	0	0.01	0.02	0.03	0.02	0.02	0.015	0.015
56	7	5	0	3.42	0.7	0.4	0.6	52	1	0.01	0.005	0	0	0	0.01	0.02	0.03	0.02	0.02	0.015	0.015
57	6	5	0	3.13	0.63	0.4	0.6	22	0.96	0.01	0.005	0	0	0	0.01	0.02	0.03	0.02	0.02	0.015	0.015
58	6	5	0	2.9	0.58	0.4	0.6	10	0.92	0.01	0.005	0	0	0	0.01	0.02	0.03	0.02	0.02	0.015	0.015
59	6	5	0	0.23	0.05	0.4	0.6	44	0.51	0.01	0.005	0	0	0	0.01	0.02	0.03	0.02	0.02	0.015	0.015
60	6	6	0	3.66	0.73	0.4	0.6	35	1.04	0.01	0.005	0	0	0	0.01	0.02	0.03	0.02	0.02	0.015	0.015
61	7	7	0	6.03	1.21	0.4	0.6	13	1.41	0.01	0.005	0	0	0	0.01	0.02	0.03	0.02	0.02	0.015	0.015
62	6	7	0	0.79	0.16	0.4	0.6	36	0.59	0.01	0.005	0	0	0	0.01	0.02	0.03	0.02	0.02	0.015	0.015
63	6	9	0	5.01	1	0.4	0.6	30	1.25	0.01	0.005	0	0	0	0.01	0.02	0.03	0.02	0.02	0.015	0.015
64	6	9	0	2.75	0.55	0.4	0.6	23	0.9	0.01	0.005	0	0	0	0.01	0.02	0.03	0.02	0.02	0.015	0.015
65	7	8	0	0.16	0.03	0.4	0.6	35	0.46	0.01	0.005	0	0	0	0.01	0.02	0.03	0.02	0.02	0.015	0.015
66	7	8	0	5.38	1.08	0.4	0.6	56	1.31	0.01	0.005	0	0	0	0.01	0.02	0.03	0.02	0.02	0.015	0.015
67	7	8	0	1.59	0.32	0.4	0.6	44	0.72	0.01	0.005	0	0	0	0.01	0.02	0.03	0.02	0.02	0.015	0.015
68	7	9	0	4.56	0.91	0.4	0.6	20	1.18	0.01	0.005	0	0	0	0.01	0.02	0.03	0.02	0.02	0.015	0.015
69	7	10	0	4.05	0.81	0.4	0.6	48	1.1	0.01	0.005	0	0	0	0.01	0.02	0.03	0.02	0.02	0.015	0.015
70	7	10	0	2.24	0.45	0.4	0.6	55	0.82	0.01	0.005	0	0	0	0.01	0.02	0.03	0.02	0.02	0.015	0.015
71	7	10	0	3.83	0.77	0.4	0.6	49	1.06	0.01	0.005	0	0	0	0.01	0.02	0.03	0.02	0.02	0.015	0.015
72	7	10	0	1.06	0.21	0.4	0.6	52	0.63	0.01	0.005	0	0	0	0.01	0.02	0.03	0.02	0.02	0.015	0.015
73	7	10	0	2.13	0.43	0.4	0.6	24	0.8	0.01	0.005	0	0	0	0.01	0.02	0.03	0.02	0.02	0.015	0.015
74	7	10	0	1.82	0.36	0.4	0.6	27	0.75	0.01	0.005	0	0	0	0.01	0.02	0.03	0.02	0.02	0.015	0.015
75	6	10	0	1.44	0.29	0.4	0.6	10	0.69	0.01	0.005	0	0	0	0.01	0.02	0.03	0.02	0.02	0.015	0.015
76	6	10	0	0.89	0.18	0.4	0.6	23	0.61	0.01	0.005	0	0	0	0.01	0.02	0.03	0.02	0.02	0.015	0.015
77	7	10	0	3.98	0.82	0.4	0.6	58	1.09	0.01	0.005	0	0	0	0.01	0.02	0.03	0.02	0.02	0.015	0.015

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. Gauging site attributes for the Tapi basin are given in Table 3.16.

Table – 3.16
Gauging sites attributes in the Tapi River Basin

Name of Gauging Site	GGST_id	Riv_id on which located	Bed level (m)	No. of u/s sub-basins	Ids of u/s sub-basins
Dedtalai	1	122	270	0	-
Burhanpur	2	165	213	1	1
Lakhpuri	3	272	259	0	-
Yerli	4	498	213	1	3
Dapuri	5	816	188	0	-
Savkheda	6	844	141	5	1, 2, 3, 4, 5
Malkheda	7	909	170	0	-
Morane	8	973	265	0	-
Gidhade	9	989	119	8	1, 2, 3, 4, 5, 6, 7, 8
Sarangkheda	10	1062	108	9	1, 2, 3, 4, 5, 6, 7, 8, 9

h) Groundwater development attributes

Information related to annual groundwater development in the Tapi basin for different districts have been available in the NWDA study. The same has been converted to grid-wise daily development by uniformly distributing the groundwater use in agricultural and urban grids in that district. District-wise groundwater development is Tapi basin is given in Table – 3.17.

Table – 3.17
District-wise groundwater development in Tapi basin

District	Dist_id	Groundwater development (MCM)
Betul	1	100
Amrawati	2	200
Akola	3	120
Khandwa	4	100
Buldhana	5	170
Khargaon	6	50
Jalgaon	7	540
Aurangabad	8	40
Dhule	9	330
Nasik	10	220
Surat	11	25

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 Tapi basin, these have been obtained from different sources and are discussed in the following:

a) Reference evapo-transpiration

The simulation model uses daily reference evapo-transpiration data to estimate the evapo-transpiration loss from different land uses. On a day, evapo-transpiration is a function of maximum and minimum temperature, average humidity, sunshine radiation, wind speed, and the latitude and altitude of a place. In the present study, daily evapo-transpiration values at various meteorological stations in the basin were not available. However, long-term monthly average meteorological variables have been available.

These variables have been used to compute the average reference evapo-transpiration in different months. CROPWAT model has been used to compute the reference evapo-transpiration from the average meteorological data for 8 stations in the basin. Penman-Monteith method has been used for the computation. The reference evapo-transpiration values obtained for different stations and for different months are given in Table – 3.18.

Table – 3.18
Average monthly reference evapo-transpiration depths at different stations

ET Station	ETS_id	Reference evapo-transpiration (mm) per day in the month											
		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Betul	1	3.31	4.30	5.41	6.23	7.23	6.05	3.49	2.97	3.74	3.93	3.32	2.91
Amrawati	2	5.22	6.68	8.03	9.17	10.48	9.26	5.49	4.68	5.19	5.60	5.29	4.69
Akola	3	3.93	5.12	6.55	7.94	10.58	8.71	5.33	4.60	5.18	4.80	3.76	3.36
Khandwa	4	4.11	5.36	7.00	8.86	11.03	9.25	5.32	4.35	5.21	4.94	3.89	3.43
Buldhana	5	4.51	5.80	7.18	8.60	9.76	7.42	4.50	3.77	4.52	4.77	4.13	3.92
Jalgaon	6	5.45	7.01	9.04	11.35	14.34	10.65	6.00	4.66	5.53	5.78	5.42	5.03
Malegaon	7	4.00	5.29	6.87	8.64	10.25	8.18	5.70	4.91	5.31	5.17	4.08	3.53
Surat	8	4.98	5.99	7.09	7.95	8.35	6.03	4.20	3.70	4.77	5.51	5.16	4.87

b) Rainfall data

Daily rainfall data at 55 rain gauge stations within the Tapi basin have been available for the years 1990, 1992, 1993, 1994, 1995, 1996, and 1997. accumulated annual values of rainfall for all the stations is presented in Table – 3.19.

Table – 3.19
Annual rainfall at different raingauge stations used in the study

Raingauge Station	Annual rainfall (mm) in different years						
	1990	1992	1993	1994	1995	1996	1997
Multai	1008.4	474.8	1328.6	1554.2	675.4	875.4	1465.9
Betul	1603.4	1084.5	1367	1517.4	1192.2	1074.1	1463.7
Atner	970.8	587.9	936	1051.15	635.8	800.4	1064.1
Chicholi	2189.5	1084.5	1705.1	1840.3	1134.2	906.5	959.8
Bhaindeshi	1470.2	830.2	1122.4	1327	854.6	1088.8	1162.6
Chandur Bazar	721.2	742.8	721.9	1060.6	615.4	894.9	987.6
Amrawati	1165.6	539.9	872.4	1146.6	255.4	605.3	1006.7
Chikhalda	2400.03	1593.6	1850.7	1636.3	1442.2	1737.6	1825
Anjangaon	731.3	482.2	698.3	716	723.4	582.6	889.6
Daryapur	1081.6	488.5	343.1	745.6	76.6	605.3	783.9
Murtzapur	1488	1030	733	880	660.4	722.6	791
Karanjia	1197.4	977.5	752	896.5	895	668.5	800
Dharni	2117.8	1075.9	1343.4	1636.3	1307.8	1157.1	915.8
Akot	1180.3	660.3	676.5	938	741.2	622.6	678.5
Telhera	1235.4	755.3	849.7	772.2	879.3	776	847.7
Shegaon	792.2	658.9	794	758.9	573	691.5	870.3
Balapur	802.7	782	738	838	579.4	618	744
Akola	1074.4	782	857	1143.3	757.9	770.2	818.3
Patur	1204	1006	976.5	1160	700.9	744	992
Mangrulpur	1234.9	995	757	1023	870	1043	815
Sirpur	657.2	642	723	628	409.2	725	854
Khandwa	1442.6	1485	1120	1276.8	914	956.8	940.1
Burhanpur	1107	893	1409	1006	1085.4	1259.02	1098
Jalgaon	766.6	778.2	856.8	779.2	581.4	695.5	757.1
Nandura	593	630.4	794	812	553	547	524.1
Khamgaon	721.2	875	692	813.4	487.6	672.1	675.6
Mekhar	1005	957	753	684.8	661.2	776.6	641
Chikhili	666	857.8	850.6	516.6	531	723.5	993.2
Raver	483.8	597	1032	704	715	614	875
Edalabad	645	545	941.4	849.7	618.1	528.6	785.2
Malakpur	656	536.8	671	600	605	707.4	1017.4
Buldana	1024.5	857.8	857.4	908.9	862.4	723.5	1039
Yaval	917	641	816	754	736.3	746	630
Bhusaval	766.6	666.5	878.3	945.2	700.3	607.3	626.8
Jamner	1053	852	773.1	887.4	764.5	596.2	887.2
Khargaon	1188.4	519.9	1148.7	464.6	367.6	922.6	531.3
Chopada	871	844	841	925	662	631	756
Erandol	1141.3	838	683	659	522.2	535	794
Pachora	839	621	741.6	402.2	541	879	799.5
Amalner	800.8	1599.8	493.4	651.5	390.4	651	575
Parola	632	877	624	785	630	631	808
Bhadgaon	915	738	749	683	613.8	833.6	966
Chalisgaon	893	690	891	527	528	849	1003
Pansemal	997.6	519.9	882.8	843.7	509.3	669.8	668.4
Sindkheda	515.8	414	446	641	413.5	553.5	754
Dhulia	431	686.6	425.5	700	496.6	639	573
Malegaon	468.4	715.8	449.5	902.5	949.1	864.4	600
Shahada	835.1	601	653	906.4	439.1	616.1	548.9
Nandurbar	967.4	652.8	891.2	976.6	601	683	1292
Sakri	575.2	453.4	665	523.4	544.6	397	474
Kalvan	619	594	615.9	1066.5	437	614	941
Chandor	781	580	563	587	668	576	706
Yeola	609	469	734	556	499	896	461.3
Taloda	1100.9	947.2	997	1161.2	674.4	843.1	984.1
Navapur	1093.5	1137.2	1350.1	1428.3	900	1207.4	1329

c) Import/export

Import/export to river segments and hydraulic structures are specified in two different files. Import/export for each river segment (or a reservoir) is specified at weekly time step. The model uniformly distributes the weekly values among different days of the week and uses the same for hydrological computations.

In the present case, no import/export either from river-to-river or river-to-reservoir or reservoir-to-river has been considered.

This completes the description of database development for the Tapi River basin. 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 in this study has been applied to the Tapi River basin to check for its linkages, computational algorithm, and performance analysis. Spatial, attribute, and dynamic data has been collected for the Tapi basin. Fifteen spatial data layers have been generated in ILWIS GIS system using remote sensing analysis and GIS analysis. The basin DEM and other topographic attributes have been obtained from SRTM data. Multi-temporal NOAA AVHRR data (1 km resolution) has been used for determining cropping pattern and delineating the irrigable command areas of different reservoirs. Landsat TM data of the basin has been used for locating major and medium 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 1995-96 has been obtained from CWC. Average evapo-transpiration depths have been worked out through CROPWAT model by using the long-term average meteorological parameters.

It needs to be mentioned here that database requirement of the model is quite extensive. Since this study has been mainly concerned with the model development and its testing for a river basin, individual efforts have been made by the study team to gather the information for the Tapi 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 Tapi basin and discussion of type of results generated by the model. A few checks related to the model computations have been discussed. Finally, annual hydrological variables for different sub-basins have been presented and comparison graphs between observed and simulated river flows at different gauging stations are presented. The limitations of the present study are also discussed.

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 run. At the end of each day, the soil moisture at each grid 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) is used as input for the groundwater simulation model for generating revised groundwater table for the subsequent month.

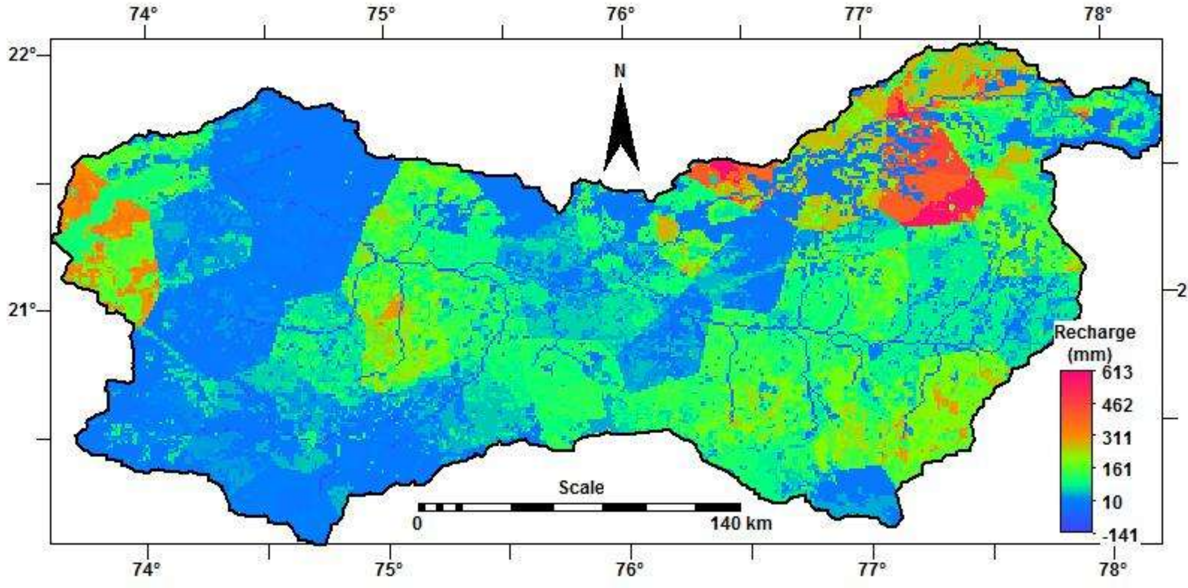


Figure – 4.1: Image showing monthly GW pumping/recharge during a month

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 actual evapo-transpiration map (shown in Figure – 4.3) represents the areas having major ET losses in the basin.

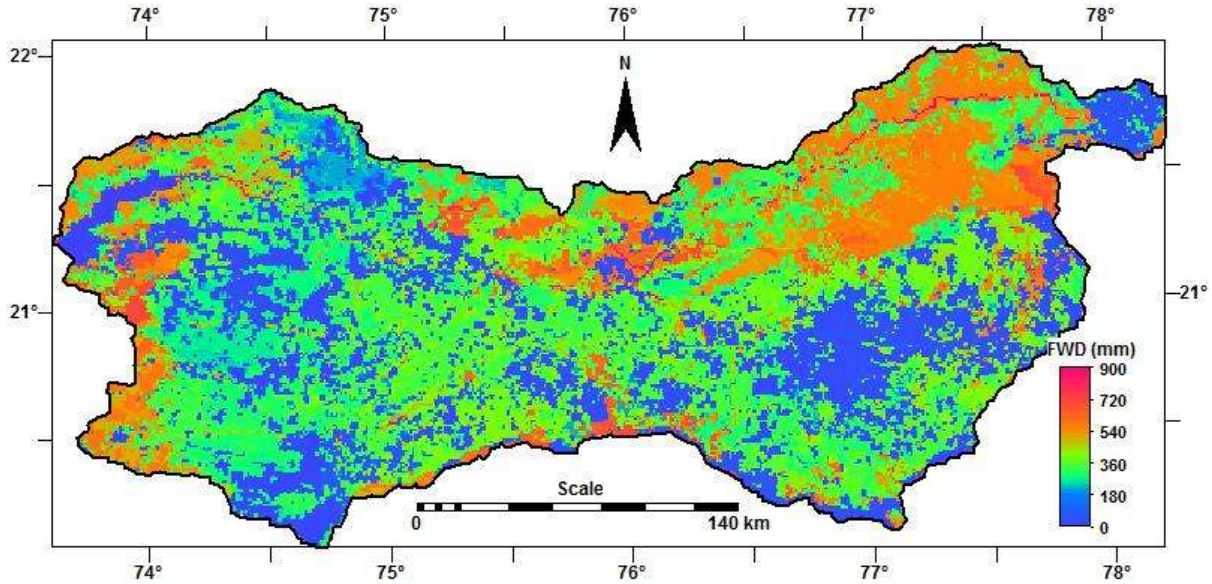


Figure – 4.2: Final soil moisture status map of Tapi basin at the end of a month

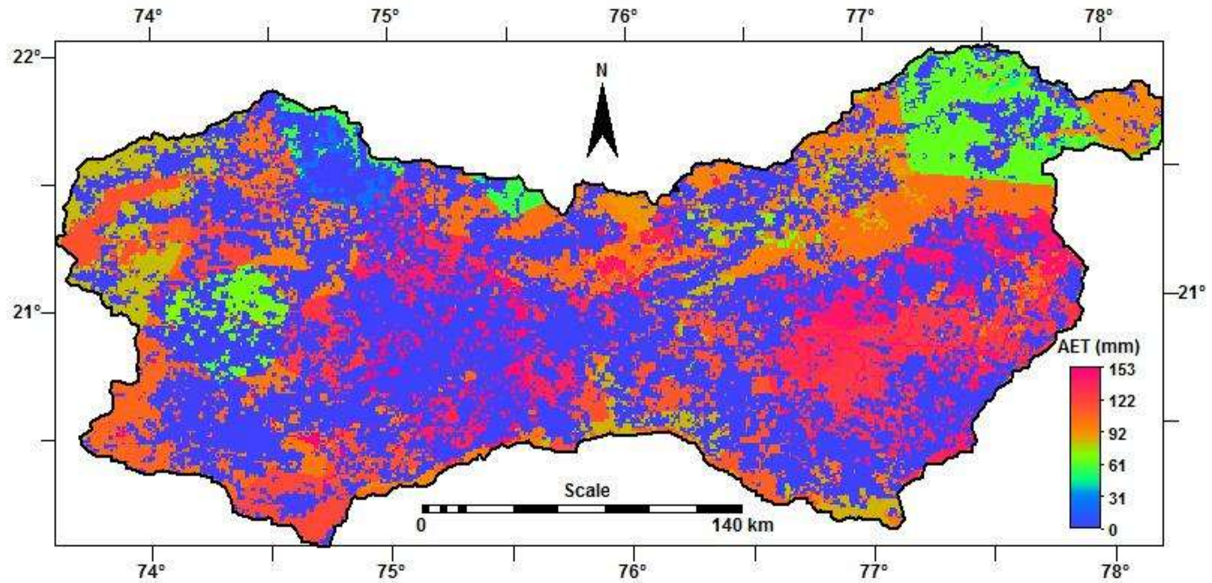


Figure – 4.3: Actual ET map of Tapi basin at the end of a month

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 presented in Table – 4.1.

Table – 4.1
Sample monthly flow table

```
---------------------------------------------------------------------------
Monthly Flow (Mm3) Results for Year 1992 and Month 08

St_Code  St_Name           Bas_Flow       Tot_Flow      SBas_Rainfall
01       Dedtalai            .1854        1704.809        3549.684
02       Burhanpur           .2738        2248.074        1145.205
03       Lakhpuri            .0415         195.559        1043.472
04       Yerli               .2910        1083.298        3947.061
05       Dapuri              .3049         201.558        1486.473
06       Savkheda           1.3802        3738.230        2562.523
07       Malkheda            .0368          32.563         393.525
08       Morane              .0469          28.252         368.398
09       Gidhade            1.7121        3953.740         795.454
10       Sarangkheda        1.8502        3985.081         404.477
11       Ukai dam           1.9759        4147.173        1363.461
---------------------------------------------------------------------------
```

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

A sample monthly working table of 32 major/medium reservoirs for a month is presented in Table – 4.2. The table shows the cumulative sum of the daily demands, supplies, spills, evaporation, inflows, import, export etc. for the entire month. A sample daily working table of Hathnur reservoir for a month is presented in Table – 4.3.

The sample table showing the hydrological details for various sub-basins is presented in Table – 4.4. The table is generated for the August 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 the domestic demand/supply, hydrological variables for different land uses, irrigation demand/supply, and reservoir details, there is a separate section in each sub-basin that 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 – 4.2
Sample output of monthly operation simulation of a reservoir

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

Table – 4.3
Sample output of Daily operation simulation of a reservoir

```
          Daily Operation Simulation of Various Reservoirs (Mm3) for the Year 1992 and Month 08
                                          Reservoir ---Hathnur
Day   Ini_St   Inflow   Import     Evap   WS_Dem   Mn_Dem   Ir_Dem   WS_Sup   Mn_Sup   Ir_Sup    Spill   Export   Fin_St
 01  253.012    2.531     .000     .421     .006     .026    1.292     .006     .026    1.292     .000     .000  253.797
 02  253.797    7.575     .000     .358     .006     .026     .285     .006     .026     .285    5.696     .000  255.000
 03  255.000  143.774     .000     .358     .006     .026     .000     .006     .026     .000  143.383     .000  255.000
 04  255.000   44.168     .000     .358     .006     .026     .000     .006     .026     .000   43.778     .000  255.000
 05  255.000   54.850     .000     .358     .006     .026     .623     .006     .026     .623   53.836     .000  255.000
 06  255.000    2.497     .000     .358     .006     .026    1.073     .006     .026    1.073    1.034     .000  255.000
 07  255.000   23.119     .000     .358     .006     .026    1.337     .006     .026    1.337   21.391     .000  255.000
 08  255.000  447.230     .000     .358     .006     .026    1.157     .006     .026    1.157  445.682     .000  255.000
 09  255.000  205.489     .000     .358     .006     .026    1.155     .006     .026    1.155  203.943     .000  255.000
 10  255.000  115.581     .000     .358     .006     .026     .223     .006     .026     .223  114.968     .000  255.000
 11  255.000   23.695     .000     .358     .006     .026     .362     .006     .026     .362   22.942     .000  255.000
 12  255.000   91.026     .000     .358     .006     .026     .416     .006     .026     .416   90.219     .000  255.000
 13  255.000  179.621     .000     .358     .006     .026    1.088     .006     .026    1.088  178.142     .000  255.000
 14  255.000   73.616     .000     .358     .006     .026     .560     .006     .026     .560   72.665     .000  255.000
 15  255.000  154.120     .000     .358     .006     .026    1.017     .006     .026    1.017  152.712     .000  255.000
 16  255.000  637.441     .000     .358     .006     .026     .015     .006     .026     .015  637.036     .000  255.000
 17  255.000  305.171     .000     .358     .006     .026     .007     .006     .026     .007  304.773     .000  255.000
 18  255.000   97.415     .000     .358     .006     .026     .007     .006     .026     .007   97.017     .000  255.000
 19  255.000  169.809     .000     .358     .006     .026     .073     .006     .026     .073  169.345     .000  255.000
 20  255.000   40.230     .000     .358     .006     .026     .722     .006     .026     .722   39.117     .000  255.000
 21  255.000  349.646     .000     .358     .006     .026     .000     .006     .026     .000  349.255     .000  255.000
 22  255.000  131.434     .000     .358     .006     .026     .182     .006     .026     .182  130.862     .000  255.000
 23  255.000     .896     .000     .358     .006     .026     .514     .006     .026     .514     .000     .000  254.991
 24  254.991   16.927     .000     .358     .006     .026     .761     .006     .026     .761   15.766     .000  255.000
 25  255.000   18.235     .000     .358     .006     .026     .990     .006     .026     .990   16.855     .000  255.000
 26  255.000    2.440     .000     .358     .006     .026    1.269     .006     .026    1.269     .780     .000  255.000
 27  255.000     .375     .000     .358     .006     .026    1.214     .006     .026    1.214     .000     .000  253.770
 28  253.770     .672     .000     .358     .006     .026    1.226     .006     .026    1.226     .000     .000  252.826
 29  252.826     .593     .000     .356     .006     .026    1.293     .006     .026    1.293     .000     .000  251.737
 30  251.737  102.665     .000     .358     .006     .026    1.129     .006     .026    1.129   97.882     .000  255.000
 31  255.000   12.168     .000     .358     .006     .026    1.098     .006     .026    1.098   10.680     .000  255.000
```

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

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

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

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

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

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

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

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

```
                    Sub-basin --- Burhanpur
                   -------------------------


          Domestic & Industrial Demands and Supply (Mm3)
         ------------------------------------------------
      Total WS Demand in Rural Area             =       .3541
      Total WS Demand in Urban Area             =       .3125
      Total GW Withdrawal for meeting WS Demand =       .6666
      Total SW Supply for meeting WS Demand     =       .0000
      Total GW Recharge from WS Discharge       =       .0000
      Total Overland Flow from WS Discharge     =       .0250


          Hydrological Details Under Different Landuses (Mm3)
         -----------------------------------------------------
                          Urban  RFed_Agr   Irr_Agr    Forest   Barren   Water      Total
Area (Sq. km)                17      1200       127       947        5       0       2296
Rainfall                11.0620  611.2870   51.8310  469.0200   2.0050   .0000  1145.2050
Surface Inflow            .0000     .0000     .0000     .0000    .0000   .0000      .0000
GW Contribution           .0000     .2980     .0489     .5004    .0000   .0000      .8474
Irr. Application          .0000     .0000     .0101     .0000    .0000   .0000      .0101
Evapo-Transpiration      2.2462    8.0024    3.7366   86.6315    .6350   .0000   101.2517
Runoff                   7.8117  372.9012   28.8318  172.3033    .8446   .0000   582.6926
Rt Zn Soil Mois. Inc.     .0577   97.5268   10.2014   51.9775   -.0306   .0000   159.7328
GW Recharge               .9714  128.7386    8.5395  158.6243    .5560   .0000   297.4299


              Irrigation Demands and Supply (Mm3)
             -------------------------------------
       Total Irr. Demand in SW_Irr Area  =       .0000
       Total Irr. Demand in GW_Irr Area  =       .2006
       Total SW Supply in SW_Irr Area    =       .0000
       Total GW Supply in SW_Irr Area    =       .0000
       Total GW Supply in GW_Irr Area    =       .0101


              Runoff Stagnated or Out of Sub-basin (Mm3)
             --------------------------------------------
       Runoff Out of the Basin             =       .0000
       Runoff Out of the Sub-basin         =      4.5643
       Runoff Stagnated in the Sub-basin   =      2.4360


         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 --- Lakhpuri
                   -------------------------


          Domestic & Industrial Demands and Supply (Mm3)
         ------------------------------------------------
     Total WS Demand in Rural Area            =       .7821
     Total WS Demand in Urban Area            =      1.1014
     Total GW Withdrawal for meeting WS Demand =     1.8834
     Total SW Supply for meeting WS Demand    =       .0000
     Total GW Recharge from WS Discharge      =       .0000
     Total Overland Flow from WS Discharge    =       .0881


           Hydrological Details Under Different Landuses (Mm3)
          -----------------------------------------------------
                          Urban  RFed_Agr   Irr_Agr    Forest    Barren     Water     Total
Area (Sq. km)                60      1188       619       435      1018         2      3322
Rainfall                14.2320  351.8520  207.7160  163.8630  304.8630     .9460 1042.5260
Surface Inflow            .0000     .0000     .0000     .0000     .0000     .0000     .0000
GW Contribution           .1421    1.8125     .2390     .0000    3.1353     .0000    5.3288
Irr. Application          .0000     .0000     .6116     .0000     .0000     .0000     .6116
Evapo-Transpiration      7.6328   52.0152   20.7557   35.2947  136.9320     .2867  252.6305
Runoff                   5.3671   71.6984   41.4819   23.5400   61.1097     .0000  203.1972
Rt Zn Soil Mois. Inc.    -.3262  120.3369   65.2080   42.6915  -10.1826     .0000  217.7276
GW Recharge              1.7886  109.2235   78.8378   62.3325  120.1422     .1860  372.3246


             Irrigation Demands and Supply (Mm3)
            -------------------------------------
      Total Irr. Demand in SW_Irr Area  =      1.3048
      Total Irr. Demand in GW_Irr Area  =      2.7027
      Total SW Supply in SW_Irr Area    =       .4828
      Total GW Supply in SW_Irr Area    =       .0253
      Total GW Supply in GW_Irr Area    =       .1035


             Runoff Stagnated or Out of Sub-basin (Mm3)
            --------------------------------------------
      Runoff Out of the Basin            =       .5282
      Runoff Out of the Sub-basin        =       .0566
      Runoff Stagnated in the Sub-basin  =       .6992


       Cumulative Results of Different Reservoirs in the Subbasin (Mm3)
      ------------------------------------------------------------------
      Number of Reservoirs in the Subbasin        =       2
      Initial Storage in Reservoirs               =     8.8570
      Total Riverflows to the Reservoirs          =    19.1306
      Total RF Contribution to the Reservoirs     =      .9460
      Total Peripheral Inflow to the Reservoirs   =      .7532
      Total Imports to the Reservoirs             =      .0000
      Total Evaporation losses from Reservoirs    =     1.0246
      Total WS Demand from the Reservoirs         =      .0000
      Total Min_Flow Demand from the Reservoirs   =      .1607
      Total Irrigation Demand from the Reservoirs =     1.2070
      Total Release for WS from the Reservoirs    =      .0000
      Total Release for Mn_Flo from Reservoirs    =      .1607
      Total Release for Irr. from the Reservoirs  =     1.2070
      Total Spill from the Reservoirs             =    12.5944
      Total Exports from the Reservoirs           =      .0000
      Final Storage in the Reservoirs             =    14.6982
```

```
                Sub-basin --- Yerli
               -------------------------


          Domestic & Industrial Demands and Supply (Mm3)
         ------------------------------------------------
       Total WS Demand in Rural Area            =      3.2875
       Total WS Demand in Urban Area            =      2.5717
       Total GW Withdrawal for meeting WS Demand =     5.4003
       Total SW Supply for meeting WS Demand     =      .4589
       Total GW Recharge from WS Discharge       =      .3304
       Total Overland Flow from WS Discharge     =      .2057


          Hydrological Details Under Different Landuses (Mm3)
         -----------------------------------------------------
                          Urban  RFed_Agr   Irr_Agr    Forest    Barren     Water      Total
Area (Sq. km)               211      5009      2400      1411      3011        41      12083
Rainfall                73.7670 1538.3490  822.2490  523.9830  973.3850   15.3280  3931.7330
Surface Inflow            .0000     .0000     .0000     .0000     .0000     .0000      .0000
GW Contribution           .3506    4.2878    2.2080     .0452   12.3044     .0000    19.1960
Irr. Application          .0000     .0000    2.0130     .0000     .0000     .0000     2.0130
Evapo-Transpiration     27.4245  127.4863   76.4810  140.7613  397.7809    5.8534   769.9340
Runoff                  39.4855  392.1657  216.6361   49.6722  252.9279     .0000   950.8875
Rt Zn Soil Mois. Inc.   -1.2894  462.9025  222.7036  122.1164  -18.6176     .0000   787.8154
GW Recharge              8.7000  547.3378  301.4118  211.4648  353.4137    3.8130  1422.3280


            Irrigation Demands and Supply (Mm3)
           -------------------------------------
        Total Irr. Demand in SW_Irr Area  =      3.4454
        Total Irr. Demand in GW_Irr Area  =      3.9399
        Total SW Supply in SW_Irr Area    =      1.7378
        Total GW Supply in SW_Irr Area    =       .1127
        Total GW Supply in GW_Irr Area    =       .1625


            Runoff Stagnated or Out of Sub-basin (Mm3)
           --------------------------------------------
        Runoff Out of the Basin            =       .2275
        Runoff Out of the Sub-basin        =       .8575
        Runoff Stagnated in the Sub-basin  =      2.1074


      Cumulative Results of Different Reservoirs in the Subbasin (Mm3)
     ------------------------------------------------------------------
        Number of Reservoirs in the Subbasin        =      11
        Initial Storage in Reservoirs               =    115.9830
        Total Riverflows to the Reservoirs          =    101.2678
        Total RF Contribution to the Reservoirs     =     15.3280
        Total Peripheral Inflow to the Reservoirs   =     10.1196
        Total Imports to the Reservoirs             =       .0000
        Total Evaporation losses from Reservoirs    =      7.0169
        Total WS Demand from the Reservoirs         =       .4589
        Total Min_Flow Demand from the Reservoirs   =       .9374
        Total Irrigation Demand from the Reservoirs =      4.3739
        Total Release for WS from the Reservoirs    =       .4589
        Total Release for Mn_Flo from Reservoirs    =       .9348
        Total Release for Irr. from the Reservoirs  =      4.3058
        Total Spill from the Reservoirs             =     51.1459
        Total Exports from the Reservoirs           =       .0000
        Final Storage in the Reservoirs             =    178.8284
```

```
                    Sub-basin --- Dapuri
                   -------------------------


         Domestic & Industrial Demands and Supply (Mm3)
        ------------------------------------------------
    Total WS Demand in Rural Area             =     3.0483
    Total WS Demand in Urban Area             =     3.2724
    Total GW Withdrawal for meeting WS Demand =     5.4802
    Total SW Supply for meeting WS Demand     =      .8405
    Total GW Recharge from WS Discharge       =      .6052
    Total Overland Flow from WS Discharge     =      .2618


          Hydrological Details Under Different Landuses (Mm3)
         -----------------------------------------------------
                          Urban  RFed_Agr   Irr_Agr    Forest    Barren     Water      Total
Area (Sq. km)               162       859      4205      1354      1925        61       8566
Rainfall                28.8760  164.8680  743.2630  212.7940  326.3230   10.3490  1476.1240
Surface Inflow            .0000     .0000     .0000     .0000     .0000     .0000      .0000
GW Contribution          1.3962     .4565    2.0899     .4769    6.8781     .0000    11.2977
Irr. Application          .0000     .0000    4.6061     .0000     .0000     .0000     4.6061
Evapo-Transpiration     17.9706   12.9220   30.7773  142.2018  226.1264    9.2971   429.9982
Runoff                  11.7781   34.6112  177.1913   18.5998   68.0051     .0000   310.1855
Rt Zn Soil Mois. Inc.     .0163   89.5201  455.1332   51.3843    8.1571     .0000   604.2108
GW Recharge               .8082   26.5073   78.3774    1.1016   30.8104    5.6730   137.6049


             Irrigation Demands and Supply (Mm3)
            -------------------------------------
     Total Irr. Demand in SW_Irr Area  =     7.8489
     Total Irr. Demand in GW_Irr Area  =     4.7662
     Total SW Supply in SW_Irr Area    =     3.9018
     Total GW Supply in SW_Irr Area    =      .4445
     Total GW Supply in GW_Irr Area    =      .2597


             Runoff Stagnated or Out of Sub-basin (Mm3)
            --------------------------------------------
     Runoff Out of the Basin            =      .0757
     Runoff Out of the Sub-basin        =      .3120
     Runoff Stagnated in the Sub-basin  =     1.2950


      Cumulative Results of Different Reservoirs in the Subbasin (Mm3)
     -------------------------------------------------------------------
         Number of Reservoirs in the Subbasin        =      15
         Initial Storage in Reservoirs               =    338.7160
         Total Riverflows to the Reservoirs          =    138.7179
         Total RF Contribution to the Reservoirs     =     10.4960
         Total Peripheral Inflow to the Reservoirs   =      6.0269
         Total Imports to the Reservoirs             =       .0000
         Total Evaporation losses from Reservoirs    =      7.7402
         Total WS Demand from the Reservoirs         =       .8412
         Total Min_Flow Demand from the Reservoirs   =      2.7320
         Total Irrigation Demand from the Reservoirs =     11.0104
         Total Release for WS from the Reservoirs    =       .8405
         Total Release for Mn_Flo from Reservoirs    =      2.6891
         Total Release for Irr. from the Reservoirs  =     10.6759
         Total Spill from the Reservoirs             =     32.0445
         Total Exports from the Reservoirs           =       .0000
         Final Storage in the Reservoirs             =    439.9742
```

```
 Sub-basin --- Savkheda
-------------------------
```

```
    Domestic & Industrial Demands and Supply (Mm3)
   ------------------------------------------------
Total WS Demand in Rural Area            =      5.9625
Total WS Demand in Urban Area            =      4.0633
Total GW Withdrawal for meeting WS Demand =      9.6451
Total SW Supply for meeting WS Demand    =       .3808
Total GW Recharge from WS Discharge      =       .2742
Total Overland Flow from WS Discharge    =       .3251
```

```
                Hydrological Details Under Different Landuses (Mm3)
               -----------------------------------------------------
                        Urban  RFed_Agr   Irr_Agr    Forest    Barren    Water      Total
Area (Sq. km)             178      3299      4256      1670      1743      106      11252
Rainfall              40.8880  732.2450  969.4950  382.5670  412.7780  24.5500  2537.9730
Surface Inflow          .0000     .0000     .0000     .0000     .0000    .0000      .0000
GW Contribution         .7983    2.0949    3.1276    1.2680    4.7795    .0000    12.0684
Irr. Application        .0000     .0000   12.3830     .0000     .0000    .0000    12.3830
Evapo-Transpiration   22.7227   37.3430   76.9426  154.5512  223.8580  14.4825   515.4175
Runoff                 6.8851   81.4711  108.7932   17.6851   45.4409    .0000   260.2754
Rt Zn Soil Mois. Inc. -2.0300  353.8220  442.5497  173.3351  -21.8688    .0000   945.8079
GW Recharge           14.4327  247.6488  347.1458   38.3447  170.0362   9.8580   817.6083
```

```
      Irrigation Demands and Supply (Mm3)
     -------------------------------------
Total Irr. Demand in SW_Irr Area  =     20.3766
Total Irr. Demand in GW_Irr Area  =      8.2928
Total SW Supply in SW_Irr Area    =     10.7126
Total GW Supply in SW_Irr Area    =      1.1882
Total GW Supply in GW_Irr Area    =       .4826
```

```
      Runoff Stagnated or Out of Sub-basin (Mm3)
     --------------------------------------------
Runoff Out of the Basin            =       .0000
Runoff Out of the Sub-basin        =      1.3958
Runoff Stagnated in the Sub-basin  =       .9542
```

```
 Cumulative Results of Different Reservoirs in the Subbasin (Mm3)
------------------------------------------------------------------
    Number of Reservoirs in the Subbasin        =       21
    Initial Storage in Reservoirs               =     302.9560
    Total Riverflows to the Reservoirs          =    3471.7260
    Total RF Contribution to the Reservoirs     =      24.5500
    Total Peripheral Inflow to the Reservoirs   =       6.6234
    Total Imports to the Reservoirs             =        .0000
    Total Evaporation losses from Reservoirs    =      14.2781
    Total WS Demand from the Reservoirs         =        .3823
    Total Min_Flow Demand from the Reservoirs   =       2.4641
    Total Irrigation Demand from the Reservoirs =      26.3611
    Total Release for WS from the Reservoirs    =        .3808
    Total Release for Mn_Flo from Reservoirs    =       2.4415
    Total Release for Irr. from the Reservoirs  =      25.8986
    Total Spill from the Reservoirs             =    3426.7610
    Total Exports from the Reservoirs           =        .0000
    Final Storage in the Reservoirs             =     336.0907
```

```
                    Sub-basin --- Malkheda
                   -------------------------


              Domestic & Industrial Demands and Supply (Mm3)
             ------------------------------------------------
          Total WS Demand in Rural Area            =      1.1333
          Total WS Demand in Urban Area            =      1.8463
          Total GW Withdrawal for meeting WS Demand =     2.7462
          Total SW Supply for meeting WS Demand     =      .2334
          Total GW Recharge from WS Discharge       =      .1680
          Total Overland Flow from WS Discharge     =      .1477


               Hydrological Details Under Different Landuses (Mm3)
              -----------------------------------------------------
                          Urban   RFed_Agr   Irr_Agr    Forest    Barren     Water      Total
Area (Sq. km)                71         65      1335         0       251        17       1739
Rainfall                15.7710    18.0200  303.9150     .0000   51.5340    4.2850   389.2400
Surface Inflow            .0000      .0000     .0000     .0000     .0000     .0000      .0000
GW Contribution           .2464      .0000     .4201     .0000     .4345     .0000     1.1010
Irr. Application          .0000      .0000     .3472     .0000     .0000     .0000      .3472
Evapo-Transpiration      9.0684      .2915   10.3990     .0000   30.5448    2.5866    50.3037
Runoff                   1.8216     3.3788   21.7880     .0000    2.9621     .0000    29.9505
Rt Zn Soil Mois. Inc.    -.8068     2.9681  107.6503     .0000   -1.3924     .0000   108.4193
GW Recharge              6.0820    11.1210  159.6774     .0000   19.8547    1.5810   196.7352


                Irrigation Demands and Supply (Mm3)
               -------------------------------------
           Total Irr. Demand in SW_Irr Area  =       .2605
           Total Irr. Demand in GW_Irr Area  =      2.8290
           Total SW Supply in SW_Irr Area    =       .1830
           Total GW Supply in SW_Irr Area    =       .0132
           Total GW Supply in GW_Irr Area    =       .1510


                Runoff Stagnated or Out of Sub-basin (Mm3)
               --------------------------------------------
           Runoff Out of the Basin            =       .0000
           Runoff Out of the Sub-basin        =       .2058
           Runoff Stagnated in the Sub-basin  =       .1748


        Cumulative Results of Different Reservoirs in the Subbasin (Mm3)
       ------------------------------------------------------------------
           Number of Reservoirs in the Subbasin        =       5
           Initial Storage in Reservoirs               =     44.2440
           Total Riverflows to the Reservoirs          =     27.7074
           Total RF Contribution to the Reservoirs     =      4.2850
           Total Peripheral Inflow to the Reservoirs   =       .8050
           Total Imports to the Reservoirs             =       .0000
           Total Evaporation losses from Reservoirs    =      2.8015
           Total WS Demand from the Reservoirs         =       .2334
           Total Min_Flow Demand from the Reservoirs   =       .4018
           Total Irrigation Demand from the Reservoirs =       .4575
           Total Release for WS from the Reservoirs    =       .2334
           Total Release for Mn_Flo from Reservoirs    =       .4018
           Total Release for Irr. from the Reservoirs  =       .4575
           Total Spill from the Reservoirs             =     27.1665
           Total Exports from the Reservoirs           =       .0000
           Final Storage in the Reservoirs             =     45.9888
```

```
                    Sub-basin --- Morane
                   -------------------------


         Domestic & Industrial Demands and Supply (Mm3)
        ------------------------------------------------
    Total WS Demand in Rural Area            =      1.4649
    Total WS Demand in Urban Area            =      1.1085
    Total GW Withdrawal for meeting WS Demand =     1.8150
    Total SW Supply for meeting WS Demand     =      .7584
    Total GW Recharge from WS Discharge       =      .5461
    Total Overland Flow from WS Discharge     =      .0887


          Hydrological Details Under Different Landuses (Mm3)
         -----------------------------------------------------
                         Urban  RFed_Agr   Irr_Agr    Forest    Barren     Water      Total
Area (Sq. km)               38       112      1652       134       570        10       2516
Rainfall                4.8050   14.5550  237.6550   24.6280   85.4560    1.2990   367.0990
Surface Inflow           .0000     .0000     .0000     .0000     .0000     .0000      .0000
GW Contribution          .0878     .1756    1.1593     .0000    1.8711     .0000     3.2938
Irr. Application         .0000     .0000     .0158     .0000     .0000     .0000      .0158
Evapo-Transpiration     3.4470     .6937   21.9534   13.8273   57.8209    1.5300    97.7422
Runoff                   .6689     .7250   19.5404     .3101    4.9942     .0000    26.2387
Rt Zn Soil Mois. Inc.   -.0773    8.9206  124.3803    2.0765   -2.0471     .0000   133.2531
GW Recharge              .9102    4.0166   72.6283    8.4134   26.5606     .9300   112.5290


            Irrigation Demands and Supply (Mm3)
           -------------------------------------
     Total Irr. Demand in SW_Irr Area  =       .0000
     Total Irr. Demand in GW_Irr Area  =       .3620
     Total SW Supply in SW_Irr Area    =       .0000
     Total GW Supply in SW_Irr Area    =       .0000
     Total GW Supply in GW_Irr Area    =       .0158


            Runoff Stagnated or Out of Sub-basin (Mm3)
           --------------------------------------------
     Runoff Out of the Basin            =       .0000
     Runoff Out of the Sub-basin        =       .0781
     Runoff Stagnated in the Sub-basin  =       .1293


      Cumulative Results of Different Reservoirs in the Subbasin (Mm3)
     ------------------------------------------------------------------
     Number of Reservoirs in the Subbasin        =       5
     Initial Storage in Reservoirs               =      8.8180
     Total Riverflows to the Reservoirs          =      3.1461
     Total RF Contribution to the Reservoirs     =      1.4900
     Total Peripheral Inflow to the Reservoirs   =       .1355
     Total Imports to the Reservoirs             =       .0000
     Total Evaporation losses from Reservoirs    =       .4518
     Total WS Demand from the Reservoirs         =       .7584
     Total Min_Flow Demand from the Reservoirs   =       .4018
     Total Irrigation Demand from the Reservoirs =       .0000
     Total Release for WS from the Reservoirs    =       .7584
     Total Release for Mn_Flo from Reservoirs    =       .4018
     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             =     11.9620
```

```
                    Sub-basin --- Gidhade
                   -------------------------


          Domestic & Industrial Demands and Supply (Mm3)
         ------------------------------------------------
     Total WS Demand in Rural Area            =      1.5757
     Total WS Demand in Urban Area            =       .2901
     Total GW Withdrawal for meeting WS Demand =     1.8658
     Total SW Supply for meeting WS Demand     =      .0000
     Total GW Recharge from WS Discharge       =      .0000
     Total Overland Flow from WS Discharge     =      .0232


           Hydrological Details Under Different Landuses (Mm3)
          -----------------------------------------------------
                         Urban  RFed_Agr   Irr_Agr    Forest    Barren     Water     Total
Area (Sq. km)                9       775      1262       772       452        19      3289
Rainfall                2.4490  195.3780  333.0700  137.8920  121.1360    5.5290  789.9250
Surface Inflow           .0000     .0000     .0000     .0000     .0000     .0000     .0000
GW Contribution          .0000     .5524    1.7188     .7552    1.2969     .0000    4.3233
Irr. Application         .0000     .0000     .5316     .0000     .0000     .0000     .5316
Evapo-Transpiration     1.2582   10.4894   34.2454   68.4870   60.3393    2.7846  174.8193
Runoff                   .6776   50.5565   82.5036   20.1467   33.6173     .0000  187.5015
Rt Zn Soil Mois. Inc.   -.1343   41.8201   64.4991   33.4495   -9.2723     .0000  130.3620
GW Recharge              .6707   92.1149  151.9274   16.5653   37.7490    1.7670  299.0273


             Irrigation Demands and Supply (Mm3)
            -------------------------------------
      Total Irr. Demand in SW_Irr Area  =       .8501
      Total Irr. Demand in GW_Irr Area  =       .2679
      Total SW Supply in SW_Irr Area    =       .4845
      Total GW Supply in SW_Irr Area    =       .0340
      Total GW Supply in GW_Irr Area    =       .0131


             Runoff Stagnated or Out of Sub-basin (Mm3)
            --------------------------------------------
      Runoff Out of the Basin             =       .0000
      Runoff Out of the Sub-basin         =       .2388
      Runoff Stagnated in the Sub-basin   =      1.1456


    Cumulative Results of Different Reservoirs in the Subbasin (Mm3)
   ------------------------------------------------------------------
      Number of Reservoirs in the Subbasin        =        4
      Initial Storage in Reservoirs               =     36.8320
      Total Riverflows to the Reservoirs          =     43.3980
      Total RF Contribution to the Reservoirs     =      5.5290
      Total Peripheral Inflow to the Reservoirs   =      6.9531
      Total Imports to the Reservoirs             =       .0000
      Total Evaporation losses from Reservoirs    =      2.3320
      Total WS Demand from the Reservoirs         =       .0000
      Total Min_Flow Demand from the Reservoirs   =       .3214
      Total Irrigation Demand from the Reservoirs =      1.2114
      Total Release for WS from the Reservoirs    =       .0000
      Total Release for Mn_Flo from Reservoirs    =       .3214
      Total Release for Irr. from the Reservoirs  =      1.2114
      Total Spill from the Reservoirs             =     27.0838
      Total Exports from the Reservoirs           =       .0000
      Final Storage in the Reservoirs             =     61.7711
```

```
                        Sub-basin --- Sarangkheda
                       -------------------------


             Domestic & Industrial Demands and Supply (Mm3)
            ------------------------------------------------
        Total WS Demand in Rural Area            =      2.0870
        Total WS Demand in Urban Area            =       .3501
        Total GW Withdrawal for meeting WS Demand =     2.3787
        Total SW Supply for meeting WS Demand    =       .0583
        Total GW Recharge from WS Discharge      =       .0420
        Total Overland Flow from WS Discharge    =       .0280


            Hydrological Details Under Different Landuses (Mm3)
           -----------------------------------------------------
                         Urban  RFed_Agr   Irr_Agr    Forest    Barren     Water     Total
Area (Sq. km)               12       582      2059       121       830        17      3621
Rainfall                1.2700   71.3810  226.1060   14.6830   89.6820    1.3550  403.1220
Surface Inflow           .0000     .0000     .0000     .0000     .0000     .0000     .0000
GW Contribution          .0000     .0000    2.6390     .0000    1.0000     .0000    3.6390
Irr. Application         .0000     .0000     .1430     .0000     .0000     .0000     .1430
Evapo-Transpiration     1.1832    9.0608   41.1454    9.8263   72.8064    2.5578  134.0221
Runoff                   .0286   13.0236   22.4468     .3538    9.0619     .0000   44.9146
Rt Zn Soil Mois. Inc.   -.0607   17.0861  122.5836    1.1552   -5.2046     .0000  135.5596
GW Recharge              .1469   32.2227   42.4909    3.3477   14.0165    1.5810   92.2246


              Irrigation Demands and Supply (Mm3)
             -------------------------------------
         Total Irr. Demand in SW_Irr Area  =       .2800
         Total Irr. Demand in GW_Irr Area  =       .1390
         Total SW Supply in SW_Irr Area    =       .1259
         Total GW Supply in SW_Irr Area    =       .0116
         Total GW Supply in GW_Irr Area    =       .0055


              Runoff Stagnated or Out of Sub-basin (Mm3)
             --------------------------------------------
         Runoff Out of the Basin            =       .0000
         Runoff Out of the Sub-basin        =       .0758
         Runoff Stagnated in the Sub-basin  =       .8958


        Cumulative Results of Different Reservoirs in the Subbasin (Mm3)
       ------------------------------------------------------------------
           Number of Reservoirs in the Subbasin        =      11
           Initial Storage in Reservoirs               =     33.2920
           Total Riverflows to the Reservoirs          =     22.1519
           Total RF Contribution to the Reservoirs     =      1.3550
           Total Peripheral Inflow to the Reservoirs   =       .4499
           Total Imports to the Reservoirs             =       .0000
           Total Evaporation losses from Reservoirs    =      2.2599
           Total WS Demand from the Reservoirs         =       .0583
           Total Min_Flow Demand from the Reservoirs   =       .8839
           Total Irrigation Demand from the Reservoirs =       .3148
           Total Release for WS from the Reservoirs    =       .0583
           Total Release for Mn_Flo from Reservoirs    =       .8693
           Total Release for Irr. from the Reservoirs  =       .3148
           Total Spill from the Reservoirs             =      7.0953
           Total Exports from the Reservoirs           =       .0000
           Final Storage in the Reservoirs             =     46.6688
---------------------------------------------------------------------------
```

4.3 Checking of Model Computations

Model computations have been checked by carrying out the water balance of different hydrological variables under various land uses and by comparing the runoff generated at each grid with the cumulative river flow in a sub-basin. An option has been included in the model for this purpose.

The overland flow generated at a grid is moved to the lower elevation grid in accordance with the flow direction. At the next grid, if there is no generated overland flow, then the incoming overland flow is absorbed in the soil and soil water balance treats this flow as input to the soil reservoir. In this situation, it is difficult to check whether the overland flow generated at various grids (after accounting for the reservoir blockage, if any) and the spills and minimum flow releases from the reservoirs actually find their way to the sub-basin outlet. So, an option has been added in the model for this purpose. Under this option, overland flow generated at a grid is not absorbed in the soil at any grid (except as inflow to a reservoir) and finds its way to the sub-basin outlet. Table-4.4 has been generated using this option, that is why, surface inflow row shows zero for all the sub-basins. The hydrological variables for all land uses (urban, rainfed_agri, irr_agri, forest, and barren land) show the correct water balance as per the following equation:

Rainfall + Surface inflow + GW contribution + Irrigation input =
Evapo-transpiration + Runoff + Soil moisture increase + GW recharge ..(4.1)

The matching of water balance for various land uses in different sub-basins confirms the computations of soil water balance module. The operation of reservoirs has been verified by checking the computations of reservoir working table as per the following equation

Final storage = Initial storage + Inflow + Import
–Evaporation – Supply – Spill – Export ..(4.2)

The movement of the overland flow towards the rivers, connectivity of rivers, blockage of flow by the reservoirs, and reservoir spill and release is checked by following equations:

Outflow from a sub-basin = Flow at sub-basin outlet
– Inflow to sub-basin from upstream ..(4.3)

Outflow from a sub-basin = Overland flow generated in sub-basin
– Outflow out of sub-basin - River flow to reservoirs
– Peripheral inflow to reservoirs + Spill from reservoirs
\+ Minimum release from reservoirs ..(4.4)

These checks have been verified for different sub-basins.

4.4 Model Application for Tapi Basin

Basin simulation model has been run continuously for the Tapi basin from June 1992 to May 1996. At the beginning of June, the soil moisture has been assumed in-between the field capacity and wilting point and different reservoirs have been assumed to be at 20 % of their storage capacities. Initially, the PPA (proposed profitable area) for each reservoir has been assumed to be 100 % and the SWFAC and BSFAC have been taken as 1. First, the GWFAC is derived from the flow data at different gauging sites for non-monsoon months. For other months, it is modified in accordance with the hydrological conditions. Next, the SWFAC and BSFAC for different sub-basins have been modified by comparing the computed flows and observed flows at different gauging sites, so as to match the flows as closely as possible.

After finalizing the SWFAC, BSFAC, and GWFAC, the PPA for different reservoirs has been computed by computing the average annual irrigation demands from the reservoirs and comparing them with the design demands. A number of trial runs of the model have been taken for all the four years till the specified PPA matches with the computed PPA. The finalized PPA for different reservoirs is given in the reservoirs characteristics table.

From the monthly results of hydrological variables for different sub-basins, annual values have been computed and the same are presented from Table 4.5 to Table -4.13. The plots of observed and computed flows at major gauging stations in the basin are presented from Figure – 4.4 to Figure – 4.8.

Table – 4.5
Annual Values of Hydrological Variables for Dedtalai Sub-basin

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

Table – 4.6

Annual Values of Hydrological Variables for Burhanpur Sub-basin

Hydrological Variables	**Annual values (MCM) for year (June – May)**			
	1992-93	**1993-94**	**1994-95**	**1995-96**
Domestic & Industrial Demands and Supply				
Total WS Demand in Rural Area	4.169	4.169	4.169	4.181
Total WS Demand in Urban Area	3.679	3.679	3.679	3.689
Total GW Withdrawal for meeting WS Demand	7.849	7.849	7.849	7.870
Total SW Supply for meeting WS Demand	0.000	0.000	0.000	0.000
Total GW Recharge from WS Discharge	0.000	0.000	0.000	0.000
Total Overland Flow from WS Discharge	0.294	0.294	0.294	0.295
Hydrological Details for the Sub-basin				
Rainfall	2492.313	2765.119	2964.518	2164.924
Surface Flow Absorbed	112.405	140.523	102.298	100.73
GW Contribution to Root Zone	119.5834	108.657	107.0804	111.007
Irrigation Application	0.6813	0.6833	0.6821	0.6912
Evapo-Transpiration Losses	925.0037	885.0826	922.2419	715.7612
Runoff Generated	1171.432	1382.27	1419.8098	1086.306
GW Recharge	519.0231	470.7961	520.136	327.8026
Irrigation Demands & Supply				
Total Irrigation Demand in SW_Irr Area	0.000	0.000	0.000	0.000
Total Irrigation Demand in GW_Irr Area	25.599	24.681	25.231	25.911
Total SW Supply in SW_Irr Area	0.000	0.000	0.000	0.000
Total GW Supply in SW_Irr Area	0.000	0.000	0.000	0.000
Total GW Supply in GW_Irr Area	0.681	0.683	0.682	0.691
Cumulative Details of Reservoirs in the Sub-basin				
Total Number of Reservoirs in the Sub-basin	0			
Total River flows to the Reservoirs	0.000	0.000	0.000	0.000
Total RF Contribution to the Reservoirs	0.000	0.000	0.000	0.000
Total Peripheral Inflow to the Reservoirs	0.000	0.000	0.000	0.000
Total Imports to the Reservoirs	0.000	0.000	0.000	0.000
Total Evaporation losses from Reservoirs	0.000	0.000	0.000	0.000
Total WS Demand from the Reservoirs	0.000	0.000	0.000	0.000
Total Min_Flow Demand from the Reservoirs	0.000	0.000	0.000	0.000
Total Irrigation Demand from the Reservoirs	0.000	0.000	0.000	0.000
Total Release for WS from the Reservoirs	0.000	0.000	0.000	0.000
Total Release for Mn_Flo from Reservoirs	0.000	0.000	0.000	0.000
Total Release for Irr. from the Reservoirs	0.000	0.000	0.000	0.000
Total Spill from the Reservoirs	0.000	0.000	0.000	0.000
Total Exports from the Reservoirs	0.000	0.000	0.000	0.000

Table – 4.7
Annual Values of Hydrological Variables for Lakhpuri Sub-basin

Hydrological Variables	**Annual values (MCM) for year (June – May)**			
	1992-93	**1993-94**	**1994-95**	**1995-96**
Domestic & Industrial Demands and Supply				
Total WS Demand in Rural Area	9.208	9.208	9.208	9.234
Total WS Demand in Urban Area	12.968	12.968	12.968	13.003
Total GW Withdrawal for meeting WS Demand	22.176	22.176	22.176	22.237
Total SW Supply for meeting WS Demand	0.000	0.000	0.000	0.000
Total GW Recharge from WS Discharge	0.000	0.000	0.000	0.000
Total Overland Flow from WS Discharge	1.038	1.038	1.038	1.040
Hydrological Details for the Sub-basin				
Rainfall	2398.466	2592.816	3781.326	1226.934
Surface Flow Absorbed	26.822	44.005	50.232	23.301
GW Contribution to Root Zone	270.9441	261.0561	255.0737	277.8506
Irrigation Application	11.5279	10.9355	9.9403	11.6563
Evapo-Transpiration Losses	1494.105	1585.611	1792.9133	857.6549
Runoff Generated	410.9714	400.2907	961.5211	247.6391
GW Recharge	618.6883	527.6575	885.1342	236.7993
Irrigation Demands & Supply				
Total Irrigation Demand in SW_Irr Area	36.9231	38.1167	37.3505	39.4626
Total Irrigation Demand in GW_Irr Area	136.1564	144.7497	145.9155	157.2311
Total SW Supply in SW_Irr Area	7.6754	7.0478	6.1166	7.5716
Total GW Supply in SW_Irr Area	0.5109	0.5162	0.5111	0.5398
Total GW Supply in GW_Irr Area	3.3419	3.3719	3.3128	3.5451
Cumulative Details of Reservoirs in the Sub-basin				
Total Number of Reservoirs in the Sub-basin	2			
Total River flows to the Reservoirs	34.626	19.556	23.729	32.866
Total RF Contribution to the Reservoirs	1.966	1.504	1.812	1.790
Total Peripheral Inflow to the Reservoirs	1.397	0.843	0.976	1.411
Total Imports to the Reservoirs	0.000	0.000	0.000	0.000
Total Evaporation losses from Reservoirs	6.891	4.577	6.201	6.598
Total WS Demand from the Reservoirs	0.000	0.000	0.000	0.000
Total Min_Flow Demand from the Reservoirs	0.766	0.766	0.766	0.767
Total Irrigation Demand from the Reservoirs	34.443	36.474	35.831	37.603
Total Release for WS from the Reservoirs	0.000	0.000	0.000	0.000
Total Release for Mn_Flo from Reservoirs	0.763	0.749	0.748	0.751
Total Release for Irr. from the Reservoirs	18.867	17.150	15.053	18.667
Total Spill from the Reservoirs	12.502	0.000	4.022	9.883
Total Exports from the Reservoirs	0.000	0.000	0.000	0.000

Table – 4.8
Annual Values of Hydrological Variables for Yerli Sub-basin

Hydrological Variables	**Annual values (MCM) for year (June – May)**			
	1992-93	**1993-94**	**1994-95**	**1995-96**
Domestic & Industrial Demands and Supply				
Total WS Demand in Rural Area	38.707	38.707	38.707	38.814
Total WS Demand in Urban Area	30.280	30.280	30.280	30.363
Total GW Withdrawal for meeting WS Demand	65.202	65.713	65.608	66.097
Total SW Supply for meeting WS Demand	3.785	3.274	3.380	3.051
Total GW Recharge from WS Discharge	2.725	2.357	2.433	2.197
Total Overland Flow from WS Discharge	2.422	2.422	2.422	2.429
Hydrological Details for the Sub-basin				
Rainfall	9628.481	9414.093	11605.99	6864.098
Surface Flow Absorbed	194.065	189.034	149.446	141.135
GW Contribution to Root Zone	706.4533	687.3059	669.1899	717.1088
Irrigation Application	43.6164	40.3287	45.8985	46.4609
Evapo-Transpiration Losses	4516.592	4797.277	5522.772	3345.773
Runoff Generated	2275.285	1613.475	2103.5728	1370.566
GW Recharge	2807.877	2286.316	3112.4576	1643.705
Irrigation Demands & Supply				
Total Irrigation Demand in SW_Irr Area	161.299	159.085	161.245	175.338
Total Irrigation Demand in GW_Irr Area	227.982	233.850	247.103	259.963
Total SW Supply in SW_Irr Area	34.835	31.458	37.192	37.285
Total GW Supply in SW_Irr Area	3.243	3.251	3.166	3.396
Total GW Supply in GW_Irr Area	5.543	5.616	5.539	5.777
Cumulative Details of Reservoirs in the Sub-basin				
Total Number of Reservoirs in the Sub-basin	11			
Total River flows to the Reservoirs	296.964	195.605	139.384	125.885
Total RF Contribution to the Reservoirs	37.907	31.887	42.365	25.449
Total Peripheral Inflow to the Reservoirs	20.931	11.254	11.439	9.513
Total Imports to the Reservoirs	0.000	0.000	0.000	0.000
Total Evaporation losses from Reservoirs	71.534	75.527	70.634	56.177
Total WS Demand from the Reservoirs	5.403	5.403	5.403	5.418
Total Min_Flow Demand from the Reservoirs	4.609	4.609	4.609	4.615
Total Irrigation Demand from the Reservoirs	225.548	219.954	227.520	250.582
Total Release for WS from the Reservoirs	3.785	3.274	3.380	3.051
Total Release for Mn_Flo from Reservoirs	4.141	4.070	4.185	4.066
Total Release for Irr. from the Reservoirs	87.003	78.856	92.961	93.229
Total Spill from the Reservoirs	120.264	74.843	27.666	27.677
Total Exports from the Reservoirs	0.000	0.000	0.000	0.000

Table – 4.9
Annual Values of Hydrological Variables for Dapuri Sub-basin

Hydrological Variables	**Annual values (MCM) for year (June – May)**			
	1992-93	**1993-94**	**1994-95**	**1995-96**
Domestic & Industrial Demands and Supply				
Total WS Demand in Rural Area	35.891	35.891	35.891	35.990
Total WS Demand in Urban Area	38.530	38.530	38.530	38.636
Total GW Withdrawal for meeting WS Demand	67.077	67.196	67.047	67.457
Total SW Supply for meeting WS Demand	6.000	5.502	6.076	5.428
Total GW Recharge from WS Discharge	4.320	3.962	4.375	3.908
Total Overland Flow from WS Discharge	3.083	3.083	3.083	3.091
Hydrological Details for the Sub-basin				
Rainfall	5416.005	5919.166	6161.013	4742.62
Surface Flow Absorbed	134.557	136.397	132.556	101.933
GW Contribution to Root Zone	603.7168	588.5397	588.4819	601.0309
Irrigation Application	261.1239	195.2007	286.32	211.1247
Evapo-Transpiration Losses	3078.914	3264.685	3246.7058	2387.05
Runoff Generated	1624.498	1346.318	1851.11	1155.454
GW Recharge	950.5036	1035.826	846.4101	896.216
Irrigation Demands & Supply				
Total Irrigation Demand in SW_Irr Area	987.6256	973.2871	976.2779	991.5776
Total Irrigation Demand in GW_Irr Area	950.5057	935.0147	939.0862	943.7895
Total SW Supply in SW_Irr Area	195.9433	129.6803	222.6179	144.5037
Total GW Supply in SW_Irr Area	32.1288	32.5697	30.8151	33.3192
Total GW Supply in GW_Irr Area	32.8933	32.8315	32.7296	33.1849
Cumulative Details of Reservoirs in the Sub-basin				
Total Number of Reservoirs in the Sub-basin	15			
Total River flows to the Reservoirs	832.006	668.513	1291.275	672.546
Total RF Contribution to the Reservoirs	42.975	37.159	53.945	43.059
Total Peripheral Inflow to the Reservoirs	34.062	18.564	44.173	23.909
Total Imports to the Reservoirs	0.000	0.000	0.000	0.000
Total Evaporation losses from Reservoirs	56.820	29.429	69.702	35.146
Total WS Demand from the Reservoirs	9.905	9.905	9.905	9.932
Total Min_Flow Demand from the Reservoirs	13.028	13.028	13.028	13.043
Total Irrigation Demand from the Reservoirs	1670.889	1663.193	1660.918	1697.580
Total Release for WS from the Reservoirs	6.000	5.502	6.076	5.428
Total Release for Mn_Flo from Reservoirs	11.581	10.913	11.512	10.806
Total Release for Irr. from the Reservoirs	809.009	491.636	895.653	612.732
Total Spill from the Reservoirs	154.067	155.197	442.856	75.439
Total Exports from the Reservoirs	0.000	0.000	0.000	0.000

Table – 4.10
Annual Values of Hydrological Variables for Savkheda Sub-basin

Hydrological Variables	**Annual values (MCM) for year (June – May)**			
	1992-93	**1993-94**	**1994-95**	**1995-96**
Domestic & Industrial Demands and Supply				
Total WS Demand in Rural Area	70.204	70.204	70.204	70.396
Total WS Demand in Urban Area	47.842	47.842	47.842	47.974
Total GW Withdrawal for meeting WS Demand	113.949	113.935	113.927	114.296
Total SW Supply for meeting WS Demand	3.169	3.373	3.376	3.178
Total GW Recharge from WS Discharge	2.282	2.429	2.431	2.288
Total Overland Flow from WS Discharge	3.828	3.828	3.828	3.838
Hydrological Details for the Sub-basin				
Rainfall	8187.767	9317.466	9725.413	6658.427
Surface Flow Absorbed	199.63	133.515	136.835	148.338
GW Contribution to Root Zone	934.0575	911.8517	895.8645	928.5823
Irrigation Application	436.3733	386.3843	525.3583	381.4218
Evapo-Transpiration Losses	4431.667	4507.898	4923.9976	3418.527
Runoff Generated	1803.063	1442.35	1334.8099	1186.677
GW Recharge	2233.363	2694.557	2794.9227	1710.798
Irrigation Demands & Supply				
Total Irrigation Demand in SW_Irr Area	1387.029	1383.92	1370.3963	1431.476
Total Irrigation Demand in GW_Irr Area	787.1853	792.1067	787.5457	832.5619
Total SW Supply in SW_Irr Area	371.5786	321.315	461.3282	314.8661
Total GW Supply in SW_Irr Area	40.4142	40.7217	39.901	41.7912
Total GW Supply in GW_Irr Area	24.305	24.2894	24.0469	24.7154
Cumulative Details of Reservoirs in the Sub-basin				
Total Number of Reservoirs in the Sub-basin	21			
Total River flows to the Reservoirs	6645.023	7615.261	9476.678	5680.342
Total RF Contribution to the Reservoirs	67.659	98.129	96.200	62.842
Total Peripheral Inflow to the Reservoirs	44.740	44.164	32.866	35.067
Total Imports to the Reservoirs	0.000	0.000	0.000	0.000
Total Evaporation losses from Reservoirs	100.891	103.011	106.480	92.037
Total WS Demand from the Reservoirs	4.501	4.501	4.501	4.514
Total Min_Flow Demand from the Reservoirs	11.890	11.890	11.890	11.904
Total Irrigation Demand from the Reservoirs	1440.751	1429.657	1418.425	1482.259
Total Release for WS from the Reservoirs	3.169	3.373	3.376	3.178
Total Release for Mn_Flo from Reservoirs	10.229	10.293	10.261	10.104
Total Release for Irr. from the Reservoirs	643.576	652.955	850.274	563.028
Total Spill from the Reservoirs	6071.423	6999.246	8637.366	5110.721
Total Exports from the Reservoirs	0.000	0.000	0.000	0.000

Table – 4.11
Annual Values of Hydrological Variables for Malkheda Sub-basin

Hydrological Variables	Annual values (MCM) for year (June – May)			
	1992-93	1993-94	1994-95	1995-96
Domestic & Industrial Demands and Supply				
Total WS Demand in Rural Area	13.344	13.344	13.344	13.380
Total WS Demand in Urban Area	21.739	21.739	21.739	21.799
Total GW Withdrawal for meeting WS Demand	32.451	32.511	32.450	32.574
Total SW Supply for meeting WS Demand	1.784	1.295	1.804	1.525
Total GW Recharge from WS Discharge	1.285	0.932	1.299	1.098
Total Overland Flow from WS Discharge	1.739	1.739	1.739	1.744
Hydrological Details for the Sub-basin				
Rainfall	1438.316	961.486	1418.653	1074.144
Surface Flow Absorbed	31.779	13.379	32.553	18.276
GW Contribution to Root Zone	119.8492	118.0775	117.5291	121.1954
Irrigation Application	31.7537	17.7107	27.3789	25.4792
Evapo-Transpiration Losses	445.9102	485.3208	537.9473	371.6714
Runoff Generated	256.9661	56.0672	214.7964	110.3556
GW Recharge	587.4247	269.6504	503.1239	391.5037
Irrigation Demands & Supply				
Total Irrigation Demand in SW_Irr Area	77.88	80.0624	75.1613	82.082
Total Irrigation Demand in GW_Irr Area	209.9123	219.0454	200.6486	217.6253
Total SW Supply in SW_Irr Area	23.608	9.2655	19.1179	16.9963
Total GW Supply in SW_Irr Area	2.1579	2.3903	2.3226	2.3887
Total GW Supply in GW_Irr Area	5.9884	6.0553	5.9392	6.0951
Cumulative Details of Reservoirs in the Sub-basin				
Total Number of Reservoirs in the Sub-basin	5			
Total River flows to the Reservoirs	194.174	27.144	279.225	115.289
Total RF Contribution to the Reservoirs	13.936	9.737	14.148	9.813
Total Peripheral Inflow to the Reservoirs	7.311	1.505	8.626	4.551
Total Imports to the Reservoirs	0.000	0.000	0.000	0.000
Total Evaporation losses from Reservoirs	19.975	6.675	19.179	16.026
Total WS Demand from the Reservoirs	2.748	2.748	2.748	2.755
Total Min_Flow Demand from the Reservoirs	1.916	1.916	1.916	1.918
Total Irrigation Demand from the Reservoirs	66.492	68.680	63.553	70.119
Total Release for WS from the Reservoirs	1.784	1.295	1.804	1.525
Total Release for Mn_Flo from Reservoirs	1.825	1.741	1.808	1.786
Total Release for Irr. from the Reservoirs	50.946	21.194	43.156	40.087
Total Spill from the Reservoirs	146.930	8.314	234.447	70.713
Total Exports from the Reservoirs	0.000	0.000	0.000	0.000

Table – 4.12
Annual Values of Hydrological Variables for Morane Sub-basin

Hydrological Variables	**Annual values (MCM) for year (June – May)**			
	1992-93	**1993-94**	**1994-95**	**1995-96**
Domestic & Industrial Demands and Supply				
Total WS Demand in Rural Area	17.248	17.248	17.248	17.295
Total WS Demand in Urban Area	13.052	13.052	13.052	13.087
Total GW Withdrawal for meeting WS Demand	21.955	22.013	21.929	22.072
Total SW Supply for meeting WS Demand	4.111	3.722	4.482	3.688
Total GW Recharge from WS Discharge	2.960	2.680	3.227	2.656
Total Overland Flow from WS Discharge	1.044	1.044	1.044	1.047
Hydrological Details for the Sub-basin				
Rainfall	1456.614	1552.821	1724.402	1288.762
Surface Flow Absorbed	16.02	21.688	28.192	7.808
GW Contribution to Root Zone	181.2007	177.6597	177.4304	181.4514
Irrigation Application	24.4137	20.822	25.234	16.6546
Evapo-Transpiration Losses	735.1925	781.4652	794.6826	593.0683
Runoff Generated	152.8434	144.6747	228.4304	83.6703
GW Recharge	494.6814	507.1432	575.0218	459.3224
Irrigation Demands & Supply				
Total Irrigation Demand in SW_Irr Area	140.2614	141.6802	135.6227	143.5053
Total Irrigation Demand in GW_Irr Area	426.3611	435.2866	413.3673	444.1931
Total SW Supply in SW_Irr Area	10.4929	6.7916	11.5605	2.4918
Total GW Supply in SW_Irr Area	3.3057	3.3738	3.1819	3.4021
Total GW Supply in GW_Irr Area	10.6217	10.6646	10.5001	10.7646
Cumulative Details of Reservoirs in the Sub-basin				
Total Number of Reservoirs in the Sub-basin	5			
Total River flows to the Reservoirs	15.961	15.613	34.388	6.240
Total RF Contribution to the Reservoirs	6.141	6.671	7.228	5.549
Total Peripheral Inflow to the Reservoirs	1.200	1.312	2.359	0.477
Total Imports to the Reservoirs	0.000	0.000	0.000	0.000
Total Evaporation losses from Reservoirs	2.656	1.555	4.197	0.983
Total WS Demand from the Reservoirs	8.930	8.930	8.930	8.954
Total Min_Flow Demand from the Reservoirs	1.916	1.916	1.916	1.918
Total Irrigation Demand from the Reservoirs	169.189	170.441	163.220	172.685
Total Release for WS from the Reservoirs	4.111	3.722	4.482	3.688
Total Release for Mn_Flo from Reservoirs	1.504	1.284	1.534	1.304
Total Release for Irr. from the Reservoirs	25.785	16.920	28.493	6.079
Total Spill from the Reservoirs	0.087	0.000	5.329	0.254
Total Exports from the Reservoirs	0.000	0.000	0.000	0.000

Table – 4.13
Annual Values of Hydrological Variables for Gidhade Sub-basin

Hydrological Variables	**Annual values (MCM) for year (June – May)**			
	1992-93	**1993-94**	**1994-95**	**1995-96**
Domestic & Industrial Demands and Supply				
Total WS Demand in Rural Area	18.553	18.553	18.553	18.604
Total WS Demand in Urban Area	3.416	3.416	3.416	3.425
Total GW Withdrawal for meeting WS Demand	21.968	21.968	21.968	22.028
Total SW Supply for meeting WS Demand	0.000	0.000	0.000	0.000
Total GW Recharge from WS Discharge	0.000	0.000	0.000	0.000
Total Overland Flow from WS Discharge	0.273	0.273	0.273	0.274
Hydrological Details for the Sub-basin				
Rainfall	3525.039	2292.218	2575.393	1450.235
Surface Flow Absorbed	69.961	23.968	25.216	18.662
GW Contribution to Root Zone	316.2885	310.9164	304.9424	317.9294
Irrigation Application	56.5069	45.913	56.1462	43.5517
Evapo-Transpiration Losses	1539.861	1459.561	1481.6304	1054.769
Runoff Generated	1383.537	201.6842	302.4374	125.0908
GW Recharge	715.7465	569.2422	696.2063	262.1887
Irrigation Demands & Supply				
Total Irrigation Demand in SW_Irr Area	172.2498	175.0598	171.2784	179.6451
Total Irrigation Demand in GW_Irr Area	333.6281	341.0092	332.2884	351.8064
Total SW Supply in SW_Irr Area	43.5324	32.6311	43.1828	30.237
Total GW Supply in SW_Irr Area	3.9202	4.1973	3.9742	4.1559
Total GW Supply in GW_Irr Area	9.0547	9.0857	8.9899	9.1596
Cumulative Details of Reservoirs in the Sub-basin				
Total Number of Reservoirs in the Sub-basin	4			
Total River flows to the Reservoirs	113.800	74.444	68.602	30.115
Total RF Contribution to the Reservoirs	16.988	14.419	18.553	9.762
Total Peripheral Inflow to the Reservoirs	19.001	8.813	15.265	6.433
Total Imports to the Reservoirs	0.000	0.000	0.000	0.000
Total Evaporation losses from Reservoirs	15.566	12.805	12.044	5.246
Total WS Demand from the Reservoirs	0.000	0.000	0.000	0.000
Total Min_Flow Demand from the Reservoirs	1.533	1.533	1.533	1.535
Total Irrigation Demand from the Reservoirs	171.020	173.201	168.959	178.140
Total Release for WS from the Reservoirs	0.000	0.000	0.000	0.000
Total Release for Mn_Flo from Reservoirs	1.360	1.256	1.357	1.255
Total Release for Irr. from the Reservoirs	83.997	66.771	77.208	51.071
Total Spill from the Reservoirs	62.620	16.836	0.582	0.000
Total Exports from the Reservoirs	0.000	0.000	0.000	0.000

Table – 4.14
Annual Values of Hydrological Variables for Sarangkheda Sub-basin

Hydrological Variables	Annual values (MCM) for year (June – May)			
	1992-93	**1993-94**	**1994-95**	**1995-96**
Domestic & Industrial Demands and Supply				
Total WS Demand in Rural Area	24.573	24.573	24.573	24.640
Total WS Demand in Urban Area	4.122	4.122	4.122	4.133
Total GW Withdrawal for meeting WS Demand	28.042	28.039	28.041	28.127
Total SW Supply for meeting WS Demand	0.401	0.431	0.411	0.340
Total GW Recharge from WS Discharge	0.289	0.310	0.296	0.245
Total Overland Flow from WS Discharge	0.330	0.330	0.330	0.331
Hydrological Details for the Sub-basin				
Rainfall	2033.588	2400.329	2605.706	1675.424
Surface Flow Absorbed	68.418	54.413	38.707	23.375
GW Contribution to Root Zone	215.0497	209.4245	209.2443	214.9501
Irrigation Application	47.7342	39.8112	38.9265	33.1223
Evapo-Transpiration Losses	1031.935	1215.032	1232.5755	862.9727
Runoff Generated	460.7364	346.1873	341.1394	148.5043
GW Recharge	490.7902	639.8204	825.5042	478.9116
Irrigation Demands & Supply				
Total Irrigation Demand in SW_Irr Area	242.353	234.037	237.340	246.874
Total Irrigation Demand in GW_Irr Area	557.446	531.032	545.976	567.778
Total SW Supply in SW_Irr Area	29.776	21.784	20.875	14.724
Total GW Supply in SW_Irr Area	5.066	5.233	5.171	5.332
Total GW Supply in GW_Irr Area	12.890	12.792	12.888	13.068
Cumulative Details of Reservoirs in the Sub-basin				
Total Number of Reservoirs in the Sub-basin	11			
Total River flows to the Reservoirs	81.061	138.577	108.573	42.463
Total RF Contribution to the Reservoirs	9.142	13.582	13.276	8.606
Total Peripheral Inflow to the Reservoirs	6.087	9.561	7.851	3.327
Total Imports to the Reservoirs	0.000	0.000	0.000	0.000
Total Evaporation losses from Reservoirs	15.164	14.456	13.542	8.278
Total WS Demand from the Reservoirs	0.687	0.687	0.687	0.689
Total Min_Flow Demand from the Reservoirs	4.215	4.215	4.215	4.220
Total Irrigation Demand from the Reservoirs	259.616	250.755	254.055	264.767
Total Release for WS from the Reservoirs	0.401	0.431	0.411	0.340
Total Release for Mn_Flo from Reservoirs	3.570	3.398	3.573	3.203
Total Release for Irr. from the Reservoirs	74.442	54.462	52.188	36.811
Total Spill from the Reservoirs	16.183	88.749	57.686	8.308
Total Exports from the Reservoirs	0.000	0.000	0.000	0.000

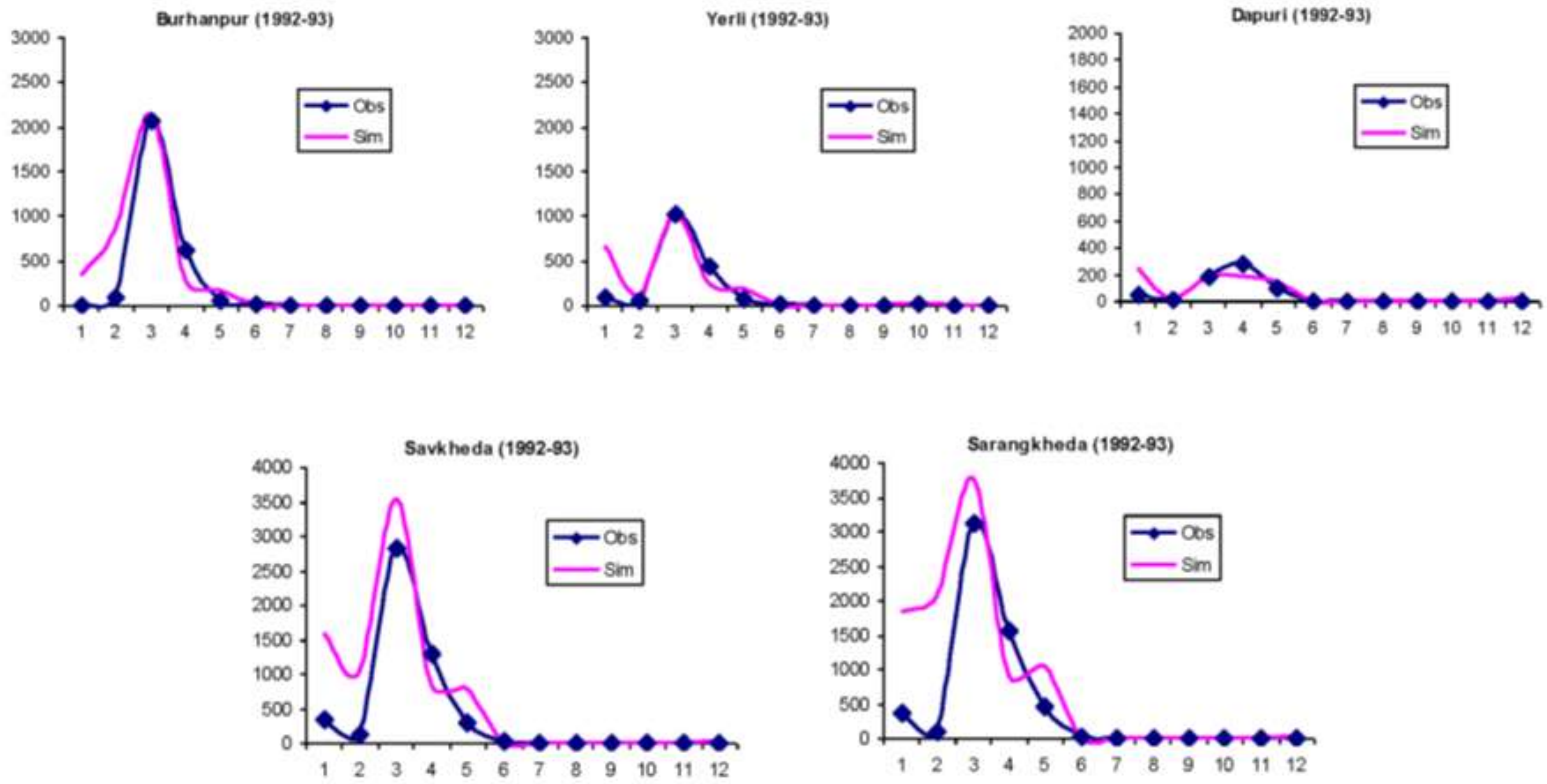


Figure – 4.4: Observed and simulated monthly flows in MCM (June 1992 – May 1993) at different gauging sites in Tapi basin

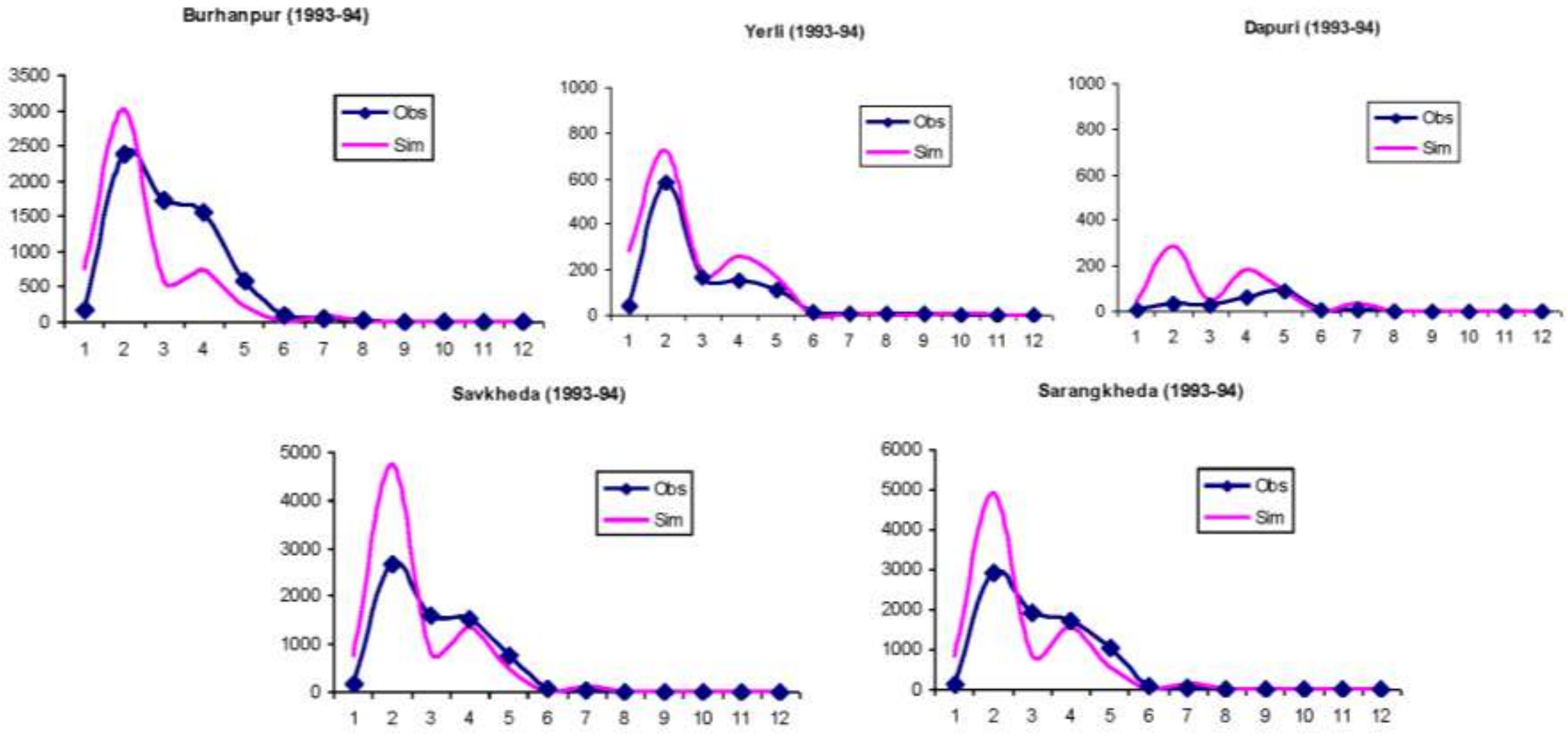


Figure – 4.5: Observed and simulated monthly flows in MCM (June 1993 – May 1994) at different gauging sites in Tapi basin

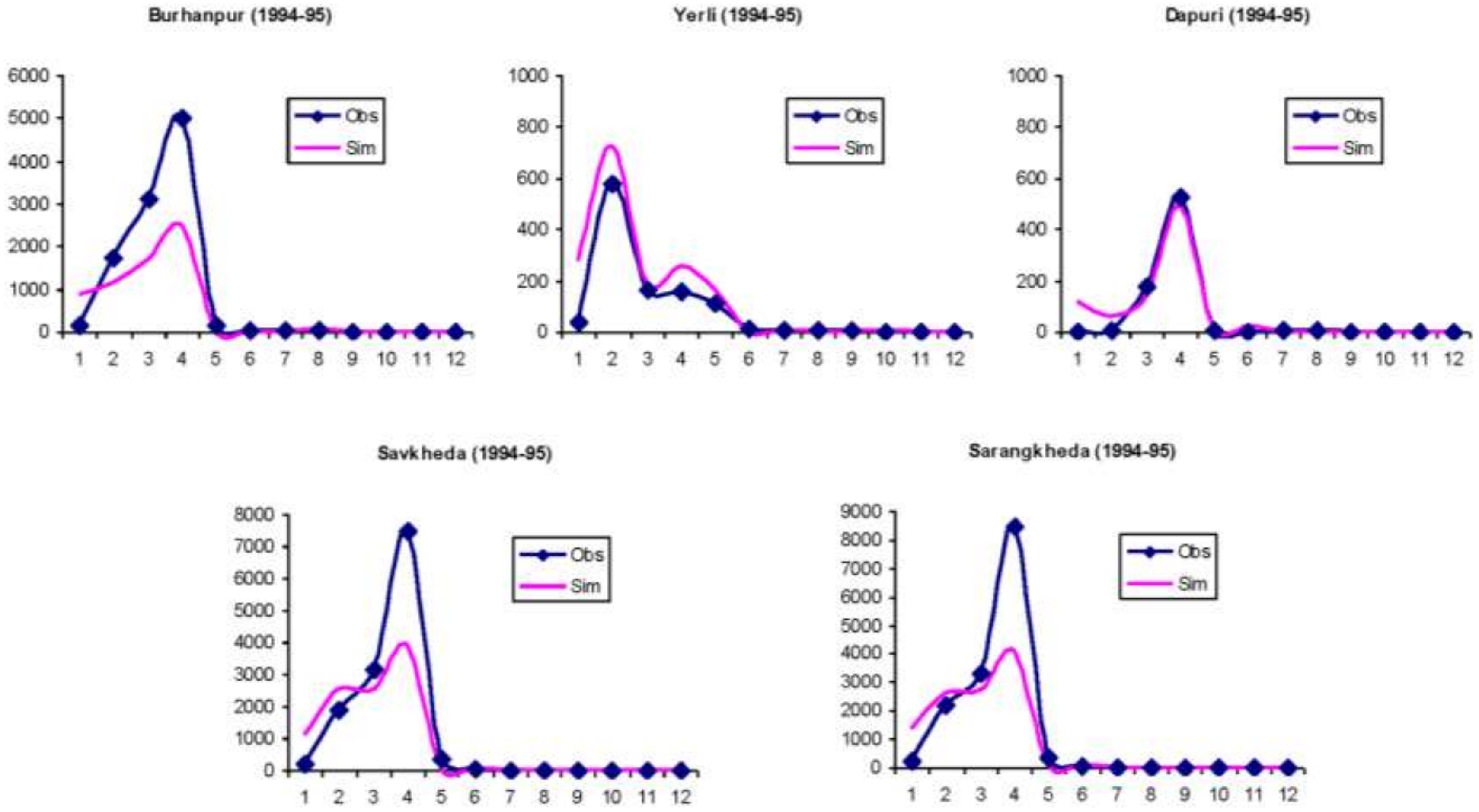


Figure – 4.6: Observed and simulated monthly flows in MCM (June 1994 – May 1995) at different gauging sites in Tapi basin

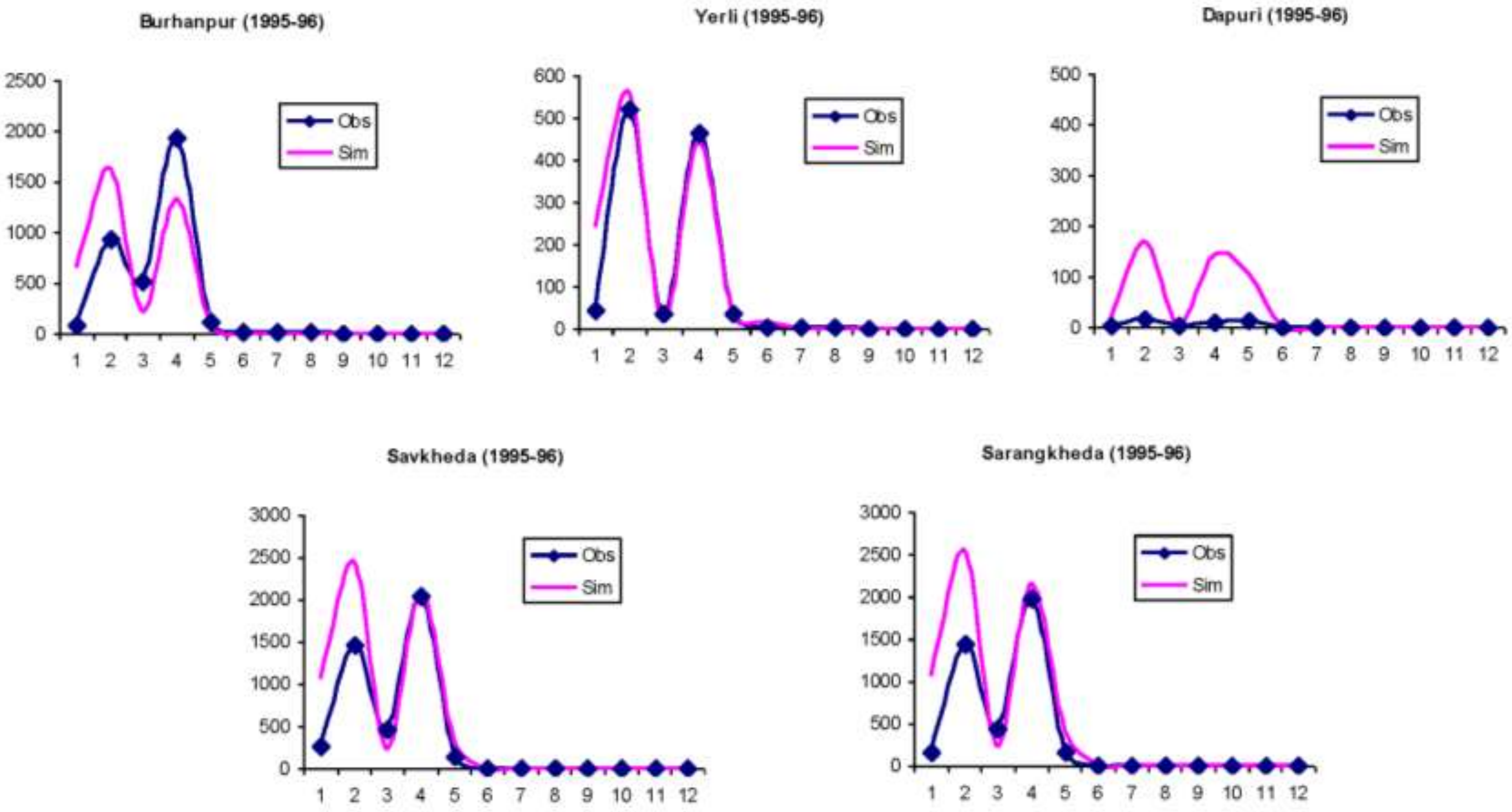


Figure – 4.7: Observed and simulated monthly flows in MCM (June 1995 – May 1996) at different gauging sites in Tapi basin

4.5 Limitations of the Present Study

In the present study, a spatially distributed basin simulation model has been developed and applied to the Tapi River Basin. Some limitations of the present study are:

a) This is the base development of the distributed river basin planning model. A number of options still need to be incorporated in the model for making it more generalized and user-friendly. The impact of wilting or stress condition on the crop is yet to be incorporated in the model.

b) The database requirement of the model is quite exhaustive. For the Tapi basin, though efforts have been made to gather and use the data as accurately as possible, yet a number of assumptions have been made and ancillary methods have been used to develop the database. For example, command area boundaries of different projects have been demarcated with the help of NOAA satellite images.

c) Most of the river basin details like cities connected to reservoirs for domestic supply, industrial demands, minimum flow demands, location and characteristics of minor hydraulic structures, crop and soil properties etc. have been assumed. Reservoir water spread area is taken as linear function of depth.

d) Long-term average monthly evapo-transpiration values have been used rather than actual observations. Actual ET estimation affects the crop water demands and subsequently the entire hydrological cycle of the basin. An error of 1 mm at a grid is equivalent to 1000 cubic meter of water for a grid size of 1 km x 1 km.

e) Groundwater simulation model is an integral part of the present model for assessing the revised groundwater depths in different months. However, groundwater table of only June, 1992 has been used in the present case for all the months.

f) District-wise groundwater development is assumed to be uniformly distributed in the urban and agricultural grids. There is a need for more detailed estimation of groundwater potential and use in different areas in different months.

g) In the present application, model assumes that water is spilled from a reservoir only after filling it up to the FRL. A deviation from this fact can affect the flows at downstream gauging sites.

This study has been mainly concerned with the model development for river basin simulation and its testing for a river basin. This task requires multi-dimensional data involving a number of Central and State agencies/ departments. There is a strong need for close collaboration of these agencies and departments for the successful execution of the model for a river basin.

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Chapter – 5
CONCLUSION

With time, we are becoming more increasingly aware of the fact that our water supplies are limited both in quantity and quality. 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. An integrated river basin planning and management approach enables us to have knowledge in space and time of what water is needed for, where, and in what amount, thereby allowing for balancing out between the competing needs.

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. Virgin flows in the basin are estimated and long-term discharge series is obtained by using a regression relationship between rainfall and discharge. Discharge corresponding to a specified reliability is then taken as the water availability for a basin. However, in this approach it is difficult to account for changes in rainfall and meteorological parameters because of climate modifications, land use/land cover area, cropping pattern, spatial and temporal groundwater development etc. 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 and establish linkages among water-related variables to simulate any situation for past, present or future conditions.

With this need in view, a spatially distributed river basin simulation model has been developed with the aim to link various components of water resources in a river basin (rainfall, evapo-transpiration, runoff, groundwater, soil moisture, irrigation, domestic and industrial demands, reservoirs 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.

The model adopts the simulation approach for assessing the spatial and temporal water availability and demands in the river basin. The model takes precipitation as the basic input in the basin. It is possible to import/export water from outside the basin to a reservoir or a river segment. It is also possible to divert water 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 and hydrological analysis is carried out for each grid. The model is linked to the ILWIS (Integrated Land and Water Information System) GIS System which is in public domain.

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. Soil moisture accounting is carried out for each grid to estimate irrigation demands and GW recharge. 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. Operation of different reservoirs/weirs is simulated using the standard linear operation policy. 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.

The river basin simulation model has been applied to the Tapi River basin to check for its linkages, computational algorithm, and performance analysis. Spatial, attribute, and dynamic data have been collected for the Tapi basin. Fifteen spatial data layers have been generated in ILWIS GIS system using remote sensing analysis and GIS analysis. The basin DEM and other topographic attributes have been obtained from SRTM data. Multi-temporal NOAA AVHRR data (1 km resolution) has been used for determining cropping pattern and delineating the irrigable command areas of different reservoirs. Landsat TM data of the basin has been used for locating major and medium 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 1995-96 has been obtained from CWC. Average evapo-transpiration depths have been worked out through CROPWAT model by using the long-term average meteorological parameters. The model results for different sub-basins of Tapi basin up to Ukai dam have been presented.

It needs to be mentioned here that database requirement of the model is quite extensive. The model involves multi-disciplinary data that is covered by a number of departments/agencies like Central Water Commission, Central Ground Water Board, Indian Meteorological Department, Agriculture Department, Statistical Directorate, Project authorities in the river basin etc. Since this study has been mainly concerned with the model development and its testing for a river basin, individual efforts have been made by the study team to gather the information for the Tapi basin as accurately as possible. Wherever actual field details could not be obtained, the same have been generated by using different ancillary means or have been suitably assumed. There is a strong need for close collaboration of various agencies/ departments for the successful execution of the model for a river basin.

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