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Name of PI & Co-PI	Dr. Deepak Khare
Institute Address	Professor, Department of Water Resources Development & Management Indian Institute of Technology Roorkee, ROORKEE 247667 Uttarakhand
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E-Mail: incsw-cwc@nic.in

FINAL REPORT

CONJUNCTIVE USE PLANNING OF WATER RESOURCES CONSIDERING SPATIAL VARIATION IN CROPPING PATTERN USING REMOTE SENSING AND GIS

(In a Canal Command of Tawa Project)

Under

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Dr. Deepak Khare, Principal Investigator

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EXECUTIVE SUMMARY

General

Introduction of canal irrigation facilities in command areas sets new hydrological regime with revised conditions of groundwater recharge and withdrawal. If water is not utilized as per the design plan or if there is a significant difference in actual and design values of demands and supplies, an imbalance is created in the ecosystem which can lead to its drastic deterioration. Therefore, it is important to manage the water resources conjunctively in the command areas after the new irrigation infrastructure has been developed. During last three decades, application of operation research techniques to water resources has produced a number of models for conjunctive use planning and management of water resources system. Often, gross or simplifying assumptions are made in planning and implementation of irrigation projects leading to significant differences at the ground level. Some examples of such simplifying assumptions are areal average cropping patterns, uniform physiographic and agro-climatic characteristics, average groundwater availability, average groundwater condition over entire command, uniform response of crops to quantity of water supplied in entire command area, etc. In actual practice, variables, parameters and processes related to irrigation water management vary both spatially and temporally. Often it is found that due to small land holding and varying preferences of farmers, crops in a command area may vary from field to field and thus their associated properties like root depth, irrigation water demand, wilting coefficient, etc many vary. Variation of crops in a command area affects the crop water requirement at any time, which directly governs the operation of the canal system. Depending on topography and water table position, groundwater depth below surface may vary both spatially and temporally. Similarly, canal system characteristics vary as per the network. One portion of the canal system may be lined while the other unlined, thus affecting the seepage rate and consequently, the water demand in different parts of the canal network and recharge into the aquifer. The application efficiency and channel conveyance efficiency may vary spatially depending on the prevalent methods of irrigation application and channel conditions. All such variations need to be considered in developing operation plans on a scientific basis. In all these circumstances, remote sensing can be looked upon as aid in planning and decision-making. The usefulness of remote sensing techniques in inventory of irrigated areas, identification of crop types, stress conditions, crop yield estimation, crop evapotranspiration (ET) determination, and identification of waterlogged and saline areas, etc.

Study area

In the present research work, a detailed study to address the conjunctive water resource management in the Tawa canal command considering both on spatial and temporal aspects has been undertaken. Tawa canal command is a planned gravity major irrigation system started in the year 1978 on completion of the dam across the Tawa river, a tributary to Narmada river. Tawa command is spread over in an area of about 5273.12 km^2 falling in the district of Hoshangabad, Madhya Pradesh, India. It lies between 22º54' N to 23º00' N latitude and 76º457' E to 78º45' E longitude. Hoshangabad district lies in the south-west part of the Madhya Pradesh state, India. The annual mean rainfall in the Tawa command is 1174.78 mm. The soils of the area are characterized by black, gray red and yellow colours, often mixed with red and black alluvium and ferruginous red gravel or lateritic soils. In the study, two sources of water (surface water and groundwater), demands of various crops in different zones, and the management aspects are considered in order to achieve optimal allocations of resources. In the modelling approach, geospatial techniques (viz. remote sensing and GIS) have been used to address the large variability of parameters governing the demand and supply processes in both space and time. An attempt has also been made to demonstrate the capability of developed model to optimally manage the deficit water availability scenario.

Data used

Reliable and authentic data is very important to carry out application based research as the result of the study depends up on spatial and thematic completeness of the data. A lot of efforts was spent in collection of spatial and non-spatial data from different organizations. Satellite images were procured from NRSE, Hyderabad. Data were checked for reliability and consistency before full-fledged analysis. Digital Elevation Model (DEM) is one of the important layers to study any aspect of water resources. The NASA's Shuttle Radar Topography Mission (SRTM) at 90 m spatial resolution and about 10 m accuracy in X, Y and Z direction has been used in the present study. Command area boundary, soil map, land use land cover map, drainage map were generated using GIS and remote sensing tools. Remote sensing technique can be used for the extraction of land use land cover information and land use change detection in the command area of irrigation projects. To evaluate the change, if any, in cropping pattern of the Tawa command, land use of Rabi season of year 1995 has been mapped using temporal multiband data of IRS 1B LISS-I. Further, the land use in Rabi season of years 1995 and 2005 are compared based on major land use classes. The comparison between land use of these two time periods indicates that the cropped area under major crop (Wheat) has increased, and this must be reflected in planning the future scenario.

Groundwater model

For the Tawa Command Area (TCA), groundwater model is prepared in Visual MODFLOW 4.2 to know the present state and behavior of groundwater with respect to aquifer parameters, recharge and withdrawals. In the present study, block centered approach for groundwater modeling has been adopted. The continuous model area is divided into square or rectangular regions called cells. Head computed at discrete points are called nodes. The network of cells and nodes are called grid or mesh. The nodal grid forms the framework of the mathematical model. This grid is prepared by importing Tawa Command boundary file from geodatabase, to define boundary in X-Y domain. A finite difference grid is designed by manipulating rows, columns and layers of cells. A series of cells oriented in the x-direction is called a row and a series of cells aligned along the y-direction is called column. A horizontal two-dimensional network of cells is called layer. Cells are designated using row and column coordinates, with the origin in the upper left corner of the mesh. The upper left cell is designated as row 1 and column 1. The upper layer is layer 1 and layers increase in number downwards. The size of the grid depends on the availability of data, the size of the area and the spatial resolution requirement of final results. For the current groundwater model, 500 m ×500 m grid is adopted with 244 rows and 406 columns. In the Tawa Command Area, most of the water available is from unconfined aquifer system, so the top phreatic aquifer is conceptualized for groundwater modelling in this study. Model domain in the vertical direction is defined in the form of two surfaces (layers). First layer is represented by the ground surface. Second layer is represented by the bottom of the alluvial aquifer. In the present investigation, one year period has been divided into two seasons starting from May to October, and November to April. Seasonal time step has been adopted for defining the initial and boundary conditions, whereas monthly time step has been used for River Narmada. Monthly time step, starting from May has been used throughout the groundwater simulation. Model has been calibrated for a 4 year time period

(May 1997 to May 2001) and validated for a period of two year (2002 to 2003). A sensitivity analysis has also been performed for the calibrated aquifer parameters and recharge and the corresponding changes have been observed in the model. By observing the calibrated aquifer parameters and sensitivity analysis results it is learned that the groundwater system of TCA is more sensitive to recharge as compared to other factors. The calibration and validation results indicates that the groundwater model for TCA has been well calibrated and has capable of predicting future state of groundwater system as a response of changed water allocation plan.

Conjunctive use model

In this study, a general mathematical model for conjunctive use of surface water and groundwater in command area of irrigation project, is formulated incorporating its major elements. The model selected for the present investigation includes surface water and groundwater as sources of irrigation, multiple users (the command area is divided into five zones as described in later part) and Crop Production Response Functions (CPRF), which defines the crop yield as intrinsic function of water supplied. The developed model has been applied over data from the Tawa Command to illustrate a practical application of distributed conjunctive use model. The command area has been divided into five zones (Fig. 7.1) based on the groundwater conditions of the area. The administrative block boundaries have been considered as boundaries of new zones. The resources availability has been assessed for each zone using the geospatial techniques and information from literature. Groundwater availability, water demands by crops are suitably estimated during the model formulation. To quantify the advantages of conjunctive use planning in economic terms, the accurate estimate of cost coefficients for each resources is considered including the cost of groundwater, surface water, benefits from different crops. The cost functions for surface water, groundwater and CPRF, optimization model and groundwater model have been coupled for optimum planning of water resources in command area. The season-wise cost of pumping has been considered in the model corresponding to the average seasonal depths to water table in each zone of the study area. Then the distributed conjunctive use model has been formulated by integrating and coupling various cost coefficients. In the present study, LINGO (version 10), a comprehensive tool designed for building and solving linear, nonlinear and integer optimization models, has been used for solving the formulated conjunctive use model (optimization model). The proposed model is a generalized formulation and can be used for any other command area, by incorporating required input data.

The developed conjunctive use model has been applied over Tawa Command Area to investigate the different scenarios of resources allocation, and suggest the optimal scenario. In the present study, following six scenarios were investigated for resources allocations in the Tawa Command:

- Scenario 1: Designed cropping pattern and irrigation intensity (Strategy 1)
- Scenario 2: Existing cropping pattern and 67% irrigation intensity/cropping intensity in Rabi and Kharif seasons (Strategy 2)
- Scenario 3: Existing cropping pattern with 67% irrigation intensity in both the seasons and changed surface water supply levels in Zone-3 and Zone-1 (Strategy 3 to 12)
- Scenario 4: Increased irrigation intensity in Rabi season (80%) and 67% cropping intensity in Kharif season (Strategy 13)
- Scenario 5: Increased irrigation intensity in Rabi season (80%) and 67% cropping intensity in Kharif season with changed surface water supply levels in Zone-3 and Zone-1 (Strategy 14 to 18)
- Scenario 6: Spatio-temporal conjunctive use approach (Strategy 19)

The accrued benefits, surface water utilization, groundwater utilization and area under cultivation in each strategy are listed in Table 1. The benefit per unit of water utilized is highest in spatio-temporal conjunctive use scenario (Strategy-19).

Table 1: Consolidated results from all strategies (S1 to S19)

S. No.	Benefits			Irrigated Area (ha)	Water Utilizes (ha-m)		Water Utilization Level (%)	
	Total (Rs)	Rs/ha	Rs/ha-m		SW	GW	SW	GW
S1	9223555000	25999	40488	354764	110473	117333	84.36	83.33
S2	8899792000	24692	43877	360436	112191	90643	85.67	64.37
S3	8899790000	24692	43877	360436	110330	92504	84.25	65.69
S4	8900917000	24695	43883	360436	112191	90643	85.67	64.37
S5	8899785000	24692	43877	360436	107569	95265	82.14	67.66
S6	8902041000	24698	43888	360436	111290	91544	84.98	65.01
S7	8899780000	24692	43877	360436	104454	98379	79.77	69.87
S8	8902946000	24700	43893	360436	109676	93157	83.75	66.16
S9	8899056000	24690	43874	360436	101285	101549	77.34	72.12
S10	8902969000	24701	43893	360436	107795	95039	82.32	67.49
S11	8896842000	24684	43863	360436	98225	104609	75.01	74.29
S12	8901258000	24696	43884	360436	105511	97323	80.57	69.12
S13	9678892000	25209	43959	383943	118122	102060	90.20	72.48
S14	9742168000	25374	44172	383943	118327	102222	90.36	72.60
S15	9743291000	25377	44177	383943	117073	103476	89.40	73.49
S16	9744414000	25380	44182	383943	115818	104730	88.44	74.38
S17	9744739000	25381	44184	383943	114435	106114	87.39	75.36
S18	9743272000	25377	44218	383943	112554	107794	85.95	76.55
S19	**9747532000**	**25388**	**44237**	**383943**	**119581**	100767	**91.32**	71.56

In the study, a separate scenario has been considered in solving the optimization model considering the existing cropping pattern estimated based on identified crops using remote sensing satellites for the *Rabi* season. It has been already discussed in earlier chapter that significant changes in cropping pattern have been occurred in the Tawa canal command. New crop such as Soyabean has been introduced in the area. Also the crop acreage for few crops have been altered. It has been seen that the cropping intensity during *Rabi* season has been changed from 67% in the design cropping pattern to 74% in the existing cropping pattern as reported. Based on the satellites imageries (RS based) crop identified for the *Rabi* season, it has been seen that the cropping intensity has been further extended to 81%. Finally, the study concludes that the proposed optimal strategy (Strategy-19) based on distributed conjunctive use model has a capability to transform the Tawa Command into a profitable, environmentally sustainable water resources system, subject to implementation of suggestions and strategies by the concerned command authority.

RS based crop identification and spatial estimation of crop water requirement

In this study, major crops were identified using satellite imageries and GPS sampling and then relationships were developed between crop coefficients of identified crops in the command and normalized difference vegetation Index (NDVI) from remote sensing data, as both are affected by leaf area index and fractional ground cover, before estimating the crop evapotranspiration. Finally, the supply (rainfall, canal irrigation) and demand (crop evapotranspiration) has been analyzed for the Tawa canal command before suggesting optimal allocations of the water. NDVI profile indicates following major crops in the command during rabi season: (i) wheat, (ii) chick-pea, (iii) sugarcane, (iv) linseed and (v) crops such as vegetables and orchards. Spatial distribution of major crops indicates highest coverage for wheat (75%) followed by chick-pea (15%), sugarcane (2.42%) and linseed (2.32%). Field surveys were conducted to capture standing crops using GPS technology.

Conclusions and recommendations

Application of mathematical model developed in the present study has been successfully demonstrated for resources allocation problem of Tawa Command. The developed model has been found capable in achieving the optimum utilization of all available resources to maximize the benefits, and in solving the existing problems of groundwater system in the command area. The modelling concept developed in the present research has extended the application of spatial technologies and system engineering to resources management problems in Tawa Command Area.

Following are some of the aspects worthy for consideration in future research:

- Research on climate change is gaining momentum in wide spectrum of fields. The vagaries of climate change and its very threatening nature to the human existence is forcing world community to undertake research on its mitigation and adaptation since controlling climate is beyond our reach. The long term climate change pattern assessment and its feasibility of considering an option for adaptation to climate change ensuring food security in future needs to be investigated.
- Recent reports indicate that nitrate concentration in some observation wells in the Tawa Command Area exceeded the permissible limits possibly due to pollutants from agricultural/municipal water use. The present model can be extended to include the water quality aspects from various sources and water quality requirement of different crops into the decision process. However, it requires detailed data on water quality.
- The cost functions for groundwater are developed considering uniform values of aquifer parameters from the entire command area. Though the specific yield for unconfined aquifers does not have any significant effect on the unit cost of groundwater but lower transmissivity may affect the unit cost. These aspects can be investigated in future work.
- In the present study, optimization and groundwater simulation model is coupled externally through an iterative process to obtain the dynamic response of groundwater system in response to various management scenarios. Other approaches like, embedding and response coefficient approach can be explored further. Present modelling concept considers the nonlinearity of groundwater pumping, however, it can be extended to include the other hydraulic management objectives, like water table depth restriction.

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CHAPTER 1
INTRODUCTION

1.1 GENERAL

Agriculture sustains life, whereas irrigation sustains agriculture. In natural state, availability of water for crops seldom meets the requirement of crop water both in, space and time. On the other hand, ever growing demands of increased world population has put tremendous pressure on agricultural sector to provide food for all. This has led to extensive development in irrigation sector in the last two centuries. As a result of this, worldwide agriculture through irrigation facilities has increased from 8 million hectares (M ha) in the year 1800 to over 301 M ha by 2010 (Siebert et al., 2010). Nearly one-fifth of this area is located in India. Figure 1.1 shows the total global irrigated agriculture in terms of percent of irrigated agriculture.

In the last three decades, more than half of the increase in total food production has come from irrigated agriculture, whereas area under irrigated agriculture occupies only 17% of world's arable land. If the recent trend in population growth continues, the agricultural production needs to be increased by 3 to 4% per year, the large share of which is expected to come from irrigated agriculture, particularly in developing countries (Tardieu, 2000). On the other hand, the resources for increasing the food production are shrinking day-by-day. This calls for improvements in the resource management to be integral part of the agricultural system, of which water is an important resource. However, in the present scenario, it has been reported and observed that inappropriate irrigation management has led to conversion of about 100 M ha of arable land into unusable land due to problems like waterlogging, salinity and reduced groundwater availability (Goel, 2003).

In India, irrigation potential has increased from 22.6 M ha in year 1951 to 102.77 M ha by year 2007 and the total investment made in the irrigation sector up to the end of tenth five year plan (2002-2007) has been more than 71,21,300 Million Rupees (Anonymous, 2010). In spite of such a large investment and phenomenal growth of irrigation potential, the performance of several irrigation projects in India has not been encouraging especially in terms of the poor performance resulting in lower crop yield and irrigation efficiency. Further, it has led to increased environmental hazards such as, waterlogging and salinity.

The inefficient utilization of irrigation potential can be attributed to managerial deficiencies in operation and management of irrigation projects and improper development of on-farm systems. Many reports estimates that a 10% increase in the present level of water use efficiency can result in, an increase of 14 M ha area which could be brought under irrigation with the existing irrigation capacities (World Bank, 2005; Anonymous, 2010). This can be achieved at a moderate investment compared to the investment that would be required for creating equivalent potential by way of new irrigation schemes.

Increase in water use efficiency can be achieved by improving the performance of water distribution system which will be governed by dynamic water requirement and water availability parameters. It is observed that in the command areas vis-à-vis surface irrigation schemes, groundwater is utilized to bridge the gap between crop water demands and surface water supplies on temporal and/or spatial scale. However, such projects are not designed with recognition of groundwater as a source of irrigation. In areas having deficit surface supplies (e.g. canal), farmers tend to over-exploit the groundwater whereas in the head reaches of canal networks, the surface water is over-utilized due to its easy availability.

These improper irrigation practices lead to environmental problems such as, rise in groundwater levels and thereby causing waterlogging, soil salinity, while on the other hand, considerable decline in groundwater levels can lead to saline water intrusion in coastal areas, reduced base flow in streams etc. These problems are posed by poor performance of irrigation systems along with increased risk of environmental degradation can only be countered if a conjunctive (integrated) water resources planning approach is adopted.

1.2 CONJUNCTIVE USE

Conjunctive use has been defined in more than one way. In general, it is defined as ‘the allocation of surface water and groundwater in terms of quantity and/or quality so as to achieve one or more objectives while satisfying certain constraints’. In other words, conjunctive use of surface water and groundwater offers a great potential for enhanced and assured water supplies at minimum cost. According to Todd (1980) "Future demand for water requires planning the maximum utilization of all of the existing supplies. This can most economically be obtained by conjunctive use of surface water and groundwater reservoirs". Kazmann (1951) pointed out that surface water and groundwater are inextricably interconnected and can not to be arbitrarily separated.

The primary aim of any water resources project based on conjunctive use concept is to optimise the combined utilization of available and proposed surface water and groundwater facilities for sustaining the supply over a longer period. The term optimisation means the achievement of the best results and may be interpreted in different ways depending on the relative importance of the specific objectives e.g. benefit out of a given volume of water, or of minimising water losses through flood runoff, evaporation and seepage. Most comprehensive optimisation schemes, however, will necessarily have to be based on some economic evaluation. Additional benefits would obviously be achieved, if a water resource system is planned and operated taking into consideration the advantages offered by the conjunctive use of surface water and groundwater.

In the early development stages of conjunctive use models, groundwater was considered as separate source of water, and actual interaction between the surface water and groundwater resources was mostly neglected. In the second stage of the evolution of these models, the partial differential equation of the interaction between surface water and groundwater resources, the physical and economic constraints and pollutant transport were considered in the descriptive conjunctive use models. In the third stage models, the nonlinear differential equations of groundwater flow were considered important in optimization models in order to estimate the groundwater contribution. Recently, the uncertainties in discharge and recharge parameters have also been considered in stochastic conjunctive use optimization models. In recent years, more complex nonlinear techniques are presented by many researchers, but the nonlinear optimization has inherent limitation of dimensionality of parameters. To overcome this limitation, the conjunctive use models are developed on gross scale (i.e. only major crops are considered in modelling; surface water and groundwater availability is not distributed in time and/or space, etc.)

1.3 NEED FOR PRESENT STUDY

Introduction of canal irrigation facilities in command areas sets new hydrological regime with revised conditions of groundwater recharge and withdrawal. If water is not utilized as per the design plan or if there is a significant difference in actual and design values of demands and supplies, an imbalance is created in the ecosystem which can lead to its drastic deterioration. Therefore, it is important to manage the water resources conjunctively in the command areas after the new irrigation infrastructure has been developed.

During last three decades, application of operation research techniques to water resources has produced a number of models for conjunctive use planning and management of water resources system. Often, gross or simplifying assumptions are made in planning and implementation of irrigation projects leading to significant differences at the ground level. Some examples of such simplifying assumptions are areal average cropping patterns, uniform physiographic and agro-climatic characteristics, average groundwater availability, average groundwater condition over entire command, uniform response of crops to quantity of water supplied in entire command area, etc.

In actual practice, variables, parameters and processes related to irrigation water management vary both spatially and temporally. Often it is found that due to small land holding and varying preferences of farmers, crops in a command area may vary from field to field and thus their associated properties like root depth, irrigation water demand, wilting coefficient, etc many vary. Variation of crops in a command area affects the crop water requirement at any time, which directly governs the operation of the canal system. Depending on topography and water table position, groundwater depth below surface may vary both spatially and temporally. Similarly, canal system characteristics vary as per the network. One portion of the canal system may be lined while the other unlined, thus affecting the seepage rate and consequently, the water demand in different parts of the canal network and recharge into the aquifer. The application efficiency and channel conveyance efficiency may vary spatially depending on the prevalent methods of irrigation application and channel conditions. All such variations need to be considered in developing operation plans on a scientific basis.

1.3.1 Use of Remote Sensing and GIS

Vastness of the command areas, time and manpower constraints in data collection and seasonal changes in the information, require fast inventory of agricultural areas. In all these circumstances, remote sensing can be looked upon as aid in planning and decision-making. The usefulness of remote sensing techniques in inventory of irrigated areas, identification of crop types, stress conditions, crop yield estimation, crop evapotranspiration (ET) determination, and identification of waterlogged and saline areas have already been demonstrated in various studies (Govardhan, 1993; Bastiaanssen, 1998; Bastiaanssen et al., 2000; Menenti, 2000; Ray et al., 2002; Singh and lrmak, 2009). Advances in remote sensing technology results in considerable saving of time and money spent in data collection.

Information is vital in reducing uncertainty, evaluating alternative courses of action and revealing new avenues. Availability of correct information at the right time to the appropriate person and at reasonable cost is a crucial factor in decision-making. Irrigation management requires large amount of data pertaining to hydrological, hydro-geological, hydro-meteorological, soil, agronomic, cropping pattern, and socio-economic parameters vis-à-vis command area. It is also required to continuously update some information for real-time resource management. A spatially distributed model for irrigation management requires data on various variables and parameters such as existing cropping pattern, soil characteristics, rainfall, groundwater depth, canal irrigable areas, etc. These data need to be efficiently stored, analyzed and retrieved in a user-friendly and interactive environment. Conventional procedure of storing, handling and updating records are slow, unsystematic, occupy large space and require large manpower. Further, such records are difficult to update. The advent of geographic information system (GIS) tools has made it possible to prepare dynamic resource maps for large areas.

GIS is computer based system designed to store, process, retrieve, and analyze spatial data attributes, can assist in water resources management by efficiently handling spatial, non-spatial and temporal information of water resources in a command area.

GIS, coupled with simulation model, can be used to assist in (a) allocation planning, (b) spatial analysis of water distribution for performance evaluation, and (c) communication between irrigation managers and stake holders/ users. Irrigation managers, working in GIS environment, can get comprehensive information in real-time for developing water distribution plans in a command area.

1.3.2 Crop Production Response Function

Agricultural yield is a function of many input variables with crop water availability, being the one of most important. In earlier attempts to find the relation between water availability and yield of a particular crop, a linear relationship between inputs and yield was assumed. Subsequently, extensive field analysis revealed that the yield is an intrinsic function of inputs like water, fertilizer, etc. (Willis et al., 1989). The assumption of 'higher the water supply, higher the yield' has been rejected after such studies. It was accepted that deficit water supply in different time periods of crop life cycle will have different impact on yield.

Many researchers have given approach to model the reduction in yield in case of deficit water supply (Stewart et al., 1977; Doorenbos et al., 1979; Gulati and Murty, 1979; Rao et al., 1988; Varlev and Mladenova, 2001; Kipkorir and Raes, 2002; Vedula et al., 2005). Most of the equations are either data dependant or site specific. However, due to its simplicity and scope for global application, the approach suggested by Doorenbos et al., (1979) is preferred by many researchers. Crop Production Response Functions help to estimate the actual yield in case of deficit irrigation system and, in some cases, excess irrigation supply. These Crop Production Response Functions, coupled with conjunctive water use planning models, can help in assessing the effect of change in water supply on total production from existing cropping pattern in the command area. Thus conjunctive use model coupled with Crop Production Response Functions can help in optimal management of the water deficit scenario (due to drought, breakdown in supply system etc).

1.3.3 Need for Distributed Conjunctive Use Model

In a typical conjunctive use model, groundwater is considered as an additional source in conjunction with surface water. The groundwater is one of the most important sources of water to satisfy the domestic, industrial and agricultural needs. Groundwater in a basin is not in a state of rest but it is dynamic in nature i.e. it is in a state of continuous movement. Any exploitation in the form of groundwater withdrawal (pumping) or recharge would change the state of groundwater. Whenever, the withdrawal of groundwater exceeds the recharge, the water table in the area falls. On the other hand, if the downward percolation in the form of recharge exceeds the pumping rate, the water table rises. In this context, the behavior of groundwater table is dependent on many factors like rainfall, type of basin, withdrawal pattern, types of boundaries conditions, etc. To evaluate the dynamic behavior of groundwater system, it is necessary to simulate the existing conditions in a region and transform them in a form of mathematical model. The mathematical modelling of the groundwater system in an area is required to predict the groundwater behavior of a particular region.

The availability of surface water and/or groundwater varies in space and time, and so is the crop water demand. To solve these problems and to optimize return from water resources utilized in the command area, the model must have capability to address the spatial variability of the involved parameters and processes.

The gross scale conjunctive use model available in literature may have capability to consider the dynamic nature of water sources but the lumped nature of model ignores the spatial variability of parameters governing the water management process. The problems like rising groundwater levels may exist in some part of command area and the optimum water allocation policy developed on gross scale may not be technically suitable for that area. The spatial variation in parameters (e.g. water demand, surface water availability, groundwater availability, system capacity etc.) calls for distributed approach in conjunctive use modelling.

The Tawa project is a multipurpose project existing on Tawa River, which is a tributary of Narmada River in Madhya Pradesh State of India. The gross command area and culturable (cultivable) command area of the project are 2,88,956 ha and 1,86,162 ha, respectively, which covers different blocks of Hoshangabad and Harda districts of Madhya Pradesh.

After the implementation of the project, as per the policy of the Government, the equitable distribution of the surface water was made. At present, it has been found that in some of the portions in the command area, waterlogging has occurred. On the other hand, adequate surface water is not available in the tail reaches of the command area. With this background, in the present study, an attempt has made to develop a distributed conjunctive use model for optimal planning and utilization of the water and land resources, and also to solve the problem of rising water table in the head reaches and water scarcity in the tail reaches of the command by using the developed model.

1.4 OBJECTIVES

In the present research work, a detailed study to address the conjunctive water resource management in an irrigation command area considering both on spatial and temporal aspects has been undertaken. Two sources of water (surface water and groundwater), demands of various crops in different zones, and the management aspects are considered in order to achieve optimal allocations of resources. In the modelling approach, geospatial techniques (viz. remote sensing and GIS) have been used to address the large variability of parameters governing the demand and supply processes in both space and time. During review meetings the objectives were also deliberated and accordingly, they were finalized. Therefore, an attempt has also been made in the present study to demonstrate the capability of developed model to optimally manage the deficit water availability scenario.

The specific objectives of the present study are:

- **To study the spatial variation of cropping pattern in command area using Remote sensing data**.

    - To study the status of present water supply system to identify the problems and their spatial extent.
    - To develop the spatial database of the study area.
    - To develop the spatial distributed ground water model simulating the dynamic behavior of ground water system, to calibrate the ground water model, and to estimate the aquifer parameters for the study area.
    - To conduct cost analysis of ground water and surface water system so to develop cost functions of surface and ground water.
    - To develop Agriculture Production Response Function.
- **To Formulate the Linear Programming Model** coupled with ground water simulation model, and cost functions to obtain optimal allocation policies for the optimal cropping pattern.
    - To develop a subroutine to transfer the output of linear programming model to ground water model and agriculture production response simulation model to reduce the computational work.
    - To create/develop the interface between database and other models, and interactive software of the conjunctive use model having user friendly interface.
- **Evaluation of Optimal Allocation Policies for the Optimal Cropping Pattern.**
    - To obtain the optimal allocation plan of surface and ground water resources through conjunctive use model.

CHAPTER 2
REVIEW OF LITERATURE

2.1 GENERAL

The present study of distributed conjuctive use modelling has been evolved from the study of water resources problems reported in various command areas of surface water projects and their solution through the applications of mathematical modelling techniques. This chapter provides a foundation, based on the previous research, for the development of a mathematical based optimization models for the planning of conjunctive use of water resources in canal command area.

Literature on the planning of conjunctive use covers different aspects of water management, which include integration of various components of water resources system of irrigation commands in an optimization modelling framework, interaction of major components, demand management aspects, relevant economic aspects and application of remote sensing and GIS technologies. The concept of crop production response functions and their integration in water management models are reviewed along with the concept of integration of dynamic groundwater response in conjunctive use model. Attention is also directed to particular water resources management problems in irrigation command areas and use of optimization and geospatial techniques i.e. remote sensing and GIS, which are used to introduce the spatial and temporal variability of the different hydrological phenomenon.

Starting with the concept of conjunctive use, representative case studies dealing with conjunctive use of groundwater and surface water in irrigation projects are presented in this chapter. Subsequently, integration of groundwater model, crop production response functions, and application of remote sensing and GIS techniques are discussed.

2.2 CONJUNCTIVE USE

Conjunctive use of surface and groundwater can be defined as the management of surface water and groundwater resources in a coordinated operation such that the total yield of such a system over a period of years exceeds the sum of the yields of the separate components of the system resulting from an uncoordinated operation (Coe, 1990).

Conklin (1946) was the first to describe the fundamental needs of conjunctive use of surface and groundwater resources. Kazmann (1951) and Banks (1953) identified the economic advantages of conjunctive use operations. They also highlighted the physical, financial and legal complexities of the problem.

Other notable authors, who dealt with the conjunctive use of surface and groundwater at early stages are: Clendenen (1954), Hall and Buras (1961), Machsoud (1961), Burt (1964), Dracup (1966), Bredehoeft and Young (1970), Milligan (1970), Roger and Smith (1970) and Chawla (1989a). They have discussed the economic advantages of such combined usages and have pointed out its effectiveness in the conservation of significant volume of water. In early stages, optimum allocation of surface water and groundwater has been attempted using different types of optimization techniques, like dynamic programming (Hall and Buras, 1961; Buras, 1963; Burt, 1964; Aron and Scott, 1971; Yang, et al., 2009), linear programming (Dracup, 1966; Milligan, 1970; Rogar and Smith, 1970; Nieswand and Gradstorm, 1971; Lakshminarayana and Rajagopalan, 1977; Vedula, 1985; Khare, 1994; Khare, 2003; Jat, 2007), simulation based models (Bredehoeft and Young, 1970; Yong and Bredehoeft, 1972; Bredehoeft, 1983; O'Mara and Duloy, 1984), multilevel optimization technique (Maddock, 1972; Yu and Hamies, 1974; Maddock and Haimes, 1975; Morel-Seytoux and Daly, 1975; Hamies and Dreizin, 1977; Sharma, 1987) and nonlinear programming (Kashyap and Chandra, 1982; Willis et. al., 1989; Lefkoff and Gorelick, 1990). However, these studies have been employed for the simplified representation of complex water resources system considering physical and operational characteristics, limited alternatives, deterministic and lumped hydrological characteristics, and limited socio-economic and environmental aspects. Most of these studies involved optimum allocation planning of water resources, considering one or two components of water resources system of the canal commands. Recently, some more studies have also been reported in the literature related to the conjunctive use modelling for canal commands (Matsukawa et al., 1992; Khare, 1994; Peralta et al., 1995; Belaineh et al., 1999; Barlow et al., 2003; Chakaravorthy and Umestu, 2003; Karamouz et al., 2004; Cai et al., 2004; Vedula et al., 2005; Pulido-velazquez et al., 2006; Khare et. al., 2006b; Khare et al., 2007).

Since the present study is concerned with distributed conjunctive use modelling in canal command using geospatial tools. Therefore, the representative case studies which incorporated the various aspects of conjunctive use modelling within an optimisation framework have been discussed in the following sub-sections.

2.2.1 Conjunctive Use in Irrigation Command

Conjunctive water use refers to the optimal allocation of groundwater along with surface water in any irrigation system. Supply deficit in the surface water in a canal system necessitates the water resources planner to explore utilization of untapped groundwater resources in the command. Both the sources of supply have its own advantages and disadvantages. Surface water usually has lower delivery and extraction cost, but tends to be variable in supply. Groundwater is expensive to extract, but is a reliable supply source. Therefore, a combination of both the sources not only decreases the risk of supply deficit but also increases the net return in long-term.

Large number of studies has been undertaken to optimize the conjunctive use of water in different canal command areas. A variety of simulation and optimization models have been used to find the optimal conjunctive water use. Such models utilize linear or nonlinear techniques with appropriate constraints incorporating single or multi-objective function.

Wills et al., (1989) presented a nonlinear conjunctive use planning model. The optimization model resulted in the maximum net benefits from the production of three crops over one year planning horizon. The cost of production includes the distribution costs of river water, fertilizers and nonlinear groundwater pumping costs. Agricultural production function has been developed from the previous studies. The groundwater hydraulic response equations have been developed using finite element method.

Latif and James (1991) used a simulation model for maximizing the net income of irrigation through cycles of wet and dry years for long term. The model determines the optimal groundwater extraction for supplementing canal to avoid adverse effects due to high (water logging and salinity) or low (high pumping cost) groundwater levels. Decision variables considered are the crop area, well size, management of allowable deficit and target depths to water table control zones.

Mohammadi (1998) carried out a work for developing irrigation system. Here surface reservoir capacity, groundwater and spring withdrawal, delivery system capacities (including canals, pumping stations and tunnels), hectares of land to be developed for irrigation and cropping pattern have been considered as interacting parts of the system apart from cost due to drainage, land leveling and irrigation network construction. The system is optimized by means of a chance constraint optimization model. The model uses mixed integer linear programming to maximize the net benefit associated with the development. Results generated by the application of the model, along with the sensitivity analysis, provide a tool to select the optimum design considering the varieties of criteria involved.

Belaineh et al., (1999) presented a simulation/optimization model that integrates linear reservoir decision rules, detailed simulations of stream-aquifer system flows, conjunctive use of surface and groundwater, and delivery via branch canals to water users. State variables, including aquifer hydraulic head, stream flow and surface water/aquifer interflow, have been represented through discretized convolution integrals and influence coefficients. Results have been applied to a hypothetical study area under several scenarios indicates that when more details are used to represent the physical system, the better is the conjunctive management.

Sarwar (1999) developed a conjunctive use model to evaluate alternate management options for surface water and groundwater. A simple water balance approach has been used to estimate the net recharge to groundwater aquifer. Here, GIS has been used to integrate the various types of spatial data inputs for modelling purpose and to display of post simulation graphics.

Singh (2003) developed conjunctive water use plan for the Bulandshahr district of Uttar Pradesh, India on the basis of available water resources. The database of the study area was generated in GIS platform. The finite difference model of MODFLOW software has been used to analyze the various alternatives scenarios of conjunctive use of surface and groundwater.

Vedula et al., (2005) developed a model for conjunctive use of a reservoir-canal-aquifer system in an existing reservoir command area in Chitradurga district, Karnataka. The integration of the reservoir operation for canal release, groundwater pumping and crop water allocations during different periods of crop season has been achieved through the objective of maximizing the sum of relative yields of crops over a year considering three sets of constraints: mass balance at the reservoir, soil moisture balance for individual crops, and governing equations for ground water flow. The conjunctive use model has been formulated by linking these constraints together as a deterministic linear programming model. The aquifer response has been modeled through a finite element groundwater model.

Kaur et al., (2007) undertook a case study on field scale using Decision Support System (DSS) to finalize alternative strategies of utilizing conjunctive water use in salt affected agricultural lands. Conjunctive use of saline and non-saline water is generally aimed at minimizing yield losses and making irrigation system flexible with much change in its operational rules. They emphasized that long-term experiments are needed to recommend plan for conjunctive water use in specific region which requires considerable time and resources including money and man power.

Bharati et al., (2008) conducted study in the Volta basin of Africa on evaluating the conjunctive use of surface and groundwater in a small reservoir-based irrigation system. They developed, calibrated and evaluated the performance of a dynamically coupled economic-hydrologic optimization model. The model consisted of a physical hydrology model WaSiM-ETH and an economic utilization model written in GAMS. The study also included development of a DSS for improving the management of land and water resources in the context of potential environmental change in the basin. Nonlinear optimization technique has been utilized for determining optimal cropping pattern.

Montazar et al., (2010) carried out water allocation planning in a deficit irrigation system. Accordingly, an integrated soil water balance model was coupled to a nonlinear optimization model based on certain economic criterion and applied for the Qazvin Irrigation Command Area, Iran. In the study, various combinations of surface water and groundwater uses have been explored along with current and proposed cropping pattern using the LINGO 10.0 optimization package. In order to utilize the available water resources in the command reasonably, they categorized four cropping scenarios considering the socio-economic requirements like food self sufficiency, employment and prevailing agricultural practices. The water table in the region varies about 20 m and the groundwater level dropped by 30 cm per year. The authors utilized the nonlinear programming techniques to formulate conjunctive use optimization model, to arrive at the optimal allocation of surface water and groundwater resources, and to maximize the net return based on the existing cropping pattern and constraints boundary. The outcome of the study suggested that conjunctive water uses in the command is feasible and can be easily implemented with least changes in the operational strategy, which will finally increase the overall benefits from different cropping activities. The study provided various possible operation scenarios in the branch canals of the command area in the normal and dry conditions, which ultimately help the planners in decision making. The study also demonstrated that, for deficit irrigation options, the mining allowance of the groundwater value of the command area is greatly reduced and groundwater withdrawal can also be restricted to maintain the river-aquifer equilibrium.

Raul et al., (2011) conducted an optimal crop planning study in the Hirakud Command Area situated at Odisha, India. The rationale behind the study was that the command during monsoon season became waterlogged, and witnessed acute shortage of irrigation water during non-monsoon season. They developed an Irrigation Scheduling Model (ISM) and a Linear Programming (LP) optimization model under hydrological uncertainty with an aim to manage available land and water resources in the command effectively. The ISM model predicted actual crop yield in the command based on different irrigation strategies. The yield estimated was then considered under LP optimization model to optimize the land and water resources in the command area at different probability of exceedance of net irrigation requirement and availability of water. Based on the study, the authors suggested that crops with less water requirement, like pulses and vegetables should be given priority and water intensive crops, like rice and sugarcane should be optimally considered during crop planning. The study also confirmed that the uncertainty factor does not show any visible impacts on the cropping pattern in the command area.

Bejranonda et al., (2011) stated that there could be a possible threat of disaster if the conjunctive water use in an irrigation system is not managed properly on long-term basis. On the short-term basis conjunctive water use may be a suitable option to overcome water scarcity. Many irrigation projects in Thailand are unable to provide sufficient surface water for the cultivation of rice which is the major cash crop for the farmers. The surface water deficiency is further exacerbated by the climate change impacts in recent years, thereby; groundwater utilization has gained momentum by the farmers to meet the surface water deficit. To assess the conjunctive water use efficacies, Plaichumpol Irrigation Project (PIP) has been considered. Further, water demand, supply and actual use in the study area have been investigated. A numerical groundwater model with a special module for simulating surface-groundwater interaction has been applied in the PIP area. The groundwater conceptual model has been defined by using the concept of hydrostratigraphic units which, in turn, are defined as geologic units of similar hydrogeologic properties. The model examines different water allocation options in the region depending on the local weather conditions and regional management rules. The authors envisaged two distinguished categories of integrated management models i.e. hydraulic management model and policy evaluation/allocation model for conjunctive water use development in the study area. Hydraulic management model deals with the management of water flows and heads whereas policy evaluation/allocation model simulates the economically efficient allocation of surface and groundwater resources. The results of the calibrated model indicated a strong seasonal surface and groundwater interaction. The model further indicates that the recharge into the aquifer is done by the canal in the dry and wet season whereas aquifer itself discharges small amount of water into the canal only during the wet period.

Komakech et al., (2011) undertook a study on the effective utilization of spate water (flood) in semi-arid region. The study was conducted in Makanya spate irrigation system lies at the outlet of Makanya catchment (300 km^2), in the South Pare mountains, in the mid reaches of the Pangani river basin in Tanzania. During high rainfall with flooded scenario, the upstream users often do not require irrigation water since it is already available in plenty. This utilization of spate water with low opportunity cost can be transformed into high value water in a spate irrigation system. However, spate irrigation system posed technical and non-technical challenges as the collective action is hampered by upstream and downstream users, high labour intensive cost due to structure needed to be repaired every time etc. Another major challenge in these systems is the changing nature of the river bed. Flash flood carries sediments resulting in rise in elevation of the irrigated lands every year. Thereby, investments in modernizing the head regulator and distribution system are less effective and needs to be done every year. On the other hand, investments in conjunctive use of groundwater could be a suitable option since it requires relatively small intervention without drastic physical alteration to the existing spate irrigation system.

Safavi et al., (2011) attempted crop planning and conjunctive use of surface water and groundwater resources using Fuzzy logic. They used the Fuzzy Inference System (FIS) to account for the experience and expert judgments of local farmers in optimal crop planning in the Najafabad plain, a part of Zayandehrood river basin in west-central Iran. The fuzzy regression was used for considering uncertainty and data ambiguity in the optimization model as well as interaction between surface water and groundwater resources. The optimization function was formulated to minimize the uncertainty in the irrigation supply in different climatic conditions. The developed model can be used for arid and semi-arid regions.

In Indian context, studies related to the water resources planning and management within an optimization framework has been reported for the agricultural areas and canal commands. Most of these studies have been found related to optimum reservoir operations (Raman and

Vasudevan, 1991), water allocation at basin scale (Devi et al., 2004), conjunctive use of surface and groundwater for the canal commands (Kashyap and Chandra, 1982; Vedula, 1985; Sharma, 1987; Chawla, 1989a,b; Khare, 1994, Rao et al., 2004; Khare et al., 2007, Raul et al., 2011).

Studies on conjunctive water use confirm that groundwater availability and its use can significantly improve the economic viability of any irrigation projects (Marques et al., 2011). Conjunctive use increases both supply and reliability. Majority of conjunctive use studies integrating dynamic groundwater response are nonlinear in nature. The nonlinear conjunctive use models have inherent limitation of dimensionality (Khare, 2003; Jat, 2007). To overcome problem of dimensionality, the conjunctive use modelling is done on gross scale. However, in gross scale conjunctive use models, the spatial distribution of parameters (demand-supply and special constraints posed by state of the system) are ignored.

2.2.2 Economic Aspects of Conjunctive Use Modelling

Except for a few isolated studies concerned entirely with optimization of a few particular physical parameters, it is almost impossible to conceive a project involving optimum water resource allocations in which economics does not involve (Khare, 1994). Full consideration of all economic aspects of a water resources system requires such a wide knowledge of cost, price and hydrologic relationships, that most of the research in this subject has been concentrated on limited part of the whole economic picture.

Cost of providing water from different sources is important for their optimum integration into irrigation water supply system. Cost estimation for the surface sources includes capital and operational and maintenance (O&M) costs of different components, like conveyance system, storage system, and distribution system. Cost of groundwater pumping is also similarly important and mainly depends upon lift and discharge. Therefore, estimation of cost of water supply from different sources and development of cost function for groundwater pumping are required for the study of least cost integration of these sources within the irrigation water supply system in command area.

Cost function can be defined as *a relationship that provides estimate of cost based on the value of one or more basic variables, such as capacity and other physical parameters* (Shidhaye et al., 1993).

Cost of providing surface water is straight forward, which depends upon the distribution cost and O&M costs (Khare, 2003). The studies dealing with cost aspects of groundwater pumping have been briefly discussed in this section.

Cost of pumping groundwater depends mainly on lift, discharge, type of strata (alluvium or rocky) and location (region). Cost functions developed/available for any region may not be suitable elsewhere because of different construction technique, labour rates, material rates and type of strata (Jat, 2007). Some of the studies dealing with the cost analysis of groundwater pumping have been briefly discussed here.

Sharma and Chawla (1977) carried out cost analysis for the tubewells to arrive at an optimal well capacity for the alluvium aquifers of North India. The capital investment and operational charges have been considered to determine the capacity of well for the lowest cost of unit volume of pumped water. Cost of providing distribution system to utilize the groundwater has also been discussed in the study.

Stoner et al., (1983) presented an optimization based methodology for economic design of a tube-well in deep aquifers. Cost function has been developed for diesel powered well. A simple equation comprising various components of cost is derived and total cost is minimized by partial differentiation with respect to certain parameter.

Gonzalez (1989) presented basic concepts applied to groundwater management in two parts. In the first part, basic concepts, like total capital & variable costs, interest and discounting rates are discussed. Second part is devoted to economic aspects of groundwater utilisation. Groundwater pumping costs have been determined for different well capacities, which are then used to determine the optimum well capacity. Minimum pumping cost as a function of depth of well is also discussed.

Spaziani and Vuro (1989) presented some cost functions based on a survey of technical and economic data referred to groundwater withdrawal in Italy. These cost functions can serve as a basis for identifying areas allowing for more economic utilisation.

Naggar (1992) obtained the groundwater production costs by computing the unit cost of pumping. Pumping cost is determined for both shallow as well as deep tubewells for alluvium areas. Cost of different components of a well have been determined for both type of wells and further cost functions were developed corresponding to the optimum capacity of wells.

Khare (1994) developed the cost function for the groundwater pumping for alluvium aquifers of North India. Cost of different components of shallow well has been determined after designing the well for a range of pumping capacities. Further, a cost function has been developed in terms of depth of water table corresponding to the optimum well capacities. Sensitivity analysis has been also carried out to ascertain the uncertainties of different design parameters. Further, he has integrated these ground water cost functions in a conjunctive use model. Based on detailed study, the author has concluded that Operation and Maintenance (O&M) cost of groundwater pumping should be considered in conjunctive use planning models. Same approach has latter been followed by Khare (2003), Jat (2007) to develop groundwater pumping cost functions, which are then integrated in conjunctive water supply models.

2.3 GROUNDWATER MODELLING

In general, groundwater models are conceptual descriptions or approximations that describe physical systems using mathematical equations. These models are not exact descriptions of physical systems or processes. Groundwater models are used to represent the natural groundwater flow in the environment to predict the effects of hydrological changes (like groundwater abstraction or irrigation developments) on the behaviour of the aquifer and are often named groundwater simulation models. Nowadays, the groundwater models are also being used in various water management projects.

2.3.1 Groundwater Flow Equations

Almost all the equations of the modern saturated groundwater flow theory owe their existence to the pioneering work of Darcy (1856). He discovered through experimentation that the saturated flow of water through a column of soil is directly proportional to the head difference and inversely proportional to the length of column. On this basis, he established a linear relationship between one-dimensional seepage velocity and the hydraulic gradient in a saturated porous medium, known as Darcy's Equation (Remson et al., 1971). Subsequently, the continuity equation for the steady state two-dimensional flow of incompressible fluids and the Darcy's Law were integrated into a single equation. The resulting equation is known as Laplace Equation in the literature on saturated flow. The theoretical work leading to this topic was done by Jules Dupuits, P. Forchheimer and Charles Slichter (Remson et. al., 1971).

The equation for two-dimensional unsteady state flow in a confined aquifer, accounting for the deformity of the aquifer and the compressibility of fluid, was derived by Jacob (1950) and further modified by DeWeist (1966) and Cooper (1966). The equation governing a two-dimensional horizontal unsteady state flow in an anisotropic heterogeneous non-leaky confined aquifer may be written as (Willis and Yeh, 1987):

$$\frac{\partial}{\partial x}\left[T_{xx}\frac{\partial h}{\partial x}\right]+\frac{\partial}{\partial y}\left[T_{yy}\frac{\partial h}{\partial y}\right]+R=S\frac{\partial h}{\partial t} \qquad (2.1)$$

where, T_{xx} and T_{yy} are the transmissivities in the X and Y directions, respectively, R is the rate of net vertical flow per unit area, S is the storage coefficient, h is the piezometric head and t is the time.

Unconfined aquifer the solution is greatly facilitated if Dupuit-Forchheimer assumptions hold good. The governing differential equation for a two-dimensional transient flow in an anisotropic, heterogeneous unconfined aquifer may be written as (Willis and Yeh, 1987).

$$\frac{\partial}{\partial x}\left[K_{xx}\,h.\frac{\partial h}{\partial x}\right]+\frac{\partial}{\partial y}\left[K_{yy}.h.\frac{\partial h}{\partial y}\right]+R=S_Y\frac{\partial h}{\partial t} \qquad (2.2)$$

Where, K_{xx} and K_{yy} are the hydraulic conductivities in the X and Y directions, respectively, R the net recharge per unit area of the aquifer and S_y is the specific yield.

The governing differential equation for three-dimensional groundwater flow can be written as follows (Bear, 1979):

$$\frac{\partial}{\partial x}\left[K_{xx}.\frac{\partial h}{\partial x}\right]+\frac{\partial}{\partial y}\left[K_{yy}.\frac{\partial h}{\partial y}\right]+\frac{\partial}{\partial z}\left[K_{zz}.\frac{\partial h}{\partial z}\right]=S_o\frac{\partial h}{\partial t} \qquad (2.3)$$

where, x, y, z are the co-ordinates in principal permeability direction; where K_{xx}, K_{yy}, K_{zz} is the principal permeability's and S_o is the specific storage.

First unsteady state equation for axi-symmetric radial flow towards a fully penetrating discharging well of an infinitesimal diameter in an infinite confined aquifer was derived by Theis (1935). The Theis equation is as follows:

$$s_d=\frac{Q}{4\pi.T}\;W(u) \qquad (2.4)$$

and $$u = \frac{r^2.S}{4.T.t}$$

where, S_d is the draw down at a distance of *r* from a well from which water being abstracted at a uniform rate *Q*, *t* is the time after the pumping started, *S* is the storage coefficient, *T* is transitivity, and *W(u)* is the well function.

These are the equations generally used for groundwater hydrology problems.

2.3.2 Aquifer Response Models

The present state of knowledge in groundwater hydrology provides adequate information to study the impact of a deterministic groundwater withdrawal and/or recharge pattern on the piezometric elevations through lumped models (Sokolov and Chapman, 1974, Chandra and Pande, 1975) or distributed models (Remson et al., 1971; Pinder and Gray, 1977).

Sokolov and Chapman (1974) proposed a water balance equation as a lumped aquifer response model. The inflows in water balance equations include the rainfall recharge, recharge from rivers, subsurface horizontal inflow, artificial recharge and inflow from other aquifers (overlying or underlying). The outflows include base flow to the rivers, outflow from the groundwater into the zone of aeration for moisture recovery lost by evapotranspiration, outflow to the overlying or underlying aquifers, subsurface horizontal outflow, groundwater outflow through springs, and groundwater pumped from aquifers. The lumped aquifer response to known inflows or outflows can be obtained by defining the groundwater storage fluctuations in terms of the piezometric head fluctuations and the storage coefficient.

The distributed groundwater flow models are based on the solution of differential equations governing two-dimensional or three -dimensional transient groundwater flows in saturated zone. Closed form or series solutions of governing equations are available only for idealized boundary and recharge conditions (Bear, 1979). These are generally based upon the assumption of homogeneity and isotropy. For predicting the aquifer response to spatially and temporally varying differential equations, have to be solved by appropriate numerical methods.

For obtaining numerical solution of groundwater flow problems two distinct types of digital computer-based methods viz., finite difference and finite element are available. Finite difference methods employ finite difference approximation to convert the partial differential equation into a determinate set of linear algebraic equations. The discretization of space, necessary for finite difference approximations, can be based upon either polygons (Tyson and

Weber, 1964) or a rectangular grid pattern. The former is generally known as Tyson and Weber model, whereas the latter as finite difference model.

The finite difference approach is a general method for calculating approximate solution of partial differential equations. This method has been programmed to solve two dimensional (Pinder and Bredehoeft, 1968) and three dimensional (Bredhoeft and Pinder, 1970) transient groundwater flow problems. This method is widely used for the groundwater problems (Remson et al., 1971; Wang and Anderson, 1981). The finite element method has been employed to obtain the solution of differential equations for the evaluation of aquifer response. This followed the development of variational principles for linear initial value problem. The finite element method is reported to circumvent many difficulties relating to irregular geometry of area, heterogeneity and boundary condition in addition to giving results of higher order accuracy (Pinder and Gray, 1977; Wang and Anderson, 1981).

Groundwater models describe the groundwater flow and transport processes using mathematical equations based on certain simplifying assumptions. These assumptions typically involve the direction of flow, geometry of the aquifer, the heterogeneity or anisotropy of sediments or bedrock within the aquifer, the contaminant transport mechanisms and chemical reactions. Due to the simplifying assumptions embedded in the mathematical equations and the many uncertainties in the values of data required by the model, a model must be viewed as an approximation and not an exact duplication of field conditions.

Groundwater models, however, even as approximations are a useful investigation tool that researchers may use for a number of applications in water resources management studies. As the computations in mathematical groundwater models are based on groundwater flow equations, which are differential equations that can often be solved only by approximate methods using a numerical analysis, these models are also called mathematical, numerical, or computational groundwater models (Rushton, 2003).

The mathematical or the numerical models are usually based on the real physics the groundwater flow follows. A number of softwares are available for solving these mathematical equations viz. MODFLOW, ParFlow, HydroGeoSphere, AQUA3D, FEFLOW, FLOWPATH etc. Application of these commercial softwares have gained pace due to their capability to solve spatially distributed groundwater response problems utilizing spatially distributed data available from geospatial techniques (Singh, 2003; Leblanc et al., 2007; Chowdhury et al., 2009; Xu, et al., 2011).

Various hydrological, geological and geo-morphological factors play a major role in the occurrence and movement of groundwater in different terrains. With advances in space technology and the advent of powerful personal computers, techniques for the assessment of groundwater resources mapping and modelling have evolved, in which remote sensing and Geographic Information Systems (GIS) are of great significance.

The utility of remotely sensed data as an efficient tool in extraction and demarcation of information regarding parameters governing groundwater behaviour (i.e. lithological, structural and geomorphological features of various rock types) has been well established through a number of studies worldwide (Ai et al., 1998; Dhiman and Keshari, 2002; Sharma and Thakur, 2007). The extraction of details from satellite imagery depends on the spectral contrast between the object and its surroundings and thus contributes to mapping and quantitative evaluation of groundwater (Moore and Deutsch, 1975). The drainage network analysis of Landsat images of Olympus-Pieria Mountain area, northern Greece by Astaras (1985) has shown that Landsat images on 1:2,50,000 scale enlarged prints are more suitable for quantitative analysis of a drainage network than topographical maps of an equivalent scale. The satellite based remote sensing frequently provides data on a relatively large scale that allows specific groundwater problems to be monitored on a long-term basis at a lower cost.

The use of satellite based remote sensing has made it possible to map large areas with greater accuracy for various resources assessment and management. GIS is an ideal problem solving environment where remote sensing data and interpretations can be merged with discrete and continuous data from various primary and secondary sources (Burrough, 1986). Many scientists showed that integration of multi-thematic maps of the Earth using Remote Sensing and GIS are useful for exploration, development and management of groundwater resources (Mattikalli et al., 1995; Adinarayana and Krishna, 1996; Kamaraju et al., 1996).

Teeuw (1995) proposed an integrated approach of remote sensing and GIS techniques to improve the technique of groundwater potential assessment in the Volta basin of northern Ghana. Several authors have highlighted the importance of coupling Remote Sensing and GIS in groundwater modelling studies (Toleti et al., 2000; Sankar, 2002; Bahuguna et al., 2003; Jagadeeswara Rao et al., 2004; Sikdar et al., 2004; Rai et al., 2005; Lokesha et al., 2005;

Nagarajan and Singh, 2009; Chowdhury et al., 2009). The application of GIS technology allows swift organization, quantification and interpretation of large quantities of hydrogeological data with more accuracy and minimal risk of human error (Pinder, 2002). The integrated approach of remote sensing, geophysics and GIS saves time and money.

Groundwater flow models are appropriate tools to assess the effect of foreseen future human activities on groundwater dynamics (Ghosh and McBean, 1997; Mao et al., 2005; Dawoud et al., 2005; Mylopoulos et al., 2007). However, models require good quality data on the physical and hydrogeological settings. The physical ones refer to topography, land use, soils, canals and drainage ditches, climate and crops demand for water. The hydrogeological settings include the aquifer system and boundary conditions, main hydraulic parameters characterizing each aquifer layer, and the dynamics of groundwater levels. All of them vary both in space and time, thus adopting a GIS in association with a model is helpful.

Xu et al., (2009) and Xu et al., (2011) used MODFLOW 2000 (Harbaugh et al., 2000) coupled with GIS to simulate the groundwater dynamics for improving the water use of irrigation system in Upper Yellow River Basin. An integrated methodology has been developed adopting loose coupling of the MODFLOW with ArcInfo to assess the impacts of irrigation water-saving practices and groundwater abstraction foreseen for the year of 2020 on the groundwater dynamics of the Jiefangzha Irrigation System (JFIS) in Hetao Irrigation District, upper Yellow River basin.

Coupling GIS technology with a process-based groundwater model may facilitate hydrogeological and hydrologic system conceptualization and characterization (Hinaman, 1993; Kolm, 1996; Gogu et al., 2001). Various examples confirm the appropriateness of GIS applications in groundwater hydrology (San Juan and Kolm, 1996; Herzog et al., 2003; Jha et al., 2007; Brunner et al., 2008; Li et al., 2008).

In the past, several researchers (from India and abroad) have used remote sensing and GIS techniques in groundwater studies with successful results (Karanth and Seshu Babu, 1978; Saraf and Jain, 1993; Chi and Lee, 1994; Krishnamurthy and Srinivas, 1995; Kamaraju et al., 1996; Krishnamurthy et al., 1996; Khan and Mohd., 1997; Ravindran, 1997; Edet et al., 1998; Saraf and Choudhury, 1998; Kumar, 1999; Krishnamurthy et al., 2000; Shahid et al., 2000; Khan and Moharana, 2002; Jaiswal et al., 2003; Rao and Jugran, 2003; Sikdar et al., 2004; Sener et al., 2005; Ravi Shankar and Mohan, 2006; Solomon and Quiel, 2006).

Groundwater models are conceptual descriptions or approximations that describe physical systems using mathematical equations, used to predict the effects of hydrological changes (like groundwater abstraction or irrigation developments) on the behaviour of the aquifer and are often named groundwater simulation models. The mathematical or the numerical models are usually based on the real physics the groundwater flow follows. These mathematical equations can be solved using commercially available numerical codes such as MODFLOW. The commercial softwares have the capability to efficiently handle and solve the distributed groundwater modelling problems.

The distributed groundwater models require spatially distributed input parameters like recharge, aquifer properties, model boundaries etc. The geospatial tools have tremendous potential of coupling with groundwater models to provide information on spatially varying inputs parameters. Most of the studies have advocated the approach of loose coupling between geospatial techniques and groundwater models. Reviewing these aspects it has been decided to utilize the potential of commercially available groundwater modelling software (Visual MODFOLW) coupled with GIS database in groundwater modelling part of present study. The distributed parameters required for groundwater model will be derived using remote sensing data in conjunction with field observed data.

2.4 INTEGRATION OF DYNAMIC GROUNDWATER BEHAVIOUR IN CONJUNCTIVE USE MODEL

The goal of a formal mathematical optimization-based conjunctive use model is optimum planning and utilization of available water resources i.e. surface water and groundwater in the best possible manner within the various restrictions. The limiting restrictions are derived from managerial considerations and physical behaviour of groundwater and surface water systems. In order to ensure that the final solution does not violate the physical laws of the system, a model simulating the behaviour and response of the system is incorporated within the management model, like integration of groundwater simulation model into the optimization model to simulate the groundwater behaviour under different water use management decisions.

An optimization model identifies an optimal management strategy from a set of feasible alternative strategies whereas a groundwater simulation model checks the feasibility of management strategy with respect to the groundwater. Integration of groundwater simulation and management models has been discussed in the literature (Gorelick, 1983; Willis and Yeh, 1987;

Peralta et al., 1991; Das and Datta, 2001). The groundwater simulation model can be combined with the management model either by using the governing equations as binding constraints in the optimization model (embedded approach) or by using a response matrix or an external coupling of optimization and groundwater models (Gorelick, 1983).

In embedding technique, the finite difference or finite element form of governing groundwater flow equations are directly incorporated as a part of the constraint set in a formal mathematical programming-based management model. Other physical and managerial constraints on heads, gradients, velocities or pumping/injection rates can be incorporated easily. Some of the unknown groundwater variables i.e. hydraulic heads, source/sink rates, existing solute concentrations and solute concentrations of the source/sink at each node may become decision variables in the optimization problem. For transient conditions, embedding approach may require relatively large computational sources.

For nonlinear problem, this approach further increases the complexity, for which global solution may not be achieved. Computational difficulties in using standard optimization packages for large scale problems are reported by Elango and Rouve (1980), Gorelick (1983) and Tung (1986). In many studies, this approach has been used to integrate the groundwater simulation and optimization models (Gorelick and Remson, 1982; Peralta et al., 1991; Keshari and Datta, 1996; Das and Datta, 2000).

The response matrix approach (Gorelick, 1983) uses an external groundwater simulation model to develop unit responses. At pre-selected well locations, the unit response describes the influence of a unit change in an independent decision variable/design variable (such as sink/source rates), upon a variety of dependent variables/other design variables (such as hydraulic head, velocity and solute concentration) at specified observation points. The assembled unit responses are used to construct the response matrix, which is included in the management model. In order to generate the unit response matrix, simulation model is required to solve several times, each with a unit stress (pumping/recharge) at a single node. The response matrix approach works on the principles of superposition. It is applicable only when the system is linear or approximately linear and the boundary conditions are homogeneous.

For highly nonlinear systems, the performance of response matrix approach is reported to be unsatisfactory (Das and Datta, 2001). Any change in boundary condition and location of the source/sink or observation wells requires several simulations to generate the responses and also requires recalculation of the response matrix. Water management models, which uses embedding or response matrix approaches for the integration of groundwater response are also called hydraulic-economic response models (Gorelick, 1983). In these approaches, inclusion of complex social, institutional and economic factors is very difficult and would further increase the complexity. In many studies, this approach has been successfully used (Maddock, 1974; Maddock and Hamies, 1975; Morel-Seytoux et al., 1980; Lall and Santini, 1989; Peralta et al., 1991; Faisal et al., 1997; Barlow et al., 2003; Srivastava, 2003; Cosgrove and Johnson, 2005).

For situations where hydraulic management, like restriction of groundwater table or head is not the sole concern, groundwater simulation and management model can be integrated through external coupling, and such models are called linked simulation optimization models (Gorelick, 1983). In external coupling approach, water management model uses the results of an aquifer simulation model as an input. Information and results from each planning period are utilized for the management during next planning period. In this approach, since simulation and management models are separate, complex social, institutional and economic factors can be considered without increasing the complexity.

In comparison with response matrix and embedded approaches, external linking enables greater economic complexity to be considered. Social and legal factors can be included into management model. Moreover, hydraulic nonlinearities in case of unconfined aquifers do not enter into the management model, because the hydraulic simulation model is separate (Gorelick, 1983). This approach is also computationally efficient as compared to the embedding and response coefficient approaches, however it requires more time resources. Using this approach, hydraulic management objectives, like head and withdrawal restriction, can also be achieved through repetitive procedure where management decisions are modified iteratively till the hydraulic criterion is satisfied. Using this approach, nonlinearity of groundwater pumping cost can be incorporated into a linear management model through successive linearization approach. Solution of such model is easy and therefore, global solution can be achieved.

In many studies, this approach has been used successfully to integrate groundwater simulation and management models (Fiering, 1965; Martin et al., 1969; Bredehoeft and Young, 1970; Young and Bredehoeft, 1972; Daubert and Young, 1982; Khare, 1994; Hafi, 2003; Karamouz et al., 2004; Rao et al., 2004; Bhattacharya and Datta, 2005; Jat, 2007).

2.5 CROP PRODUCTION RESPONSE FUNCTION (CPRF)

The relationships among crop, climate, water and soil are complex as many biological, physiological, physical and chemical processes are involved. All components of this relationship affect the crop growth and yield. Amongst all, water is the most important component which can be quantified with ease and accuracy (Hexem and Heady, 1978). Significant amount of research information on effect of water on crop yield is available (Stewart et al., 1973; Hexem and Heady, 1978; Barrett et al., 1980; Fapohunda et al., 1984; Martin et al., 1984; Rajput and Singh 1986; Sharma and Alonso Neto, 1986; Farshi et al., 1987; Singh et al., 1987; Rao et al., 1988; Willis et al., 1989; Islam et al., 1990; Dinar et al., 1991; Hoorn et al., 1993; Parihar et al., 1997).

However, for practical application, this information must be formulated into a mathematical relation between major components to allow a meaningful analysis of crop response to water at the field level (Doorenbos et al., 1979). The relationship between crop yield and water supply can be determined when crop water requirements and crop water deficits, on the one hand, and maximum and actual crop yield on the other can be quantified (Stewart et al., 1977). These numerical relations between crop yield and water supplied is termed as crop production response functions.

Water interacts strongly with other management inputs such as fertilizer in increasing crop yield. In initial development phases of crop production response functions, the relation between yield and water supply has been assumed to be linear (Stewart and Hagan, 1973; Hanks and Hill, 1980). Later on, attempts have been made to develop crop production response function of various forms by considering water, fertilizer, rainfall, daylight hours, temperature and soil characteristics. These functions were of Cobb-Douglas form, Mitscherlich-Spillmand form or polynomial form (Hexem and Heady, 1978). However, many of the parameters used in these function are neither statistically significant nor easily measurable, particularly in developing countries (Hexem and Heady, 1978).

Attempts have also been made to develop mathematical relation among crop production, water and fertilizer in polynomial forms using extensive field data (Willis et al., 1989). However, due to complexity and site specific applicability, applications of these functions have been limited in irrigation planning and management projects. Subsequently, crop production response functions for individual crops have been developed using observed data on water supply and final yield of respective crops. In general, the relation between crop yield and water supply has been modelled using polynomial forms of equation (Gulati and Murty, 1979; Farshi, et al., 1987, Islam, et al., 1990, Hoorn et al., 1993).

The advent of physiologically based crop models, such as the Decision Support System for Agrotechnology Transfer (DSSAT) suite (Tsuji et al., 1994; Tsuji et al., 1998), GOSSYM (Baker et al., 1983), etc., provide the first principal simulation of plant growth and development. Model simulation is able to include many specific processes and localized factors due to inclusion of detailed process description and rich input data sets. Although these models have been used for specific types of irrigation analysis (Epperson et al., 1992; Epperson et al., 1993) but there has not been significant development of these types of models to determine Crop Production Response Functions, perhaps owing to their complexity.

Several functions relating crop production to water use have been developed, and they have, to a great extent, facilitated discussions on the relationship between the two elements in quantitative terms. These functions can be broadly divided into two groups. The first group related the crop yield (either total dry matter or harvestable part of the plant, e.g. grain, fruit) to water applied (or supplied) to the field. Water applied in this sense may include water applied to meet crop water requirement, pre-planting irrigation, leaching, and precipitation. Kipkorir et al., (2002) referred to the functions in this group as water production response functions. The second group related the crop yield to seasonal evapotranspiration or transpiration. These functions are referred to as Crop Production Response Functions (Kipkorir et al., 2002).

Further, there are two general forms of Crop Production Response Functions. They include those that relate crop yield to total seasonal evapotranspiration (Stewart and Hagan, 1973; Hanks, 1983); and those that relate yield reduction to water deficit at some specified period of crop growth, which usually coincides with the phenological stages of the crop (Jensen, 1968; Minhas et al., 1974; Sunder et al., 1981). The crop production response function which relates yield reduction to water deficit at some crop growth stages are formulated by postulating that water deficits in each growth stages have unique effect on crop yield, and the effect of water deficit at one growth stage is dependent on the others. Two types of dependence are postulated: the multiplicative-type and the additive-type (Tsakiris, 1982). The multiplicative-type suggests that crop water deficit in two or more growth stages may reduce crop yield in a multiplicative manner, while the additive-type suggests that the effect of water deficit in two or more growth stages may reduce crop yield in an additive manner. The multiplicative-type functions imply that crop will fail to produce if there is no evapotranspiration in any growth stage while the additive-type functions imply that lack of evapotranspiration at any growth stage may not necessarily lead to total crop failure but could have severe impact on yield performance. Typical examples of multiplicative-type crop production response functions are Jensen (1968), Minhas et al., (1974), and Bernardo et al. (1988) and the additive-type crop production response functions include the models proposed by Stewart et al. (1977), Doorenbos et al., (1979) and Bras and Corodova (1981).

Crop Production Response Functions (CPRF) have immense applications in irrigation water management and planning. They are useful in evaluating economic implication of different levels of crop water use and in determining irrigation strategies when water supply is limited (English, 1990). With these functions, the decision makers can assess irrigation water needs to meet production targets or, conversely, estimate likely crop production for fixed volumes of water.

Traditional irrigation planning and scheduling methods have not generally been amenable to determination of CPRF. Techniques based upon reference evapotranspiration and crop coefficients (Doorenbos and Pruitt, 1977) typically assume that irrigation is to be applied with the goal of fully meeting plant water requirements; this "full irrigation" strategy thus disregards the "deficit irrigation" region of the yield–irrigation domain, the region where crop production response functions provide the most valuable information. Moreover, many reference evapotranspiration models do not account soil water as a water source to the plant; this omission of the possibility of "soil water mining" may lead to overestimation of irrigation needs (Mugabe and Nyakatawa, 2000).

Yield reduction models based upon evapotranspiration (ET) ratios (Doorenbos and Kassam, 1979) cannot provide crop yield in absolute terms (i.e. mass of grain per unit cultivated area), and these models have no endogenous optimization capacity. Optimization schemes such as dynamic programming have been applied to determine CPRF based on the ET ratio-yield reduction model (Bras and Cordova, 1981 and Paul et al., 2000), but this process still does not find absolute yield values.

In order to plan, design or manage irrigation systems for full irrigation (irrigation time and amount), the analyst should apply crop production response functions to meet crop water demands over a planning period to maximize the available benefit. The available water must be allocated among the intraseasonal periods based on crop water response values to maximize profit (Paul et al., 2000) by considering the uncertainty and randomness in optimization parameters. Rainfall is the main source of uncertainty in arid and semi-arid areas that affect irrigation scheduling due to its large spatial and temporal variations (Martin et al., 1990; Sunantara and Ramfrez, 1997). Ramirez and Bras (1985) showed the importance of the stochastic of irrigation input in the context of a single crop using direct stochastic dynamic programming for optimal irrigation scheduling. In most cases, CPRF have been used to deal with water allocation among the intraseasonal periods ignoring the rainfall uncertainty (Rao et al., 1990; Mannocchi and Mecarelli, 1994; Vedula and Nagesh Kumar, 1996; Kipkorir and Raes, 2002) which were shown inadequate by Ganji et al., (2006).

Although the analyst must rely upon CPRF that relate water use to crop yields to design the irrigation system, the inherent uncertainty of production function makes it virtually impossible to predict yield exactly. Hence it is impossible to know precisely what level of water use will maximize the profits (English, 1981). Actually any inaccurate forecasting about the required demand will increase the risk of loss. Nevertheless, some researchers attempted to predict the crop yields and benefit for deficit irrigation, ignoring inherent crop water demand uncertainties.

Ghahraman and Sepaskhah (1997) used a deterministic nonlinear optimization procedure to show that one can increase the net benefit by decreasing crop water allocation utilizing a seasonal basis model. In their models, irrigated land area is increased in accordance with the decrease in crop water allocation and the corresponding net benefits were found to be increased; however, they had ignored the uncertainty in crop water demand. Ganji et al., (2006) developed a constraint state formulation for stochastic control of the weekly full irrigation strategy to deal with the inherent uncertainty in crop water demand. The proposed weekly model was based on the first and second moment analysis of the stochastic soil moisture state variable similar to that of Fletcher and Ponnambalam (1998) model, considering soil moisture at saturation and deficit as the maximum and minimum bounds, respectively. The proposed stochastic optimization methodology is applied to weekly water allocation of winter wheat and found satisfactory results for both mean and variance of the soil moisture state variables in association with the derived optimal irrigation polices.

In order to investigate the long-term net benefit of deficit irrigation considering uncertainty, the proposed methodology of Ganji et al., (2006) has been extended for deficit irrigation case. Here, economical aspect of the deficit irrigation is studied utilizing the indicator functions in the continuity equation for the soil moisture variable. The extended methodology was then applied for winter wheat, for different levels of deficit irrigation, utilizing a mean approximation of the well-known crop water production function of Jensen (1968) as an objective function for the weekly stochastic optimization model. Also, a weekly simulation model was used to validate the results of the proposed stochastic model. The results showed that if the crop demand's uncertainty is ignored then deficit irrigation cannot improve net benefit values in the long-term horizon when there are no constraints on capital, energy, labor or other essential resources.

Hexem and Heady (1978) provided a classic discussion of crop production response function derivation and use. In spite of the utility of crop production response function, determination of yield–irrigation relationships can be quite expensive in terms of resources and time, as it has traditionally relied upon extensive experimentation (Russo and Bakker, 1987 and Zhang and Oweis, 1999). Even after long-term data collection, experimentally derived functions are not geographically portable (Clumpner and Solomon, 1987).

The limitation of site specific applicability of crop production response function was solved by Doorenbos et al., (1979) by providing generalized from of CPRF. These production response functions estimate the ratio of actual yield of crop to the maximum yield based on the relative water supply (ratio of actual water supply to the crop to the maximum crop water demand). They empirically derived yield response factors (K_y) for individual growth stages (i.e. establishment, vegetative, flowering, yield formation, or ripening) and also for the total growing period. Yield response factor introduced by Doorenbos et al., (1979) represents the sensitivity of crop growth stage to the water deficit. These yield response factors are similar to the yield sensitivity factors given by Jensen (1968). Further procedures to convert Jensen's yield sensitivity factors to yield response actors and vice-versa were developed (Kipkorir and Raes, 2002), as in many agro climatic regions field data for any one of these factors are available. However, Jensen's sensitivity indexes approach is not widely used due to data limitations. (Kipkorir and Raes, 2002).

In few studies, attempts have been made to integrate these crop production functions in integrated resource planning in command area of irrigation projects (Barrett and Skogerboe, 1980; Willis et al., 1989; Azaiez and Hariga, 2001; Vedula et al., 2005; Wesseling and Feddes, 2006).

CHAPTER 3
STUDY AREA

3.1 GENERAL

The general description of the selected study area is given in this chapter. It covers general aspect of location, physiographic, climate, drainage, hydro-geology, and water resources of the study area. Finally, the creation of geo-database and some of the thematic maps developed for the study have been discussed briefly, and presented in this chapter.

3.2 SALIENT FEATURES OF STUDY AREA

3.2.1 Location

Tawa canal command is a planned gravity major irrigation system started in the year 1978 on completion of the dam across the Tawa river, a tributary to Narmada river. Tawa command is spread over in an area of about 5273.12 km^2 falling in the district of Hoshangabad, Madhya Pradesh, India. It lies between 22º54’ N to 23º00’ N latitude and 76º457’ E to 78º45’ E longitude. Hoshangabad district lies in the south-west part of the Madhya Pradesh state, India. The district lies between north latitude from 21º54’ to 23º00’ N and longitude from 76º47’ to 78º42’ E. The district spans over an area of 10,037 km^2. It is a longitudinal irregular shape of command area with River Narmada being its northern boundary. South portion of the district occupied by Satpura Range whereas the northern plains include isolated knolls and low stony ridges. Tawa and Ganjal are the other main rivers of area. It is bounded by Sehore and Raisen districts in the North. In the East its boundary marches with Narsimahpur district. The two Satpura plateau districts Chindwara and Betul bound the district in the South, and Dewas district in the North-west (Figure 3.1).

Hoshangabad town, the district head quarter is situated along the south bank of Narmada River overlooking Vindhya range lies 75 km South from State capital Bhopal. The area is well connected with rest of India by rail route and roads. Itarsi is the most important railway junction in the district. Hoshangabad and Itarsi lie on Delhi-Chennai, Delhi-Bangalore and Delhi-Mumbai railway routes. State Highway No 21 and 22 pass through the district. The villages in the district are approachable by fair motorable tracks. Tawa dam site is about 9 km from Bagra Tawa Railway station and 33 km from Itarsi railway station on Central Railway.

Tawa dam site is situated in Ranipur Town of Kesla Block of Itarsi Tehsil of Hoshangabad district. For administrative convenience, the district is divided into 10 blocks. The block headquarters are located at Khirkiya, Harda, Timrani, Seoni Malwa, Hoshangabad, Kesla, Babai, Sohagpur, Pipariya and Bankheri. Tawa Command area falls under Kesla, Hoshangabad, Seoni Malwa, Timrani, Harda, Babai, Sohagpur and Pipariya blocks of Hoshangabad District. The location map of the study area is presented in Figure 3.1.

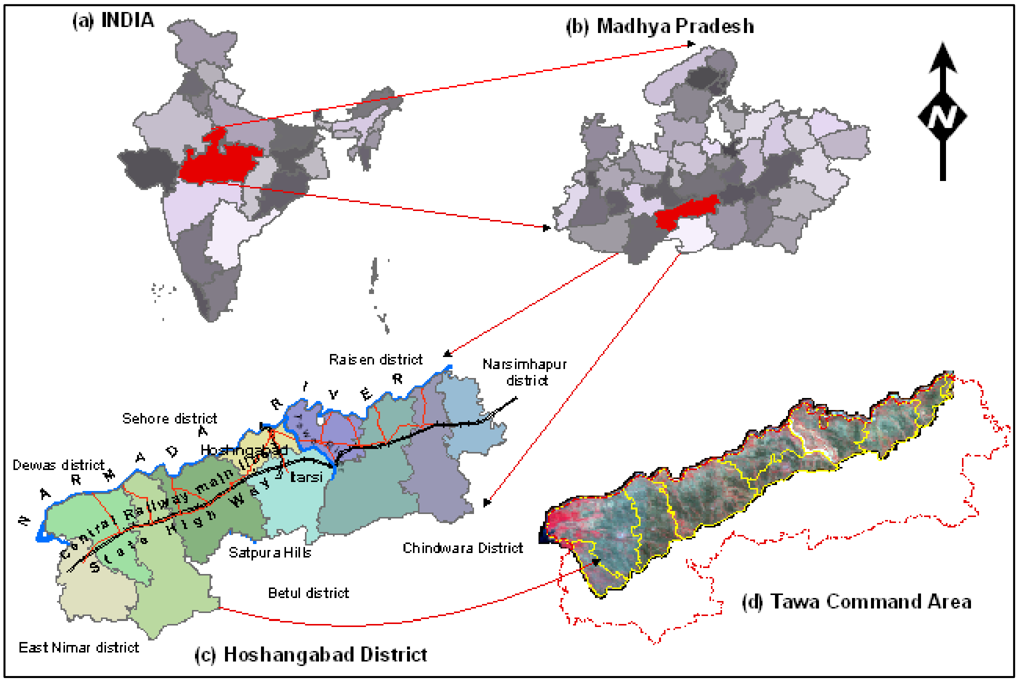


Figure 3.1 Location map of the study area

3.2.2 Climate of Study Area

3.2.2.1 Rainfall

Proper crop planning in an irrigated area requires quality analysis of rainfall data as well as its correct interpretation. A poor, faulty analysis affects the sowing date, rainwater availability, irrigation need, and ultimately the net returns from the command. In the present study, 40 years daily rainfall data were analyzed for the Tawa irrigation project on weekly, monthly and annual basis, to arrive at analytical conclusion for better irrigation planning. The rainfall has been analyzed using daily rainfall data collected from India Meteorological Department (IMD), Pune for 40 years from 1971 to 2010 and ten local stations spread over in and around the Tawa command area from the State Data Centre, Bhopal, Madhya Pradesh.

Thiessen polygon (Voronoi diagram) provides the area of influence of each gauge station in and around the study area. The perpendicular bisector of each line joining two stations generates the area of influence (polygon). Once the area of influence (thiessen weight) is assessed for individual stations, average rainfall received in the area is estimated using the following equation:

$$\bar{P} = \sum_{i=1}^{N} (P_1 A_1 + P_2 A_2 + \ldots \ldots + P_N A_N)/A \quad (3.1)$$

Where,

$\bar{P}$ = Average rainfall; P_N = Rainfall for individual station; A_N = Area of influence (Thiessen weight) for individual station; A = Total area. The average annual rainfall received in the area using Thiessen polygon is 1036.18 mm as presented in Table 3.1. The Thiessen polygon drawn utilizing the local stations is shown in Figure 3.2.

Table 3.1: Station-wise average rainfall and corresponding Thiessen weight

S. No.	Station	Lat.	Long.	Avg. rainfall (mm)	Thiessen Area (km^2)	Thiessen Weight	Weighted Rainfall (mm)
1	Babai	22.7	77.9	924	554.9	0.11	97.2
2	Bankhedi	23.8	78.5	1176	41.2	0.01	9.2
3	Harda	22.3	77.1	1052	972.9	0.18	194.0
4	Hoshangabad	22.8	77.7	1197	332.6	0.06	75.5
5	Itarsi	22.6	77.8	1148	435.3	0.08	94.8
6	Khirkia	22.2	76.9	828	714.4	0.14	112.2
7	Pipariya	22.8	78.4	1055	235.6	0.04	47.1
8	Seoni Malwa	22.5	77.5	1173	862.9	0.16	191.9
9	Sohagpur	22.7	78.2	988	368.5	0.07	69.0
10	Timarani	22.4	77.2	1014	754.9	0.14	145.1
	Total			**1055**	**5273.1**		**1036.2**

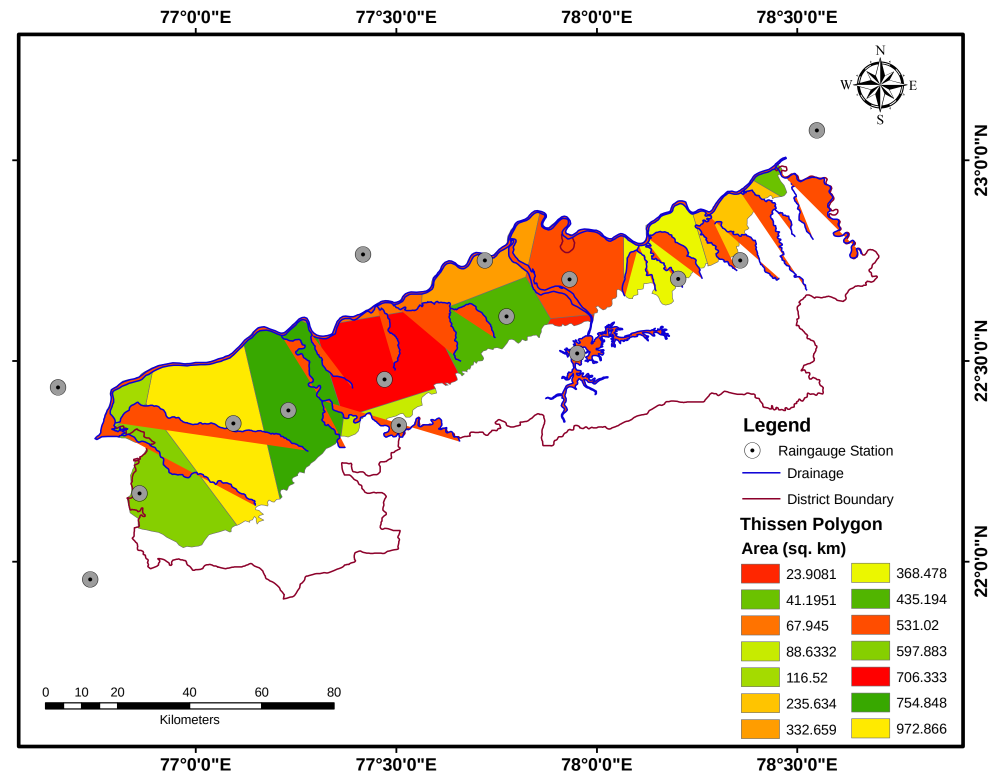


Figure 3.2 Thiessen polygons over Tawa command

Histogram analysis (frequency of occurrence) based on the annual mean rainfall data confirms that 75% of the rainfall events are in the range of 751 mm to 1500 mm. Extreme rainfall with more than 1501 mm is also witnessed in 17.5% of the rainfall events occurring in the command area. The histogram of rainfall is shown in Figure 3.3.

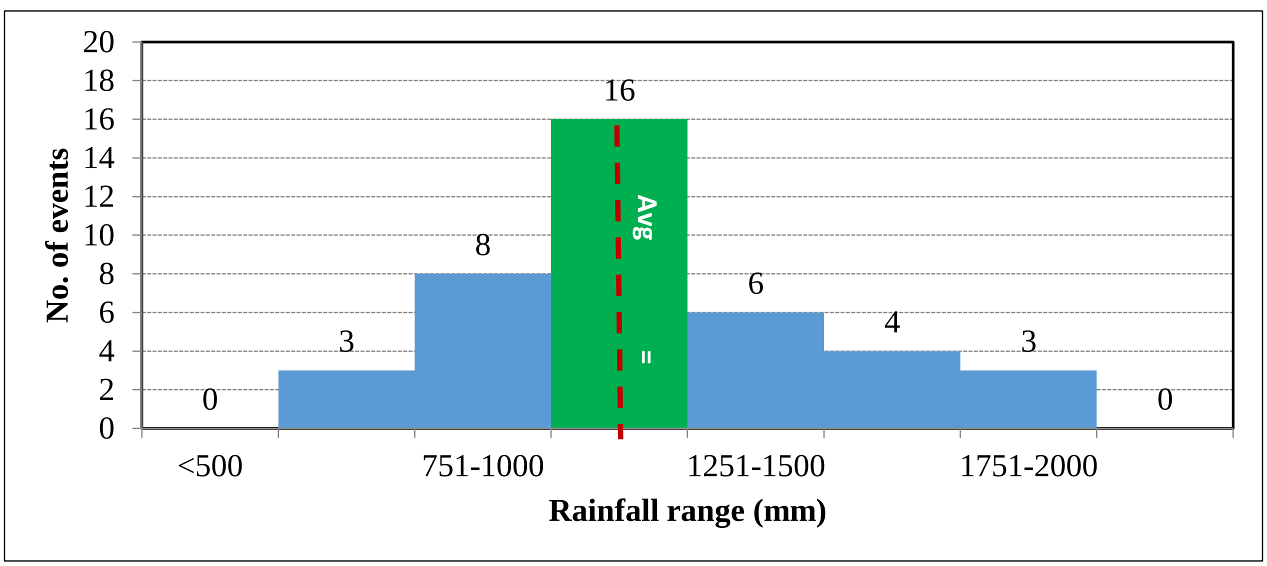


Figure 3.3 Histogram analysis of rainfall for the period 1971-2010

Statistical analysis of rainfall for the period 1971-2010 is made for weekly, monthly, and annual rainfall. Mean monthly rainfall varies from 0.83 mm in the month of April to 404.27 mm in the month of July. Whereas, mean weekly rainfall varies from 0.06 mm in the Standard Week (SW) 16 to 97.94 mm in the SW 33. The weekly coefficient of variation suggested that the variation is maximum during the standard monsoon weeks (SW 26 to SW 37) indicating fluctuating rainfall pattern in the region. Similar trend is also seen for the four monsoon months viz. June, July, August and September indicating considerable variation of rainfall during monsoon. Minimum value of standard deviation is 2.74 during April and 0.16 during SW 16. It indicates better weather stability in the period. The annual mean rainfall in the Tawa command is 1174.78 mm. The standard deviation of annual series of rainfall is 302.04 mm. Annual coefficient of variation and coefficient of skewness in the region are 0.26 and 0.59 respectively.

3.2.2.2 Temperature

The temperature characteristics in the region based on the analysis of temperature data for the period 1971 to 2002 indicated that the mean annual temperature is 29.60°C with standard deviation of 0.42°C. The temperature starts rising from beginning of February and peak is reached in the month of May touching the mercury at 41ºC (Normal). The winter season commences with November and temperature dips to 11ºC in the month of December. The temperature characteristics in the region can be summarized as extreme with intense summer and winter periods.

3.2.2.3 Humidity

The relative humidity during summer is least in the month of April i.e. about 18.1% and is maximum in August i.e., 86.7%.

3.2.2.4 Wind

Wind is very important factor for evapotranspiration and crop water requirement. The study area is relatively free from storm. It has storms during hot summer months, but the velocity of wind is not very high. During the month of June, the average wind speed is around 7.55 km/h and the lowest wind speed is in the month of November and its average is 3.25 km/h. Seasonal and annual mean wind velocities are 5.27 and 4.32 km/h in the morning hours and 7.06 and 5.65 km/h in the evening hours respectively.

3.2.2.5 Evaporation and evapotranspiration

The area receives rainfall in the order of 1174 mm during the monsoon. Studies carried out by the Narmada project authority indicate that out of monsoon rainfall, about 465 mm is evapotranspiration losses during the monsoon. Of the remaining 693 mm a part goes off as surface runoff and only a part is available for soil saturation, subsurface flow and recharge to the groundwater body.

3.2.3 Physiography of Study Area

Physiographically, the district has two natural divisions, the valley covering the central and northern parts of the district and the hills covering the whole of south. The hills in the district belong to the Satpura system, which rise in continuous chain of forest covered hills. Between these hills and Narmada is the fertile valley a strip of nearly level country about 24 km in width, with slopes gently down towards the Narmada River. Figure 3.4 shows the IRS P-6 LISS III image showing Hoshangabad district with thick green forest on Satpura hills and valley portion covering Tawa command. The maximum altitude of the ground surface is at Dhupgarh near Pachmarhi (1352 m above MSL) and minimum at Mahendgaon (253.5 m above MSL).

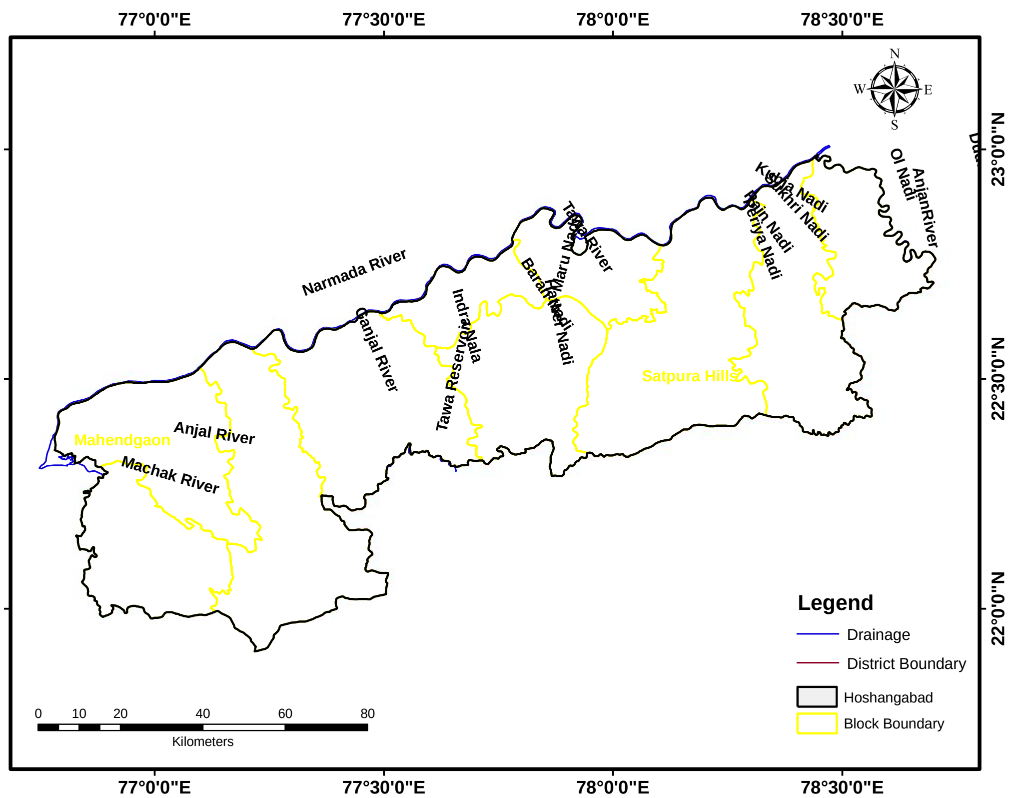


Figure 3.4 Physiography of Hoshangabad district

3.2.3.1 Land use and land cover

Land use and land cover (LULC) map for the Tawa command has been generated using LISS-III image. Eight land use classes have been considered viz. dense forest, sparsed vegetation, water bodies, waste land, built-up area, exposed river bed including sand, and agriculture which further segregated into irrigated and non-irrigated. Agriculture is the dominant of all the classes with 77% coverage of total area. Built-up area includes major townships such as Hoshangabad, Itarsi and Harda. Tawa river falling at Narmada near Hoshangabad becoming one the major tributaries of Narmada. Left bank canal (LBC) and Right bank canal (RBC) are emerging from the two end of Tawa reservoir irrigating about 60% of the total grossed command area with an irrigation intensity of more than 150%. The LULC map is presented in Figure 3.5 and the different land use classes with their area coverage in the command are given in Table 3.2.

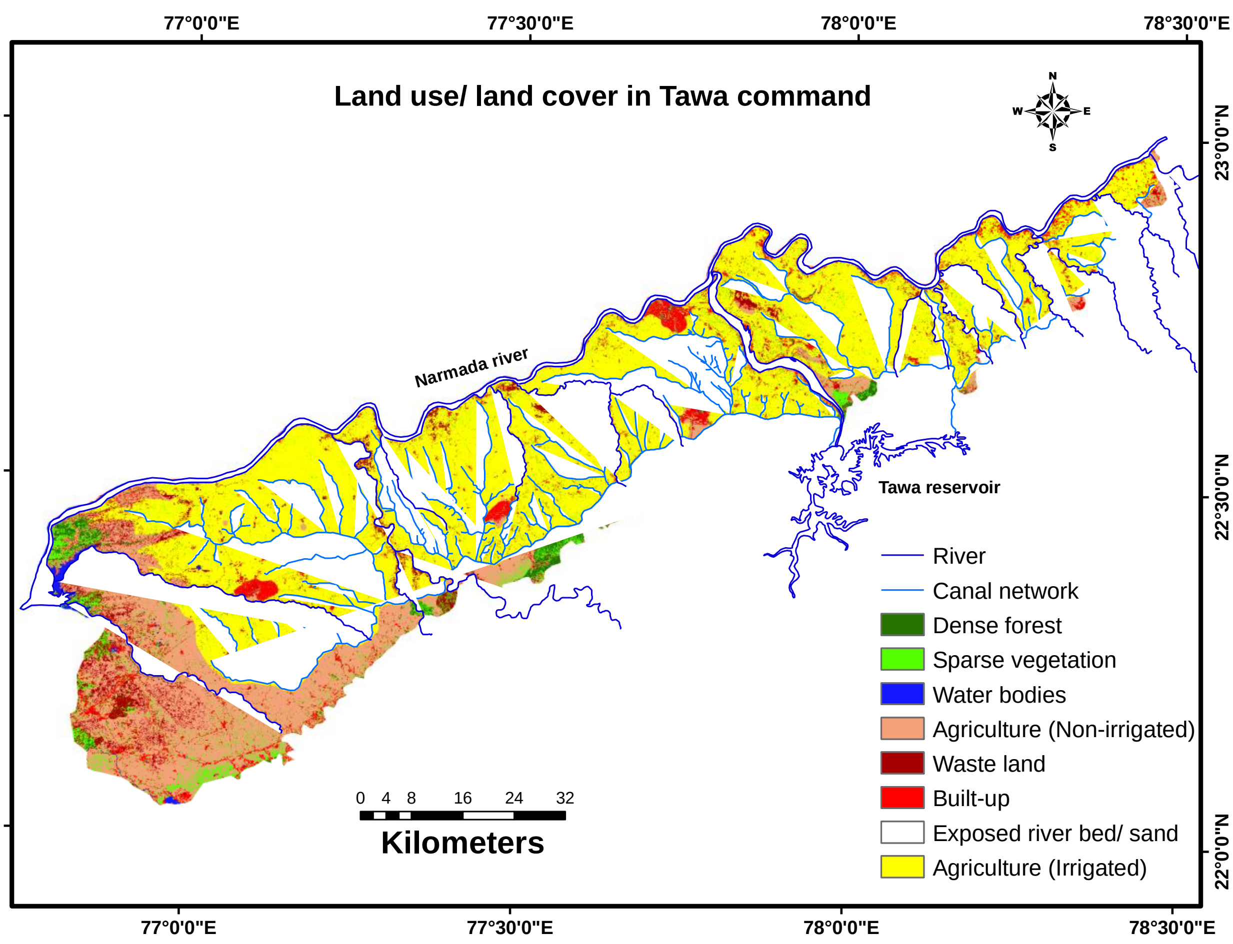


Figure 3.5 LULC map of the Tawa command

Table 3.2: Land use land cover in the Tawa command

LULC type	Area (km^2)	% cover
Dense forest	58.89	1.12
Sparse vegetation	339.44	6.45
Water-bodies	148.18	2.81
Agriculture (Non-irrigated)	935.76	17.77
Waste land	242.71	4.61
Built-up	323.17	6.14
Exposed river bed/ sand	39.40	0.75
Agriculture (Irrigated)	3177.49	60.35
Total	**5265.04**	**100.00**

3.2.3.2 Cropping pattern

Tawa command consists of two irrigation systems. Both the systems are located in the left and right bank of Tawa reservoir with a planned capacity to irrigate an area of 0.247 M-Ha. The cropping intensity in the command is given in Table 3.3, indicating 138% and 125% crop intensity during *Kharif* (June-Sept) and *Rabi* (Oct-Feb) seasons respectively. Originally the cropping pattern suggested by Agricultural Department was Paddy, Cotton, Pulses, Jawar, Groundnut in *Kharif* ; Wheat, Gram in *Rabi* and Fodder crop in summer. Later on, Soyabean crop was introduced in the Tawa command, resulting in considerable change in the cropping pattern and designed irrigation requirement. Along with the change in cropping pattern, the irrigation requirement changes with type of crops. A water intensive crop like paddy when replaced with crops like Soyabean, the irrigation requirement in the command reduced resulting in increased availability of water in the command. The analysis of the different crops grown in the command during 1995-96 to 2002-03 (Table 3.4), revealed that the irrigated area under Gram is reduced from 67,825 ha to 27,176 ha. Similarly the area under Wheat is increased every successive year with crop acreage of 62,306 ha in the year 1995-96 to 1,03,780 ha during 2002-03, a percentage increase of 60%.

Table 3.3: Cropping intensity in the Tawa command

S. No.	Name of Canal	Crop Intensity		
		Season	% of CCA	Area in Ha
1	Left Bank Canal CCA 1,86,162 Ha	*Kharif*	67	124,728.00
		Rabi	67	124,728.00
		Summers	4	7,448.00
	Total =		138	256,904.00
2	Right Bank Canal	*Kharif*	58	35,208.00

CCA 60,702 Ha	*Rabi*	67	40,673.00
Total =		125	75,881.00
Grand Total =			**332,785.00**

Table 3.4: Cropping pattern for different years in the Tawa command

Year	**Existing crop in the command (Area in Ha)**						
	Soyabean (*Kharif*)	Wheat	Gram	Soyabean (*Rabi*)	Pulses	Linseed	Others
1995-96	75830	62306	67825	14648	2682	1290	7031
1996-97	75000	71792	39972	30971	296	94	3974
1997-98	76200	95560	30725	20619	342	53	1924
1998-99	-	76489	38353	23816	-	56	-
1999-00	-	99397	27176	13839	-	34	-
2000-01	-	99579	-	-	-	-	-
2001-02	-	108873	29814	2624	-	-	-
2002-03	-	103780	32548	6128	-	-	-

3.2.3.3 Soil

The soils of the area are characterized by black, gray red and yellow colours, often mixed with red and black alluvium and ferruginous red gravel or lateritic soils (Fig 3.6). These soils are commonly known as black cotton soils. About 15% of the area is covered by sandy loam soils and remaining part is occupied by clay loam with big pockets of sandy clay loam and sandy loam for the area lying east of Tawa river. In between Tawa and Ganjal rivers about 60% is clay, 15% with clay loam and about 8% is sandy clay loam. Area covering west of Ganjal river is occupied by the clayey soil and clayey loam.

With the exceptions pointed out above, the Narmada valley is a continuous strip of rich black soil, only broken occasionally by strips of poorer cultivation. Generally speaking, the eastern part of the valley, particularly the Sohagpur Tehsil is poorer than the western. In fact Sohagpur Tehsil is the poorest in the district, and except around Sohagpur where there is a fertile land, the characteristic deep black soil of Hoshangabad portion of the valley is but little met with moreover, in Sohagpur Tehsil the valley is cut by numerous rivulets and nullahs, which scour away the fine particles of soil and bring down large deposits of sand from Mahadeo hills. In Hoshangabad Tehsil the streams are less numerous. The plain tract around village Jaiselpur (on the Babai Hoshangabad road) is one of the richest in the district. Further west in Seoni-Malwa

Tehsil the valley is broader, the black soil stretches right upon the foot of the hills, which occupy a smaller area in this Tehsil than in other tehsils.

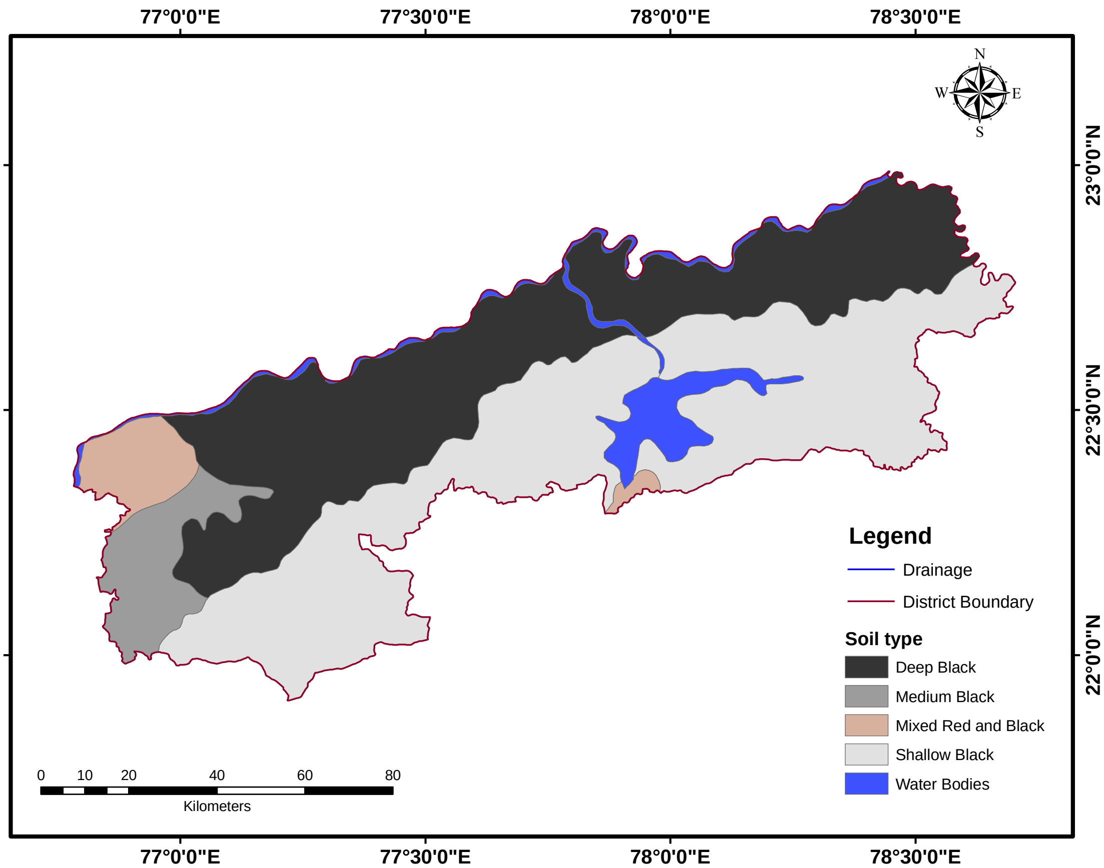


Figure 3.6 Soil Map of the Hoshangabad district

3.2.3.4 Geohydrology

The district is geologically divided into alluvium, Deccan traps, Gondwanas, Bijwaras and Archeans. The north western part of the district comprises of archean, granites and geneisses and crystalline limestone of Bijwaras. In this region, groundwater occurs mostly under phreatic condition and in confined nature below the crystalline lime zone. Northern part of the district, adjoining the Narmada river is covered with alluvium which makes for more than 50% of the entire district area and almost covers total Tawa command area except a few patches of granite on North-West. It is reported that all the alluvial aquifer zones constitute a single aquifer system. The unconfined aquifer along the southern fringe adjacent to Gondwana passes laterally to the north into a number of aquifer zones separated by thick clay zones. The thickness of alluvial ranges between 15m at Pathrai to 160 m at Tinsari. The top phreatic aquifer ranges in thickness from 2 to 10m and is encountered in the depth range of 4 to 20 mbgl. The phreatic alluvial aquifer mostly comprises of fine to medium grained sand with intercalations of clay and silt, and at places also of coarse sand or gravel.

3.2.3.5 Infiltration

Infiltration tests were carried out in the Tawa command using Double Ring Infiltrometer on 09-10th April 2011 in three different villages viz. Jhaalabad, Dhogari, and Krishnapur. Infiltration tests are undertaken to find the rate of infiltration of water i.e. speed at which the water transmit into the soil. The infiltration rate depends on the soil texture (size of the soil particles) and soil structure (arrangement of the soil particles). It is helpful in categorizing the soil from irrigation point of view of an area. The estimated average infiltration rate (cm/h) in the area was found in the range of 2.5 cm/h to 4.5 cm/h as shown in the Figure 3.7.

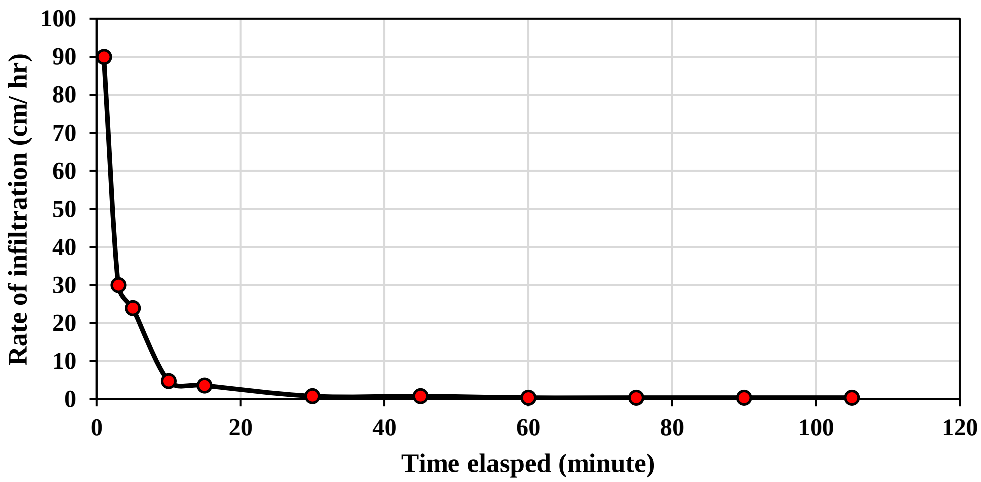


Figure 3.7 Chart showing average infiltration rate in the Tawa command

3.2.4 Water Resources of Study Area

3.2.4.1 Surface Water

Narmada river is the main river of the area which is flowing from east to west direction. It originates from the Amarkanthak plateau and after flowing through Shahdol, Mandla, Jabalpur, and Narsingpur District, enters into the Hoshangabad district from the north-eastern side. River Tawa is one of the major tributary of the Narmada River and flows from south to north and merging into Narmada. River Denwa originates from south-eastern part of the Hoshangabad district from the hilly range of Pachmarhi and flows from east to west direction before merging into the Tawa River (south of Ranipur) where Tawa dam is constructed. The rivers draining the area, in the western part are Morand, Ganjal and Ajnal. The Morand River joins the Ganjal River near Chidgaon and flows towards Narmada River. Eastern boundary of the district is marked by the Dudhi river which flows almost towards north and take westerly diversion before meeting the Narmada river. Drainage network and major rivers in the Tawa command is shown in Figure 3.8.

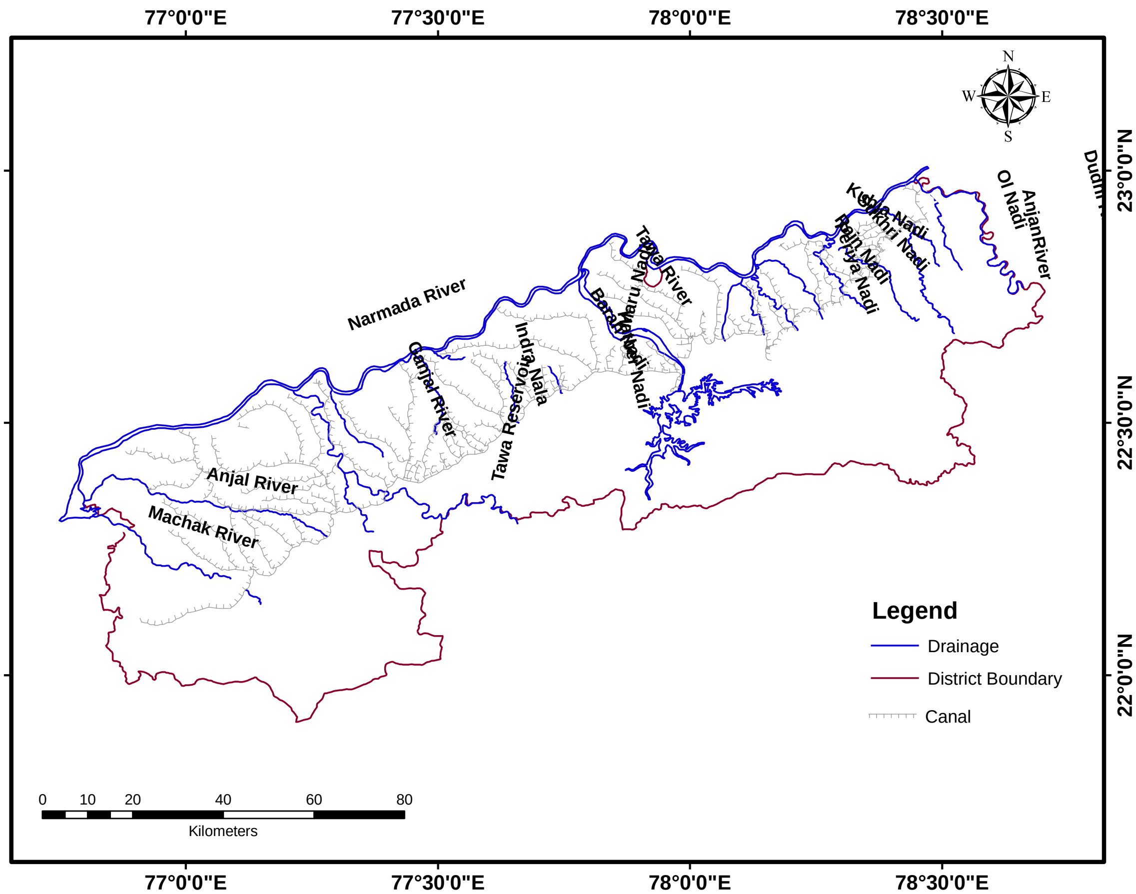


Figure 3.8 Drainage map of the study area

3.2.4.2 Groundwater

Groundwater table data and exploratory well data have been collected for a period of 10 years. The gross groundwater draft estimated as 8.11 MCM during the monsoon period and 81.04 MCM during the non-monsoon period. This amount is negligible as compared to surface water irrigation. Block wise ground water draft has been given in Table 3.5.

Table 3.5: Groundwater draft (Anonymous, 2003)

Name of Block	Groundwater position data (H.M.)	Population of wells	Draft (H.M.)
Piparia	37685	2697	7773

Name of Block	Groundwater position data (H.M.)	Population of wells	Draft (H.M.)
Sohagpur	18191	2176	2690
Babai	25602	2208	1977
Hoshangabad	27826	2208	3543
Kesla	14537	1322	6170
Seonimalwa	47022	1755	5319
Timarani	17186	460	2967
Harada	8608	650	2387

It is reported that there was a general decline in the water level in the area till 1975. In the Tawa command, the trend reversed to a rising groundwater level since 1976, the time since regular canal irrigation commenced in the area. This rise in groundwater level over the years is of the order of 2 m in general and more than 2.5 m in certain patches (Anonymous, 1995). It is reported that approximately 34000 ha of this command area is classified as waterlogged in the Tawa command after commencement of irrigation where water table lying between 0-3 m, out of which 330 hectares has completely gone out of production according to official estimates. Unofficial estimates put this figure about the order of 3000 ha (Bowonder et al., 1987).

3.2.4.3 Irrigation

Tawa project is a major surface irrigation project existing on River Tawa which is a tributary of Narmada river. About 60 percent of the total area of Hoshangabad district is irrigated by Tawa canal system. Data regarding canal network and its characteristics were collected from different sources. With the commencement of this project, rise in ground water table identified by authorities and local people in the command area. Tawa canal command and canal network is shown in Figure 3.9.

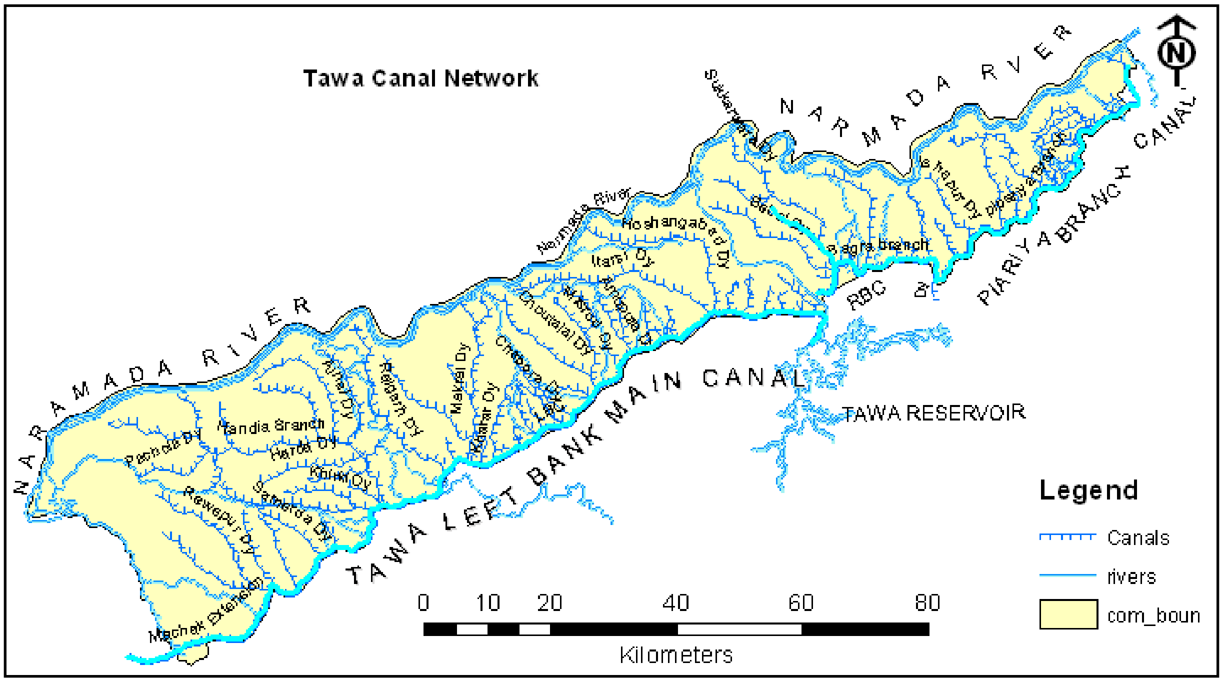


Figure 3.9 Tawa command and canal network

The project is designed to provide annual flow irrigation of 0.333 Mha in service area of 0.247 Mha of Hoshangabad district through Left Bank Canal (LBC) and right bank canal (RBC) System. The Gross Command Area (GCA) is 0.401 Mha and the Culturable Command Area (CCA) is 0.247 Mha where the annual irrigation proposed is 0.333 Mha. The entire system is unlined except few stretches. The LBC starts from Ranipur and runs parallel to Narmada river course along limits of the foot hill pediments of Satpura. This canal takes off directly from the reservoir with a head discharge of 103.6 cumec. The first 6.44 km length is lined with thick concrete. The Handia branch canal with a head discharge of 29.9 cumec take off from the main canal at 92 km point. The Right Bank Canal (RBC) is taken through a tunnel from Kamthi and runs parallel more or less to the course of Narmada river. The distributary system has been planned along the drainage divide. Due to topographic difference between right and left bank canal the right bank canal has been taken through 6 km long tunnel. Bagra branch canal and Pipariya branch canal takes off on either side of the pickup weir. The Bagra canal is 60 km long. The total length of the distributaries and minors on the RBC system is 450 km. In the year 1975 irrigation was commissioned through the Left Bank Canal (LBC) system. The dam was completed in the year 1978. The water course system below 40 ha outlet and drainage system was completed under Ayacut Development Programme from 1981 to 1986. Tawa canal system characteristics are given in Table 3.6.

Table 3.6: Tawa canal system characteristics

S. No	Canal name	Block	Lined/unlined	Canal length (km)	Wetted perimeter (km)	Wetted area (km^2)	No of running days	
							Mon soon	Non mon soon
1	Tawa main	Hoshangabad	L	22.80	37.07	0.18	12	131
2	Tawa main	Kesla	u	38.40	36.70	1.41	12	131
3	Tawa main	Seoni Malwa	u	24.50	32.48	0.80	12	131
4	Tawa main	Timurni	u	21.00	26.80	0.56	12	131
5	Tawa main	Harda	u	2.75	22.00	0.06	12	131
6	Pipariya Br	Sohagpur	u	24.50	12.52	0.31	23	137
7	Pipariya br	Pipariya	u	27.00	7.80	0.21	23	137
8	Bagra Br	Sohagpur	u	9.00	12.52	0.11	23	137
9	Bagra Br	Babai	u	14.40	12.50	0.10	23	137
10	Harda Br	Harda	u	25.60	9.02	0.23	12	131
11	Handia Br	Timurni	u	22.40	17.03	0.38	12	131
12	Distributary	Hoshngabad	u	148.00	9.39	1.39	12	131
13	Distributary	Sohagpur	u	52.00	6.15	0.32	23	137
14	Distributary	Kesla	u	48.00	9.89	0.47	12	131
15	Distributary	Babai	u	135.00	6.50	0.88	23	137
16	Distributary	Pipariya	u	36.80	2.56	0.09	23	137
17	Distributary	Timurni	u	124.84	5.18	0.65	12	131
18	Distributary	Harda	u	160.98	3.87	0.62	12	131
19	Distributary	Seoni Malwa	u	140.00	9.89	1.38	12	131
20	Distributary	Khirkiya	u	4.80	1.70	0.01	12	131
21	Minors	Seoni Malwa	u	303.00	2.50	0.76	12	131
22	Minors	Sohagpur	u	115.00	3.00	0.35	23	137

3.3 DETAILS OF DATA SOURCES AND SOFTWARE TOOLS

For the present study, data have been collected from various organizations like National Remote Sensing Center (NRSC), Survey of India (SOI), Geological Survey of India (GSI), Central Water Commission (CWC), Central Ground Water Board (CGWB), Directorate of Census Operations, State Irrigation Department and State Data Center (SDC) to obtain topographical map sheets, satellite images, geological and soil maps, ground water data, surface water data, agricultural and socio-economic data. Some technical reports and maps were collected on existing scenario of the command area, salient features about the command area, canal network details and Tawa index map from CGWB, Chief Engineers Office, Narmada Bhawan and State Data Center, Bhopal. Details regarding data collection and its features have been given in Table 3.7 and Table 3.8.

Table 3.7: Data collected and data sources

S.No	Data		Scale		Year/date	Source
I) Thematic Maps (Hard Copy)						
1	Topographic Maps 55 Series: F/9, F/13, J/1, J/5, J/9 F/2, F/6, F/10, F/14, J/2, J/6, J/10 B/15, F/3, F/7, F/11, F/15, J/3 B/16, F/4, F/8		1:50,000		1979	SOI, Bhopal
2	District Planning Map		1:250, 000		2000	SOI, Dehradun
3	District Resource map		1:25,000		1976	GSI, Bhopal
4	Revenue Maps				2001	Directorate of census operations
5	District Census Hand Book				1991 and 2001	Directorate of Census Operations, Bhopal
II) Remote Sensing Data (Digital)-						
	Sensor		Path	Row		
6	IRS IB LISS II				16-03-92, 30-09-92, 08-05-93, 18-11-95, 10-12-95, 23-01-96, 14-02-96, and 29-03-96.	State Data Center, Bhopal
7	**LandSat 7 ETM+**		**145**	**044**	**01-10-2000, 19-11-2006**	www.glcf.edu.net
8	ResourceSat LISS III		97 98	56 56	22-02-05 and 13-11-05. 27-02-05 and 18-11-05.	NDC, NRSA, Hyderabad
III) Hydrological, Geological and Meteorological data						-
		Format	Scale			
9	Water Table data	Hard and soft copy	monthly		1992 to 2006	State Data Center and CGWB Bhopal
10	Stage Discharge data	Hard copy	monthly		1980 to 1983 and 1995 to 2003	CWC, Bhopal
11	Litholog Data	Hard copy	-		-	CGWB, Bhopal
12	Rainfall Data	Hard copy	monthly		1997 to 2001	CGWB, Bhopal
13	Pan evaporation data	Hard copy	monthly		1980-1984	CGWB, Bhopal

Table 3.8: Sensor specifications

Specification	IRS IB, LISS-1	IRS P6, LISS-III	Landsat TM
Spectral Bands (µm)	0.45 - 0.52 (B1)) 0.52 - 0.59 (B2) 0.62 - 0.68 (B3) 0.77 - 0.86 (B4)	0.52 - 0.59 (B2) 0.62 - 0.68 (B3) 0.77 - 0.86 (B4) 1.55-1.70 (B5)	0.45 - 0.52 (TM1) 0.52 - 0.60 (TM2) 0.63 - 0.69 (TM3) 0.76 - 0.90 (TM4) 1.55 - 1.75 (TM5) 10.40-12.50 (TM6) 2.08 - 2.35 (TM7)
Spatial resolution (m)	72.5	23.5	30, 120 for TM6
Swath width (km)	148	141	185
Radiometric resolution (bits)	7	7	8

3.3.1 Software Tools

ArcGIS 9.3 is used for spatial database creation and ERDAS 9.2 is used for digital image processing.

In this chapter description about the study area has been discussed in a detailed manner. Data sources, data requirements, and its collection have been discussed. Primary GIS database has been presented in this chapter. In the next chapter, trend analysis has been investigated for different climatic variables. Tawa canal command is an intensive irrigated area spread over more than 5000 km^2. In recent times the state of Madhya Pradesh where the Tawa command is situated has taken several measures to boost the irrigation efficiency across the state.

CHAPTER 4
DATABASE CREATION AND ANALYSIS

4.1 GENERAL

Any study related to natural resources assessment and management requires the analysis of large volumes of spatial and non-spatial data. These data have to be organized and analyzed in a proper manner to achieve the defined objectives. The success of application based research depends upon qualitative and quantitative aspects of data sets. In present day environment geospatial techniques/models are one of the best tools to capture, analyze and to manage data as computer hardware and software continue to improve with time, which are also becoming more affordable.

Remote sensing data satisfies the data requirement of waterlogging problem. Numerous sensors with different spatial, temporal and radiometric resolutions are available these days to capture the data regarding earth surface all over the world including India's IRS mission. The one of the best tool to organize, manage and analyze remote sensing data is to integrate it with a Geographic Information System (GIS). Presently, GIS and remote sensing are the basic tools along with conventional modeling techniques to assess natural resources as well as for planning and management as these involves huge volumes of data sets. In this chapter the methodology adopted to assess waterlogging using geospatial and numerical ground water modeling techniques has been discussed. Figure 4.1 shows the main steps in the study starting from data collection to final analysis.

4.2 DATA COLLECTION

After identification of the problem, data collection is the first step for further analysis. Reliable and authentic data is very important to carry out application based research as the result of the study depends up on spatial and thematic completeness of the data. Sometimes, original data is not available for the study undertaken, so in such cases one can use collection techniques such as interviews or questionnaires to extract the data from a group of respondents. At other times, one can use data that has already been collected. It may be useful in its original form, or change its format to fit our needs. Access to this kind of secondary data is increasingly becoming available in electronic form. Collected data may be spatial and non-spatial in nature and available as hand written documents, drawings, digital data and spread sheets at different scales and levels. After the data has been collected from different sources, it may have to be collated and managed so that it can be easily understood and interpreted. This process is called data collation and will usually require summarizing and tabulating the information.

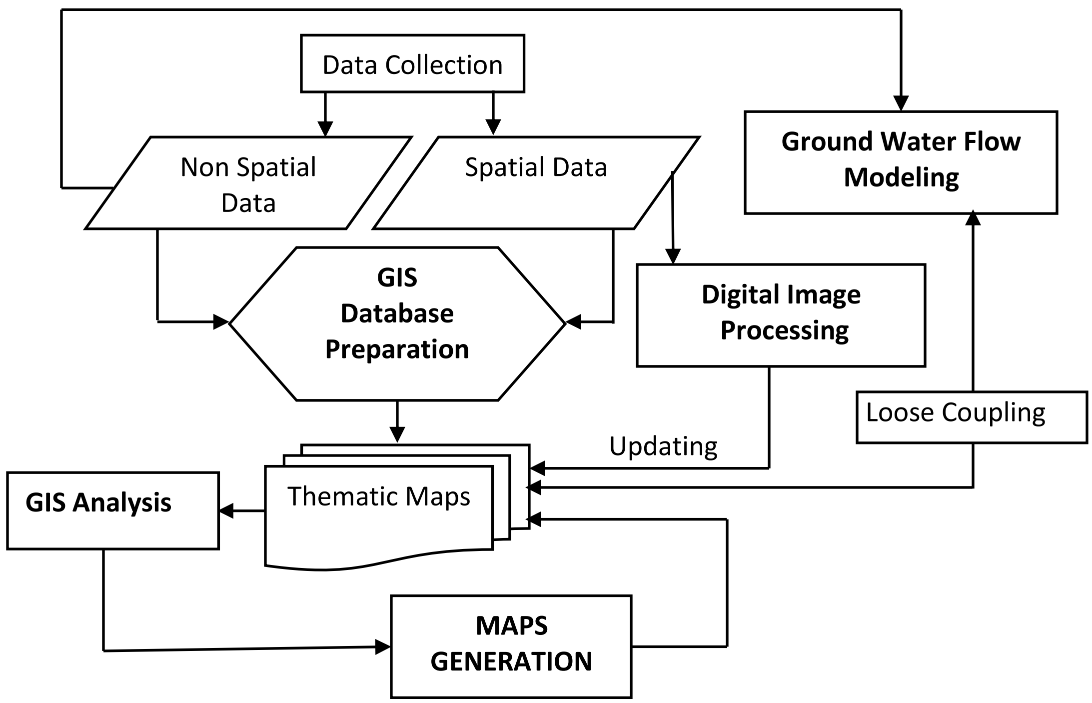


Figure 4.1 Flowchart of the adopted methodology for database analysis

4.2.1 Spatial Data

Spatial data sets are generalization or simplification of real world features. Useful data sources in GIS are topographical and other thematic maps, aerial photographs, satellite images, census data and other ancillary information. This spatial data may be available in the form of paper maps and digital data.

4.2.2 Non Spatial Data

It is commonly known as attribute data in GIS. Non spatial data characterizes the spatial data.

4.2.3 Checking of Data

Before carrying out any analysis, the data collected needs to be thoroughly examined and checked in order to have an error free analysis. Especially, conventional method of collection and management of large volumes of hydrological and meteorological data are cumbersome and requires patience to manage data as to err is human nature. In India, the data obtained from different organizations regarding rainfall, water levels and stage discharge data etc are generally available as hand written documents so there may be chances of errors while entering or copying from records. Use of automatic data recording systems is not common form of data storage. Types of data collected and steps before GIS database creation has been explained in Figure 4.2.

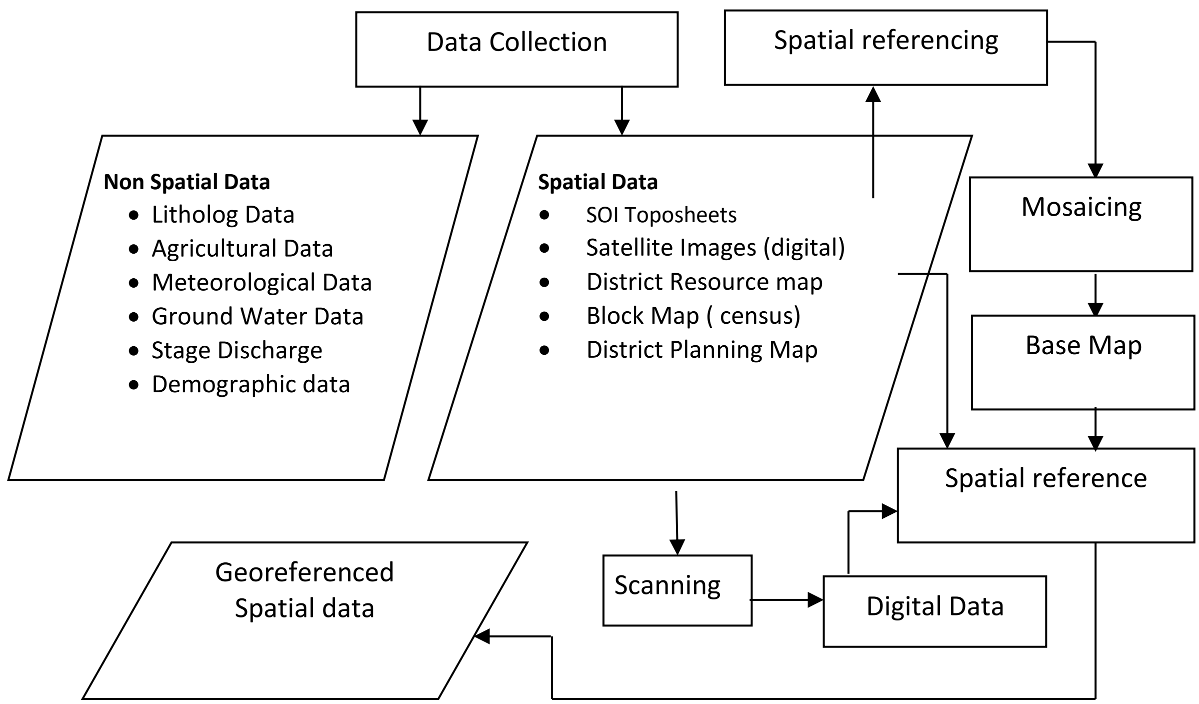


Figure 4.2 Flowchart showing data collection for the study

The method of checking errors for each data set is different. Water table data has been checked with rise and fall analysis for each well. Problematic wells have been deleted from further analysis. Location of observation wells have been checked with village name as wells as with latitude and longitude to prepare spatial map. Litholog data has been compared with reference to geology maps obtained from GSI) and SOI) and literature from different sources. Similarly, Stage discharge data has been checked with rise and fall analysis on a monthly basis. Finally, tabular database has been prepared in excel spread sheets.

4.2.4 Soft Copy Conversion

Spatial data collected from different sources is in hard copy form except satellite images. To convert into digital form these maps have been scanned with A0 size color Scanner. Twenty topographical map sheets, District Planning Map and District Resource Map have been scanned at 300 dpi in RGB mode, while Command area index, canal network and tehsil maps have been scanned at 200 dpi in Black and White mode.

4.3 GIS DATABASE GENERATION

Data Base Generation is one of the foremost and indispensable step for any task related planning, management and assessment of natural or manmade resources. It is a huge and challenging task. Creation of database involves geo-referencing of different datasets, generation or compilation, processing and analysis, formatting and structuring, storing and retrieval of spatial (maps) and non-spatial (tabular and attribute) data. It is particularly important that the data be presented in the form of maps to facilitate spatial analysis. In this context, standard scales of mapping and format for mapping is essential. To ensure uniformity, the base maps have been prepared with the help of topographical map sheets. The base maps so prepared will be utilized in the preparation of thematic maps for transferring the thematic details as derived from the satellite data analysis.

The spatial data generally refers to map formats comprising primary and derivative layers. The important primary layers include geology, soil, land use / land cover, contour, drainage, transport network, watersheds and administrative boundaries, etc. and from these derivative layers, such as hydrogeology, land capability, digital elevation model, are synthesized.

The non-spatial data include socio-economic data and ground based observation related to natural resources, which act as collateral data to spatial data. The spatial and non-spatial data if used conjunctively can provide meaningful information that can be used for various applications related resources management.

4.3.1 Geometric Correction:

Remotely sensed image data gathered by a satellite or aircraft are representations of the irregular surface of the Earth. Even images of seemingly flat areas are distorted by both the curvature of the Earth and the sensor being used. Rectification is necessary for spatial data without projection. Rectification is the process to assign projection system and location information to data. Rectification is not necessary if there is no distortion in the image. For example, if an image file is produced by scanning or digitizing a paper map which is in the desired projection system, then that image is already planar and does not require rectification unless there is some skew or rotation of the image. Scanning and digitizing produce images that are planar, but do not contain any map coordinate information. These images need only to be georeferenced, which is a much simpler process than rectification.

Geo-referencing refers to the process of assigning map coordinates to image data. The image data may already be projected onto the desired plane, but not yet referenced to a proper coordinate system. Rectification, by definition, involves geo-referencing, since all map projection systems are associated with map coordinates. Image-to-image registration involves geo-referencing only if the reference image is already georeferenced. Registration is the processes of making an image conform to another image. In many cases, images of one area that are collected from different sources must be used together. To be able to compare separate images pixel by pixel, the grids of each image must conform to the other images in the data base. After rectification, pixels of the new grid may not align with the pixels of the original grid, thus the pixels have to be resampled.

Resampling is the process of extrapolating data values for the pixels on the new grid from the values of the source pixels. Nearest neighbor resampling is the best method for remotely sensed data which uses the value of the closest pixel to assign to the output pixel value and also it transfers original data values without averaging them as the other methods do; therefore, the extremes and subtleties of the data values are not lost. Some spectral integrity of the data may be lost during rectification. If map coordinates or map units are not required in the application, then it may be wiser not to rectify the image. An unrectified image is more spectrally correct than a rectified image. However for GIS based analysis rectification is necessary. Figure 4.3 shows the step involved for geometric correction.

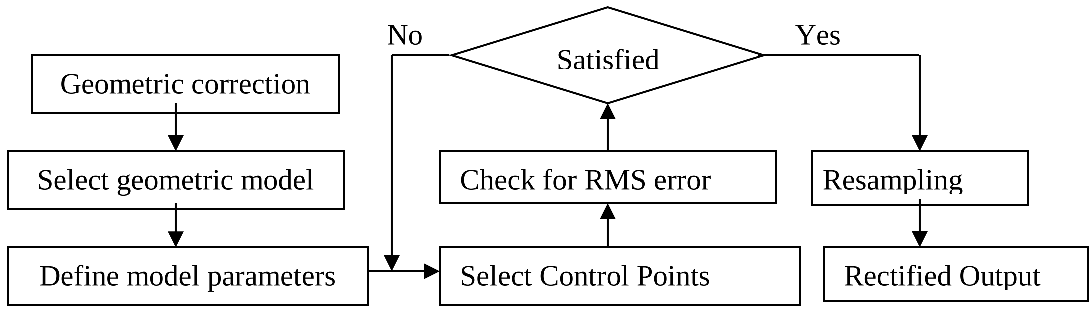


Figure 4.3 Steps for geometric correction of spatial data

4.3.2 DEM Generation

Digital Elevation Model (DEM) has many potential real-life applications, especially in the field of water resources. DEM generated through mass points do not yield better results. Spot heights, contours, drainage, canal network have been used to generate TIN, in order to define near real topography. Spot heights and contours as mass points, drainage, canal network and transport network are defined as break lines so as to break the slope along these. Break lines define and control surface behavior in terms of smoothness and continuity. As their name implies, break lines are linear features and have a significant effect in terms of describing surface behavior when incorporated in a surface model. Break lines typically represent either natural features, such as ridgelines or streams, or built features, such as roadways. Soft break lines are used to ensure that known z-values along a linear feature are maintained in a TIN. Soft break lines can also be used to ensure that linear features and polygon edges are maintained in a TIN surface model by enforcing the break line as TIN edges. However, soft break lines do not define interruptions in surface smoothness. Hard break lines define interruptions in surface smoothness. They are probably the most common and easily understood type of a break lines. Hard break lines are typically used to define streams, ridges, shorelines, building footprints, dams, and other locations of abrupt surface change.

4.4 REMOTE SENSING DATA INTERPRETATION

Digital remote sensing data can be used effectively for research and application based studies to monitor, observe, measure and detect natural or manmade resources or phenomena. In present day world of advanced technology where most remote sensing data are recorded in digital format, virtually all image interpretation and analysis involves some element of digital processing. Digital image processing may involve numerous procedures including formatting and correcting of the data, digital enhancement to facilitate better visual interpretation, or even automated classification of targets and features entirely by computer. In order to process remote sensing imagery digitally, the data must be recorded and available in a digital form suitable for storage on a computer tape or disk. Obviously, the other requirement for digital image processing is an image analysis system**,** with the appropriate hardware and software to process the data. Several commercially available software systems have been developed specifically for remote sensing image processing and analysis.

4.4.1 Steps in Image Analysis

Some of the common image processing functions are Preprocessing, Image Enhancement, Image Transformation, Image Classification and Analysis. Preprocessing functions involve those operations that are normally required prior to the main data analysis and extraction of information, and are generally grouped as radiometric or geometric corrections. Radiometric corrections include correcting the data for sensor irregularities and unwanted sensor or atmospheric noise, and converting the data so they accurately represent the reflected or emitted radiation measured by the sensor. Geometric corrections include correcting for geometric distortions due to sensor-Earth geometry variations, and conversion of the data to real world coordinates on the Earth's surface. Image enhancement, is solely to improve the appearance of the imagery to assist in visual interpretation and analysis. Image classification and analysis operations are used to digitally identify and classify pixels in the data. Classification is usually performed on multi-channel data sets and this process assigns each pixel in an image to a particular class or theme based on statistical characteristics of the pixel brightness values. There are a variety of approaches taken to perform digital classification. Figure 4.4 shows the methodology for digital image classification. The two generic approaches which are used most often, namely supervised and unsupervised classification.

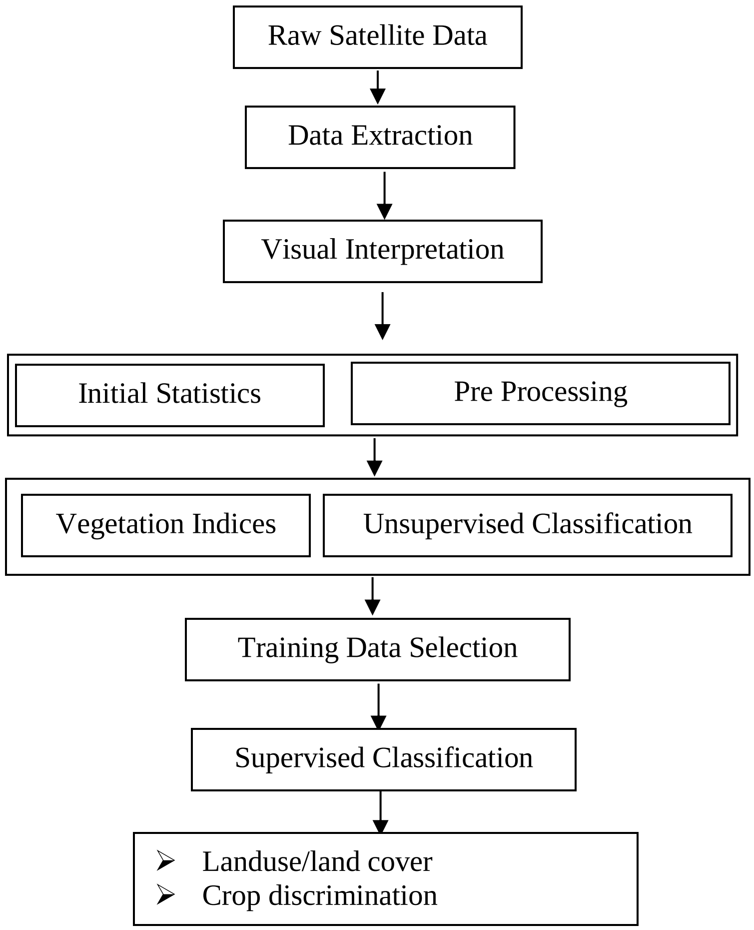


Figure 4.4 Flow chart of methodology for digital image classification

In the present study, image analysis has been done to identify landuse/land cover, major crops and waterlogging in the irrigation command area. There is no single, right way to approach the image interpretation process. Specific goals of the task will determine the image interpretation process employed. Various methods have been adopted to classify the data. After pre processing the data, images have been examined visually and using spectral profiles. First of all unsupervised classification has been performed to know the number of separable information classes initially with 35 classes. Supervised classification with raw data does not yield better results to identify major crops and waterlogging. So vegetation indices have been used to spectrally enhance the data. Tasseled cap transformation, NDVI, and NDWI were used to classify the above mentioned classes. Classification has been done with raw data along with enhanced bands. Few images generated are provided in Figures 4.5 to 4.7.

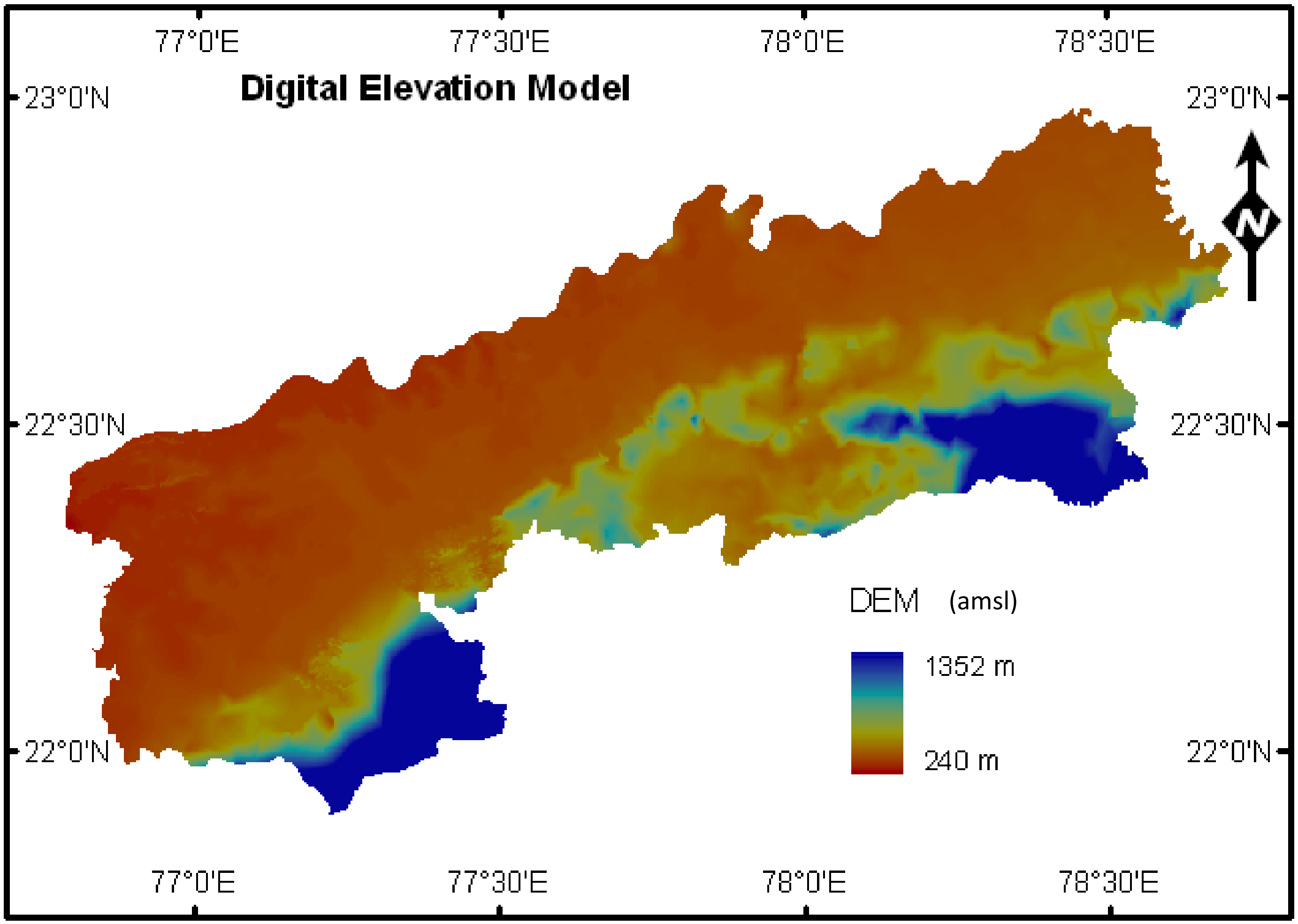


Figure 4.5 DEM of Hoshangabad district

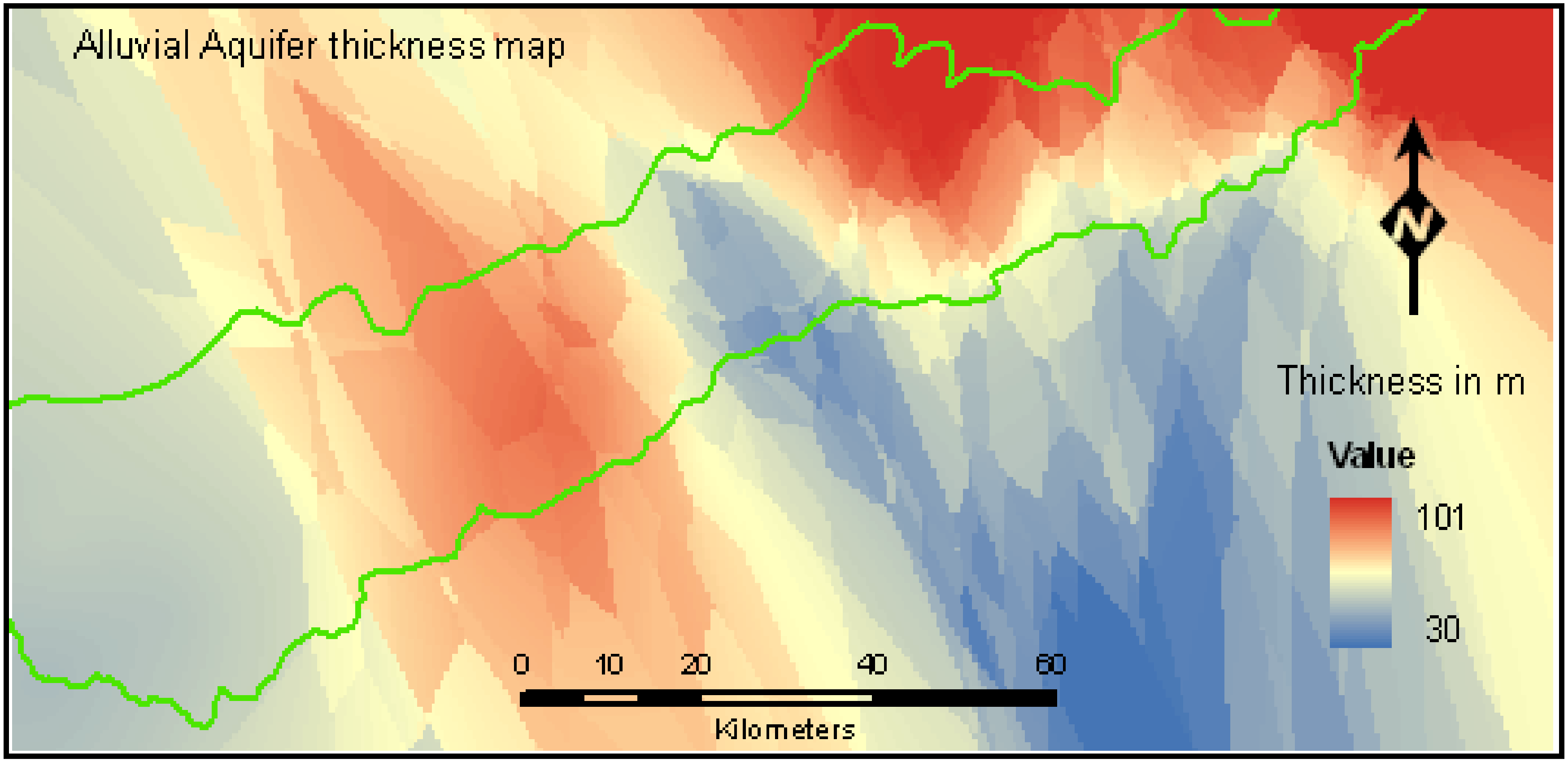


Figure 4.6 Thickness (mbgl) of Alluvial Aquifer in TCA

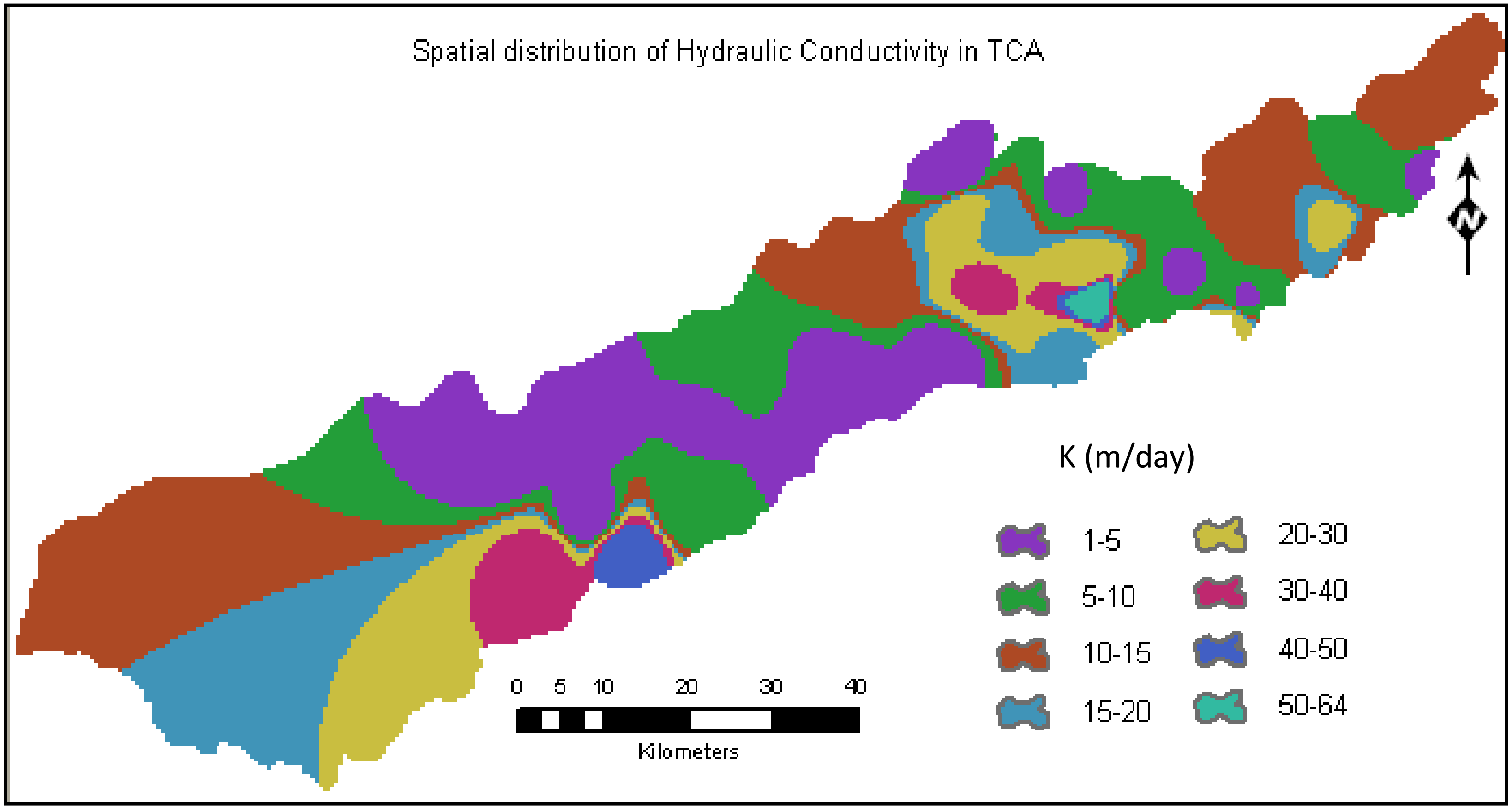


Figure 4.7 Spatial distribution of hydraulic conductivity (K) of Tawa alluvial aquifer

4.5 CHANGE DETECTION

For IRS IB LISS I data, with the help of change detection method LULC has been delineated as availability of temporal datasets for this sensor. After visual interpretation of different data sets, six classes have been identified on the image and cropping pattern is identified on the images with temporal data. Figure 4.8 shows the IRS IB-LISS I temporal data set for a part of the study area. It can be seen that stages of standing crop over the area. In the month of November, Rabi season starts over the command area (Fig 4.8 a). Initial stages of the field can be seen with field preparation which shows water in the fields and the next image (Fig 4.8 b) shows the grown-up crop and in the last image (Fig 4.8 c) showing after crop cutting in most of the areas. Wheat and Gram are the main crops in rabi season. Both these crops have been identified visually as of staggered cropping pattern.

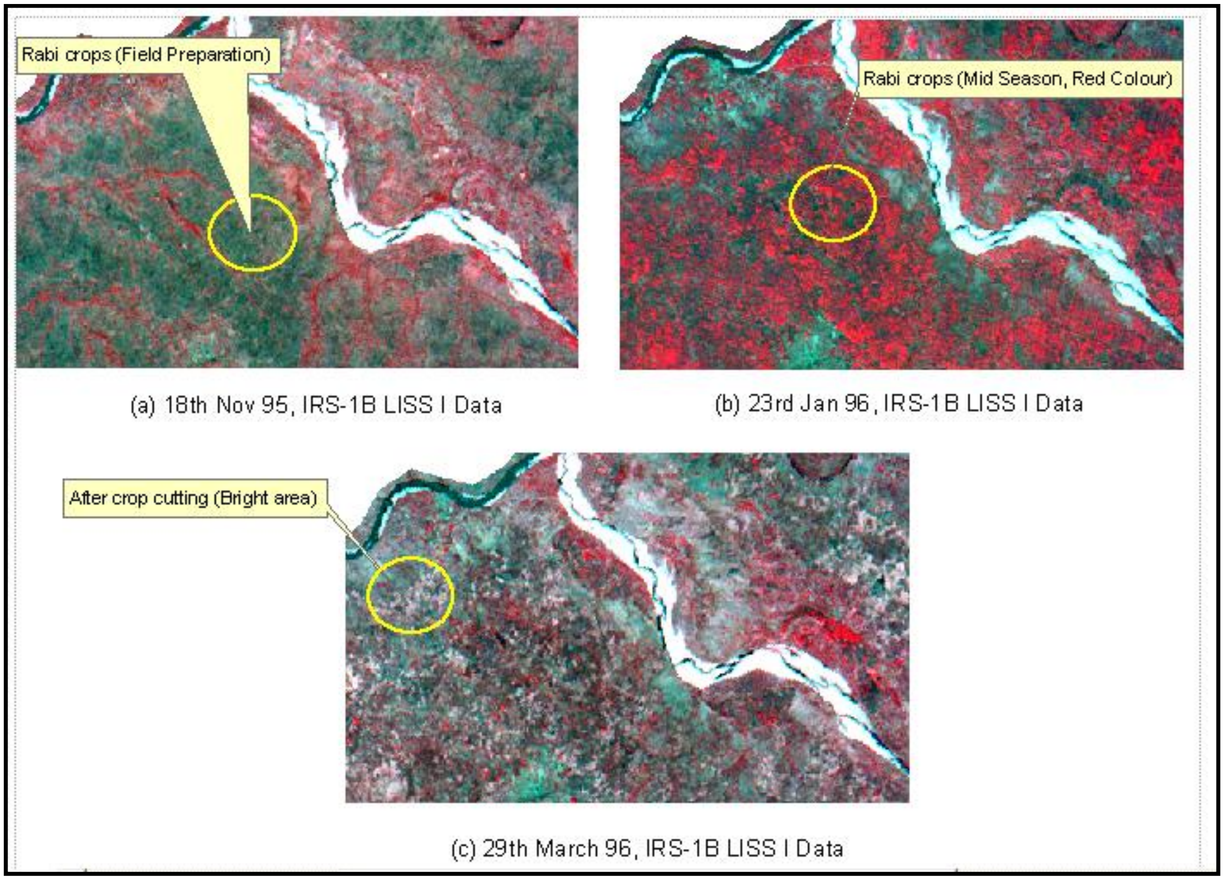


Figure 4.8 Different stages of crops

There is not much difference in DN values in visible region but in NIR band there is a marked difference between December and January images as high DN values of green vegetation in NIR band for January image. Low DN value in December image shows the moisture in the fields. This factor is very important to delineate rabi acreage and extent of wheat crop. Band 4 is spectrally distinct with all visible bands as stated earlier. The difference in DN values of both the images in NIR band is useful to use change detection algorithm to separate crops under Rabi season.

Change detection has been done for these images using NIR band and the results are shown in Figure 4.9. By using this technique rabi crop acreage has been delineated. Final classification has been done using change image along with raw image data to delineate land use/land cover classes. Final classified image for the year 1995 -96 IRS 1B LISS-I data is given in Figure 4.10.

One important note is that whole Tawa command area is not covered in IRS LISS-I and Landsat ETM+ data sets. So common area from all the images have been taken for comparison of the results. Whole command area is considered using IRS P6 LISS-III, 2005 dataset

4.5.1 Vegetation Indices

Vegetation indices are defined as dimensionless, radiometric measures the function as indicators of relative abundance of green vegetation, percentage green cover. These indices normalize external and internal effects such as sun angle, and the atmosphere, canopy back ground, topography etc., for consistent spatial and temporal comparisons.

In this study Normalized Vegetation index (NDVI), Tasseled Cap Transformation (TCT) and Normalized difference water index (NDWI) have been used with different datasets for accurate crop discrimination and to assess waterlogging. Based on the results obtained from classification of raw data sets vegetation indices have been used to enhance the classification accuracy.

4.5.1.1 NDVI

NDVI measures amount of green vegetation in an area. NDVI calculations are based on the principle that actively growing green plants strongly absorb radiation in the visible region of the spectrum while strongly reflecting radiation in the Near Infrared region. Using this principle NDVI images have been created for IRS–P6 LISS III images to identify different crops and general LULC in the study area. Figures 4.11 and 4.12 show the NDVI images for both February and November images respectively. Positive values of NDVI represent vegetation and NDVI values varies from 0.63 to -0.41 and 0.62 to -0.47 for 27-Feb-2005 and 18-Nov-2005 images respectively. In Figure 4.11 rabi/wheat crop and vegetation in forest region has been enhanced by making other features subtle as wheat crop is in mid-season with green stuff. In Figure 4.12 forest region and vegetation along streams have been enhanced. So these images have been used to enhance the classification accuracy.

4.5.1.2 NDWI

NDWI has been in use for several applications as mentioned in Section 4.4.2.2. gNDWI is useful for canopy moisture content detection, fNDWI and xNDWI are to delineate open water features. Water bodies have distinct and clear representation in the imagery. However, very water bodies (canal, pond)/turbid water can be misclassified for soil while saturated soil can be misclassified as water pixels. Just by looking at the tone and colour of a pixel it is difficult to tell the difference between suspended sediment and water bodies (canal, pond). Very shallow water will have the same colour and brightness as very turbid water. In agricultural fields this problem is very common. From this study, classification results show that water bodies (canal, pond) is mixing with fields having water and soil properties. For this purpose xNDWI images have been developed for the study area and these are shown in Fig 4.13 and 4.14 for February and November IRS P6 datasets respectively. From Fig 4.13 and 4.14, NDWI values vary from 0.64 to -0.15 and 0.81 to -0.18 for February and November images respectively.

Positive values of xNDWI indicates water bodies and canopy moisture content. By observing NDVI and NDWI images it is easy to identify agricultural crops, water bodies and forest region. In the command area we can visualize the major crops, water bodies and other features separately.

4.5.1.3 Tasseled Cap Transformation

Tasseled Cap Transformation is one of the most successful index to reduce the dimensionality as well as to enhance the information content into different components. ‘Tasseled cap’ transformation (TCT) is a method of rotating satellite data such that the majority of the information is contained in fewer components or features that relate directly to physical scene characteristics (Kauth and Thomas 1976). The TCT has three orthogonal components. The coefficients, developed by Crist (1985), have been used for transforming the ETM+ imagery into brightness, greenness and wetness variables. These indexes are given in Equations 4.7 to 4.9.

$$B = 0.0243_{tm1} + 0.4518_{tm2} + 0.5524_{tm3} + 0.5741_{tm4} + 0.3124_{tm5} + 0.2303_{tm7} \quad (Eq\,4.7)$$

$$G = -0.1603_{tm1} - 0.2819_{tm2} - 0.4939_{tm3} + 0.794_{tm4} - 0.0002_{tm5} - 0.1446_{tm7} \quad (Eq\,4.8)$$

$$W = 0.0315_{tm1} + 0.2021_{tm2} + 0.3102_{tm3} + 0.1594_{tm4} - 0.6806_{tm5} - 0.6109_{tm7} \quad (Eq\,4.9)$$

TCT components have been generated only for Landsat 7 ETM+ data as for other data sets dimensionality is only 4 spectral channels. Figures 4.15 and 4.16 show the TCT for 01-Oct-2000 and 19-Nov-2006 images respectively. It is clearly identified on these images, soil, vegetation and water bodies have been enhanced by TCT. We can identify there is not much vegetation (Fig 4.16 b) is visible in these images as agricultural fields are in initial stage. These components have been used while performing classification and waterlogging assessment.

From the results of supervised classification with raw data, NDVI, NDWI, TCT and DEM has been used while supervised classification along with raw data to separate agriculture fields (current fallow) from built up class and barren, and shadow from water bodies.

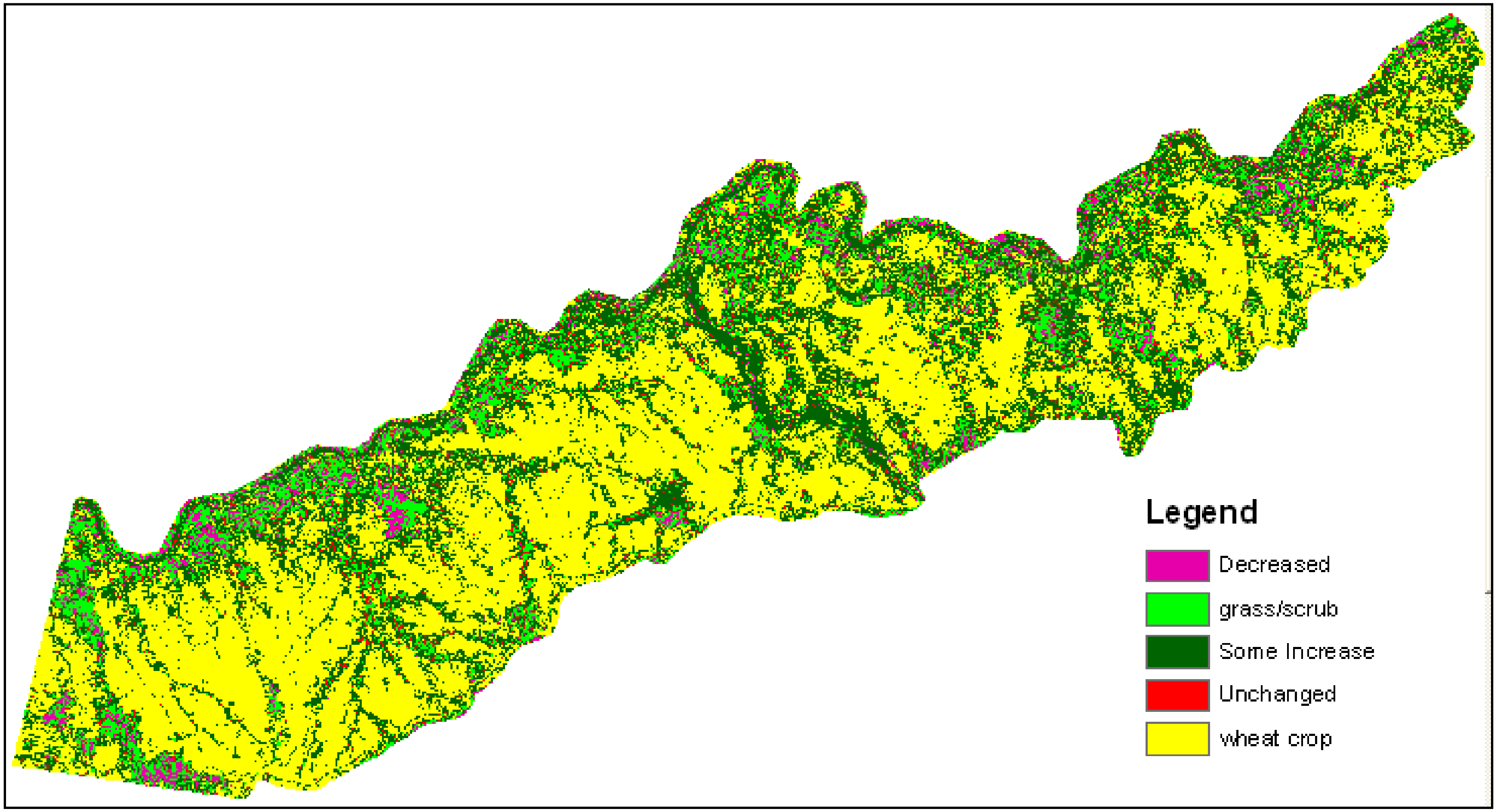


Figure 4.9 Change between Dec 95 and Feb 96 IRS LISS-I images

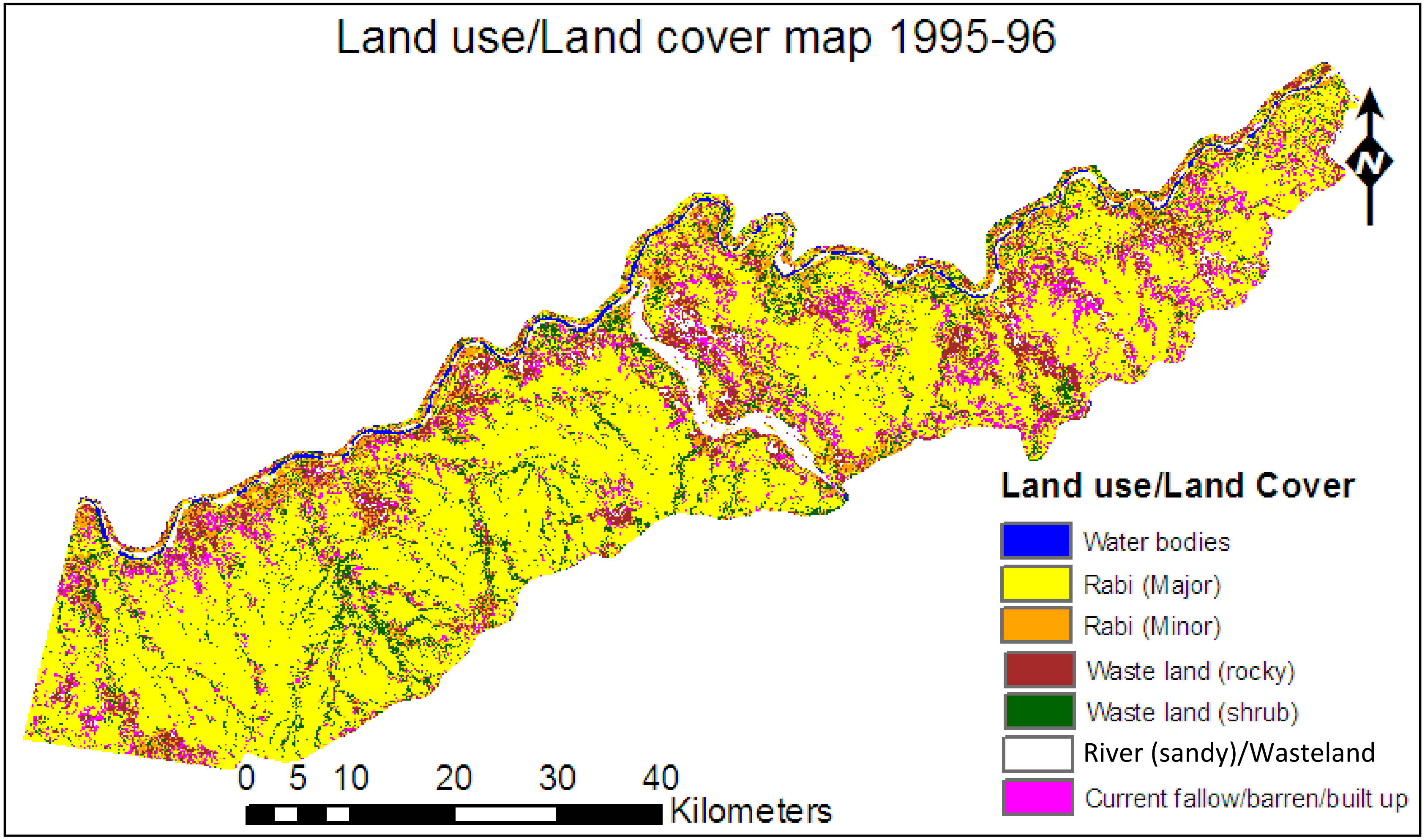


Figure 4.10 LULC map from IRS 1B- LISS I Data for the year 1995-96.

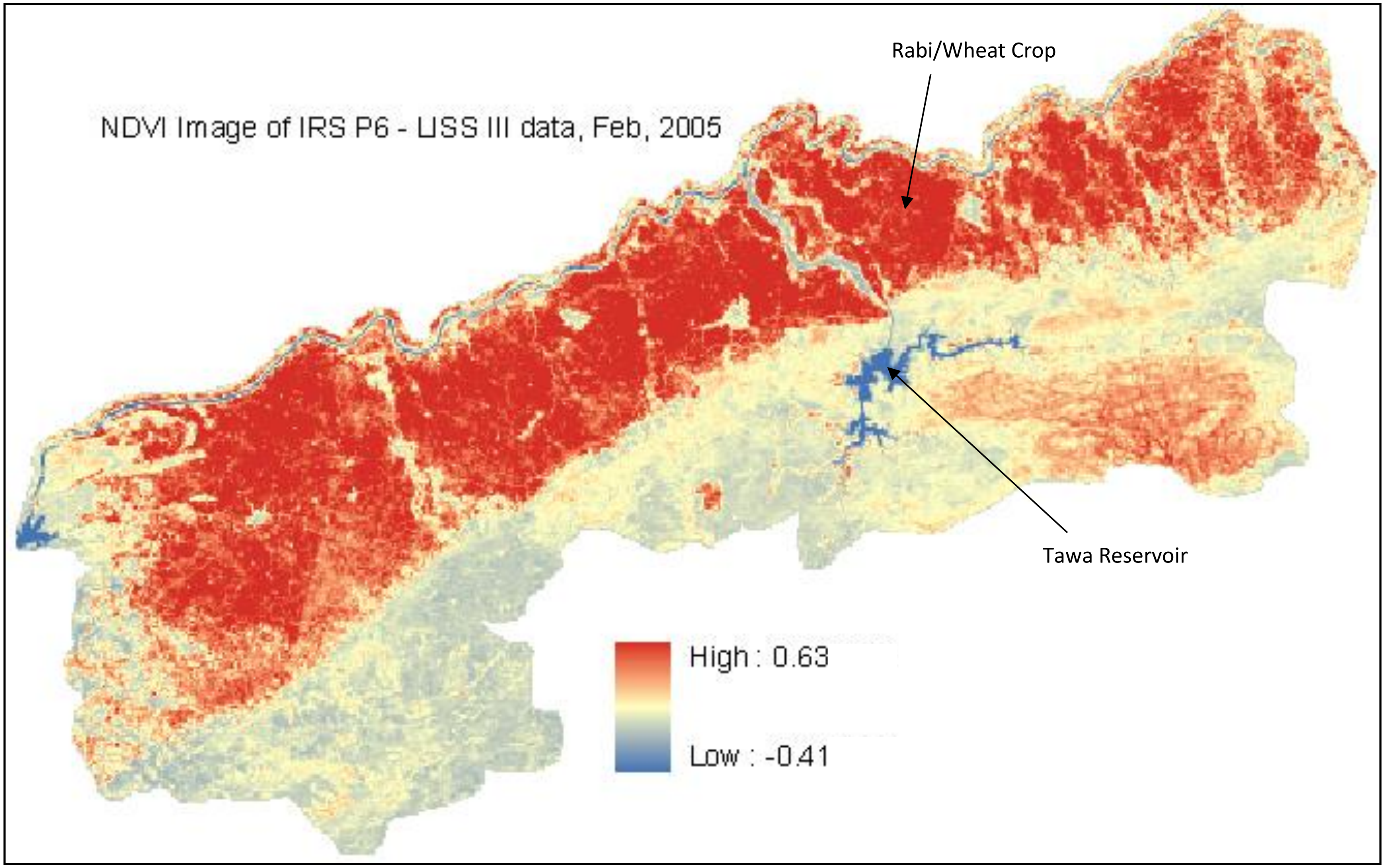


Figure 4.11 NDVI image of IRS P6 LISS III data, Feb 2005

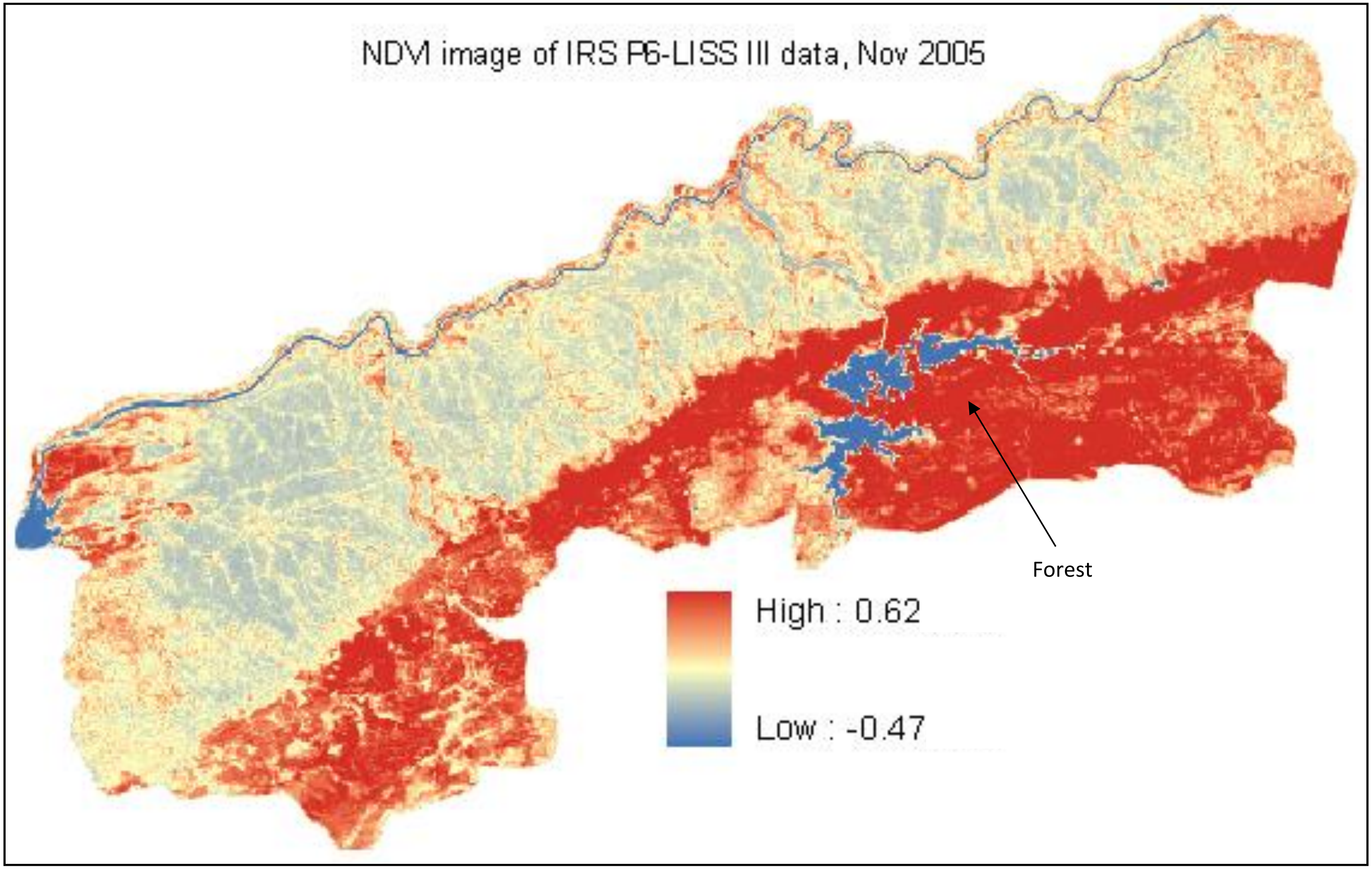


Figure 4.12 NDVI Image of IRS P6 LISS III data Nov 2005

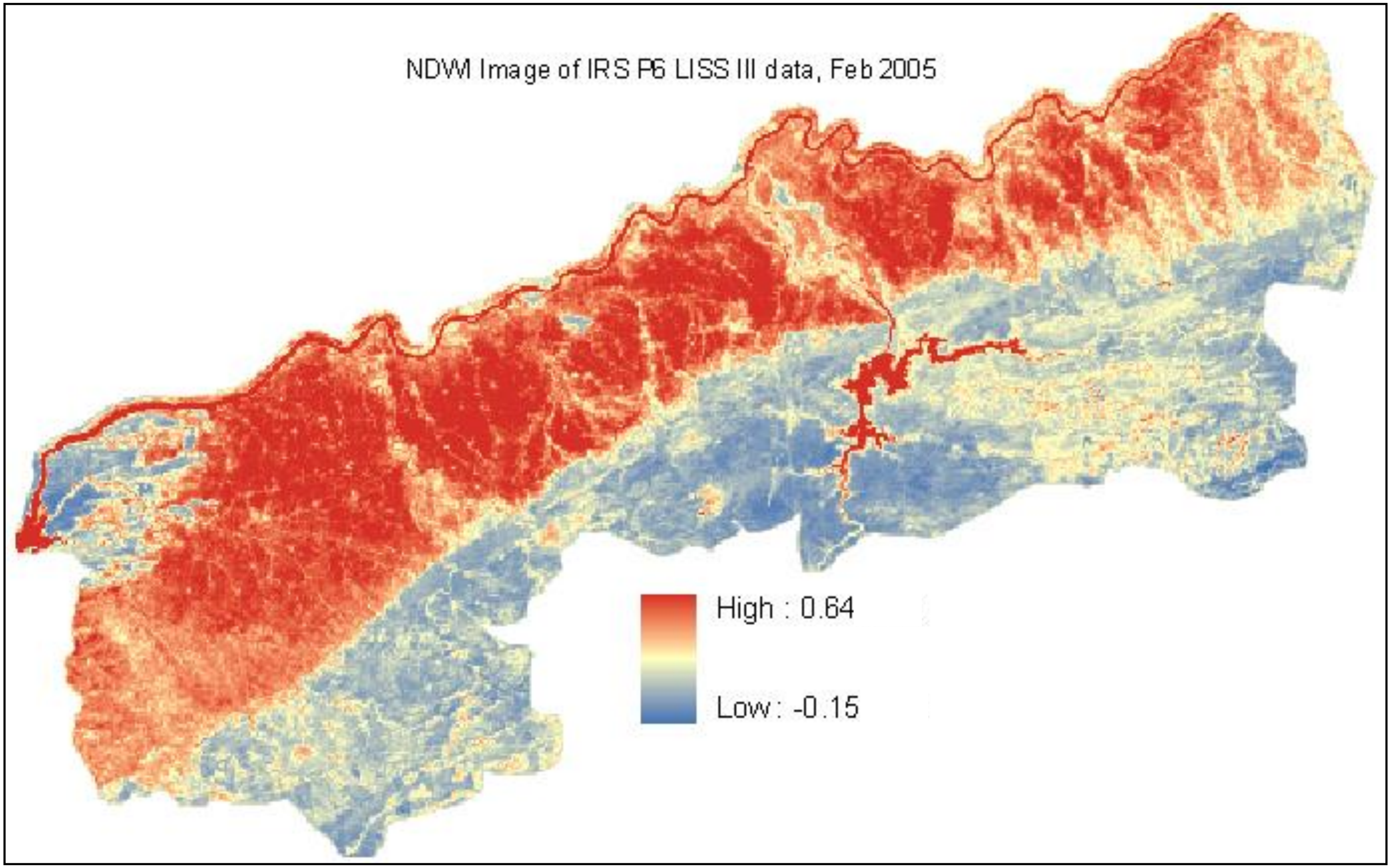


Figure 4.13 NDWI Image of IRS P6 LISS III data, Feb 2005

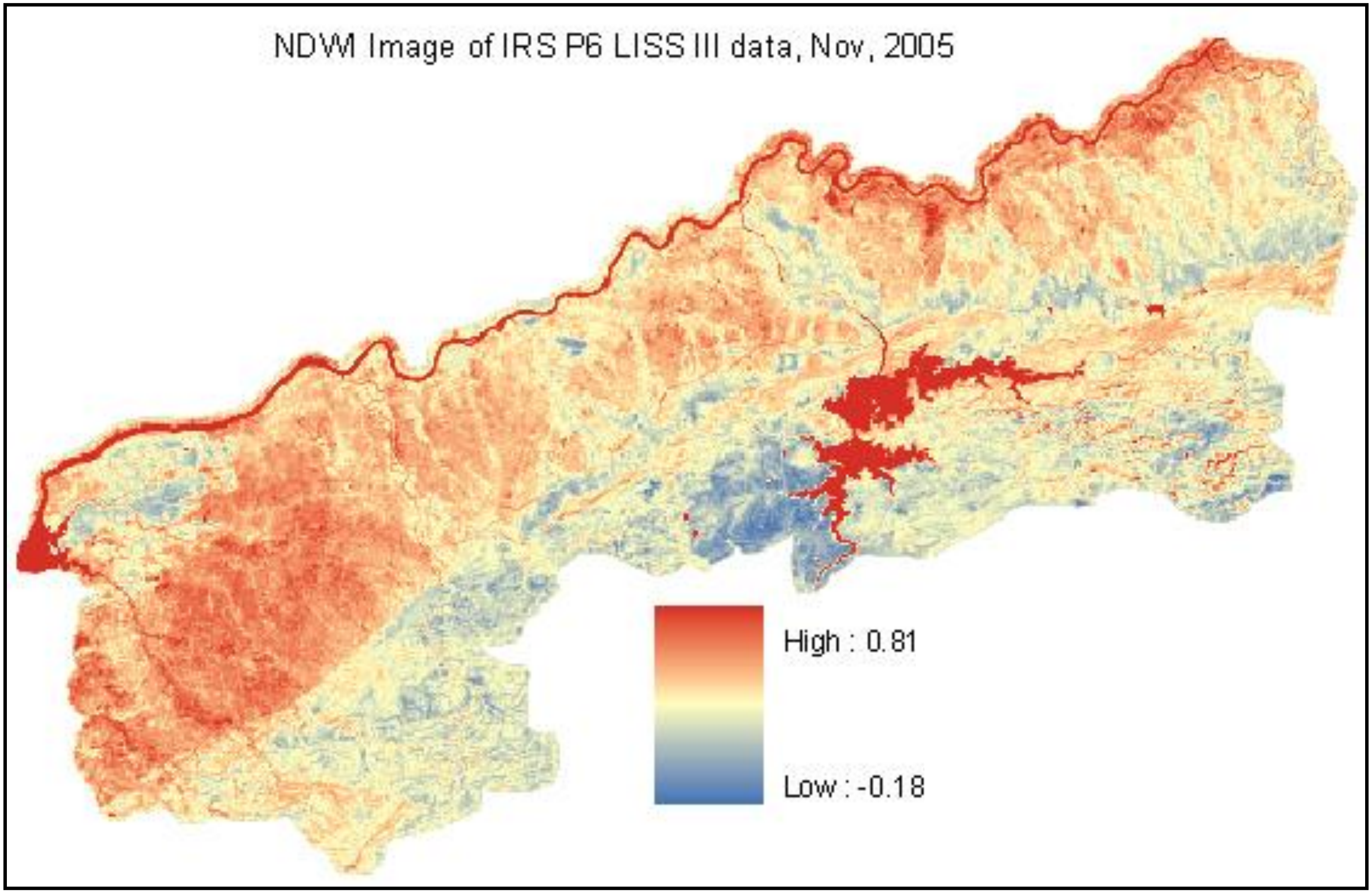
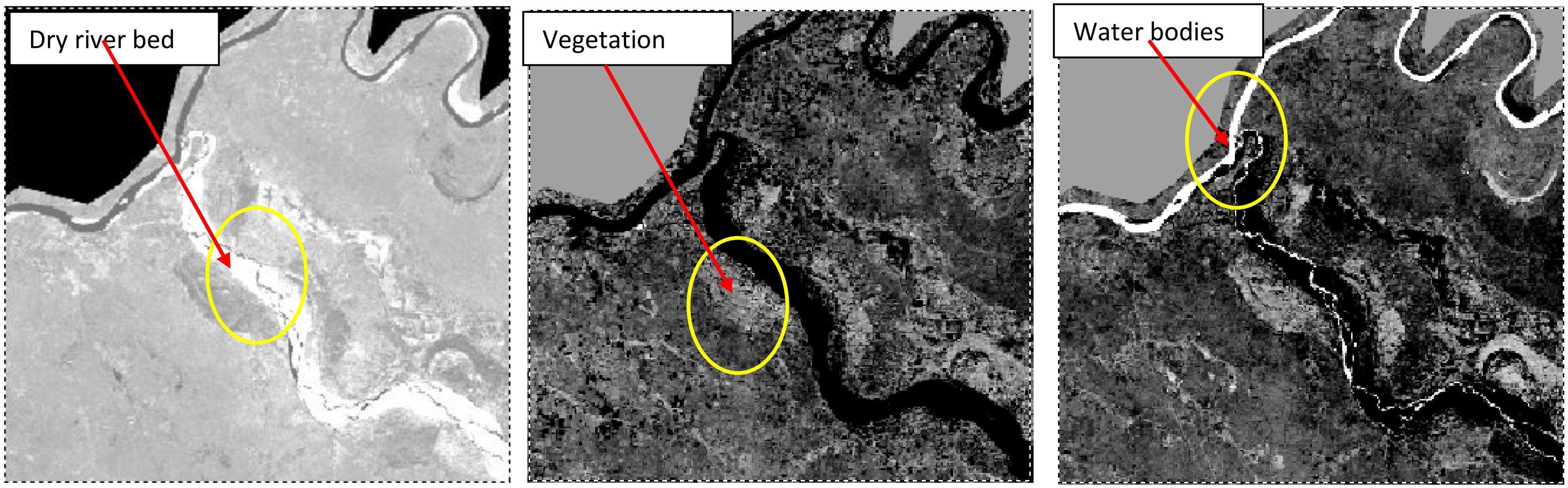


Figure 4.14 NDWI image of IRS P6 LISS III data, Nov 2005



(a) Brightness **(b) Greenness** **(c) Wetness**

Figure 4.15 TCT images for Landsat7 ETM Data, Oct 2000

(a) Brightness **(b) Greenness** **(c) Wetness**

Figure 4.16 Tasseled cap Images for Landsat7 ETM Data, Nov

4.5.2 Supervised Classification Using Vegetation Indices

As per Section 4.6.3 same procedure has been adopted to do classification using vegetation indices and DEM as an additional information along with raw data. Same training data has been used except for built up and current fallow which were refined to reduce the error. From separability index it has been identified for 27-Feb-2005, green, NIR, NDVI and DEM has got more separability for the selected signatures. For 18-Nov-2005, Red, NDWI and DEM has got maximum separability and for ETM data for both datasets, there is no change for the selected training data while using TCT components and DEM for classification (Table 4.1). So it did not affect the separability index. Maximum separability has been achieved for all band combinations. However water feature in the fields have been enhanced with TCT wetness component in ETM+ data. In all the cases built up is mixed with barren land. Rabi (minor) crops have been identified properly as compared to raw data classification.

Table 4.1: Transformed Divergence Separability for various datasets using vegetation indices and DEM

Year	Data	Best Separability	Index	
		Band Combination	Average	Min
27 Feb 2005	IRS P6 LISS III	B1(Green), B3(NIR), DEM & NDVI	1997	1733
18 Nov 2005	IRS P6 LISS III	Red(B2), NDWI &DEM	1981	1714
19 Nov 2006 01-Oct-2000	ETM+	No change between any band combination	2000	2000

Classification has been done using the best band combination mentioned in Table 4.10 for all the data sets. Classified images using vegetation indices have been shown in Fig 4.25 to 4.30. Area of different land use/land cover classes using vegetation indices for different datasets has been given in Table 4.2. Further it is important to assess the accuracy of the classified datasets to know how well the classification and training data is.

4.5.3 Accuracy Assessment

One of the most common forms of expressing classification accuracy is the preparation of a classification error matrix (confusion matrix or contingency table). Error matrix compare on category by category basis, the relationship between known referenced data and the corresponding results of an automated classification. In the present study accuracy assessment has been done by using stratified random method so as to represent the samples according to the number of pixels in each land use/land cover class. A general guideline for sample size is a minimum of 50 samples for each class category to be included in the error matrix. Further if the area is very large (more than a million acres) or the classification has a large number of vegetation or land use/land cover classes (more than 12 categories), the minimum number of samples should be increases to 75 or 100 sample per category (Congalton and Green, 1999).

Table 4.2: Error matrix showing classification accuracy of 18-Nov-2005 IRS P6 LISS III data

Classified Data	Reference Data											
	Water Bodies	Crops (noncom)	Rabi (minor)	Rabi (major)	Deciduous (moist)	Barren	River (sand)	built up	rocky outcrop	Dry fields	Row Total	UA (%)
Water Bodies	87	0	0	0	0	0	0	0	0	0	87	100.0
Crops(noncommand)	3	11	1	0	0	0	0	0	0	0	15	73.3
Rabi (minor)	0	3	39	4	0	0	0	3	0	0	49	79.5
Rabi(major)	0	1	1	231	0	0	0	0	0	0	233	99.1
Deciduous (moist)	0	0	0	0	216	0	0	0	9	5	230	93.9
Barren	0	0	0	0	0	59	2	6	0	8	75	78.6
River (sand)	0	0	0	0	0	3	48	1	0	0	52	92.3
built up	0	0	2	0	0	10	0	23	0	12	47	48.9
rock outcrop	0	0	0	0	4	0	0	0	81	0	85	95.2
Dry fields	0	0	2	0	0	13	0	12	0	100	127	78.7
Column Total	90	15	45	235	220	85	50	45	90	125	1000	
PA (%)	96.6	73.3	86.6	98.3	98.1	69.4	96.0	51.1	90	80.0		
overall accuracy	**89.5%**											
KHAT	0.87											

Table 4.3 shows the representative randomly selected sample pixels from the reference image of supervised classification using vegetation indices and DEM along with raw data. However this criteria has not met with rabi (minor) crops case in this study. By observing the confusion matrix overall accuracy of the classification is good. But for built up and current fallow, current fallow and barren there is a confusion. Forest classes are not mixed with any other class except (rock outcrop) as DEM has been used as additional information in this case. Major crops (wheat) have been classified accurately. There is no misclassification of water

bodies also. KHAT ($\hat{k}$) statistics is a measure of difference between the actual agreement between reference data and an automated classifier and the chance agreement between the reference data and a random classifier. $\hat{k}$ can be defined as

$$\hat{k} = \frac{\text{observed accuracy} - \text{chance agreement}}{1 - \text{chance agreement}} \qquad \text{(Eq 4.10)}$$

In the error matrix it shows $\hat{k}$ is 0.87, represents the observed classification is 87 percent better than one resulting from chance. Classification accuracies for built up and barren are poor whereas water bodies, major crops, forest are classified accurately. Error matrix reveals that NDWI and DEM along with raw data have enhanced the classification accuracy as compared to Raw data classification. NDWI enhance the water pixels in the command area. So this classified image can be used to prepare a LULC map for the study area. The respective classified images have been shown in Fig 4.17 to Fig 4.21.

Table 4.3: Area under different land use/land cover using vegetation indices

Date	27-Feb-05	18-Nov-2005	19-Nov-2006	18-Nov-05	
	Part of Tawa Command			Tawa Command	Hoshangabad Dist
Sensor	IRS P6 LISS III	IRS P6 LISS III	ETM+	IRS P6 LISS III	
Land Use/Land Cover	Area in (Ha)				
Built up land	7433	6685	3435	7812	8460
Rabi (major) crop	167575	182866	131030	275324	334215
Rabi (minor) crop	57397	41537	70413	71093	90945
Current fallow/barren	27621	21458	78000	61218	77628
Crops (non command)		6459	-	8440	93286
Deciduous (moist)	16968	639	-		301074
Water Bodies	5300	5852	2711	12431	32249
Water bodies (canal, pond)			2562	-	
River (sand)	6799	7638	6140	8332	10424
Barren/Rocky	13734	21139	-		49202
Waste land(rocky)		0.17		24266	88517

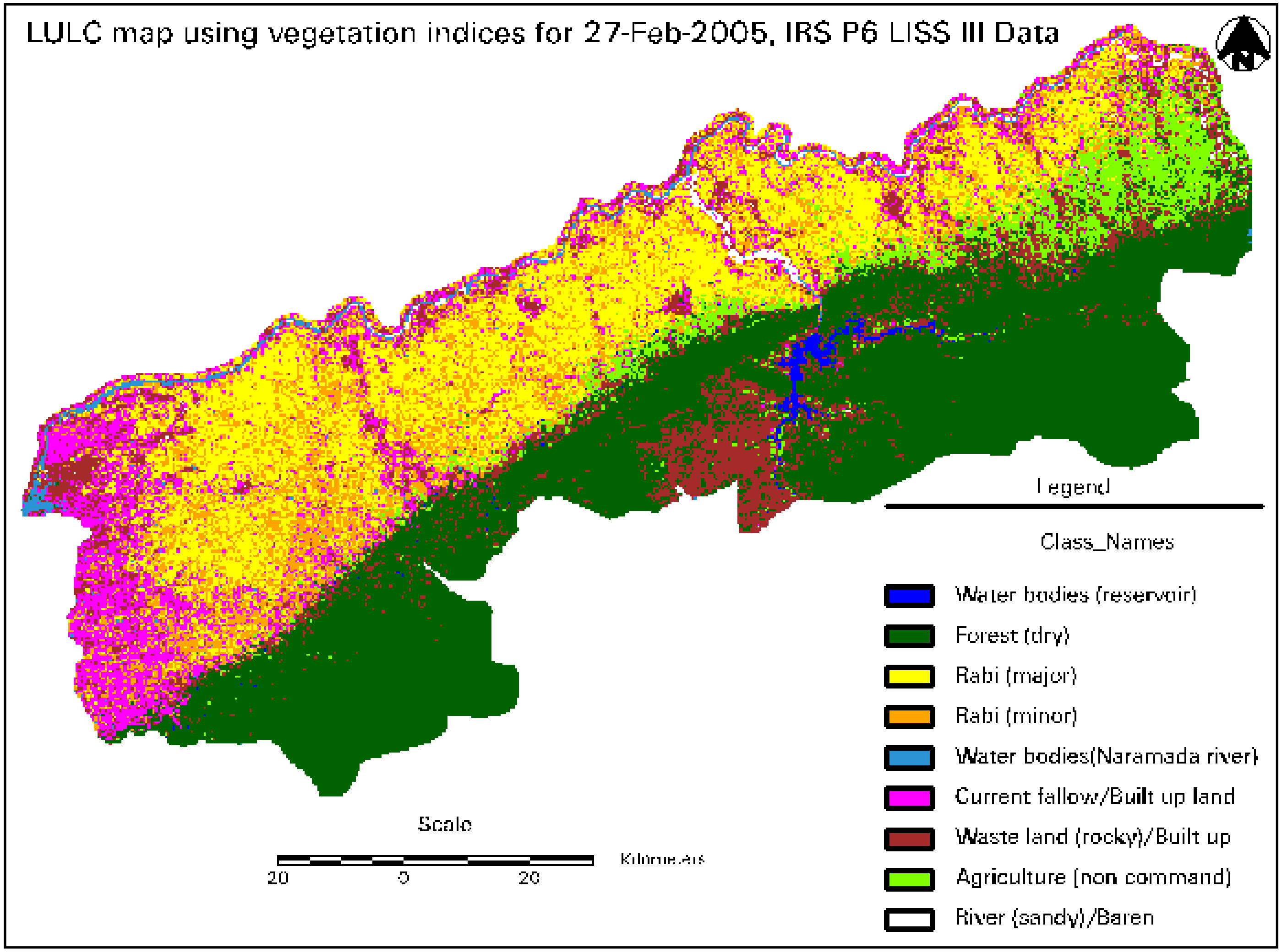


Figure 4.17 Classified Image using vegetation indices for 27-Feb-2005 IRS P6 LISS III data

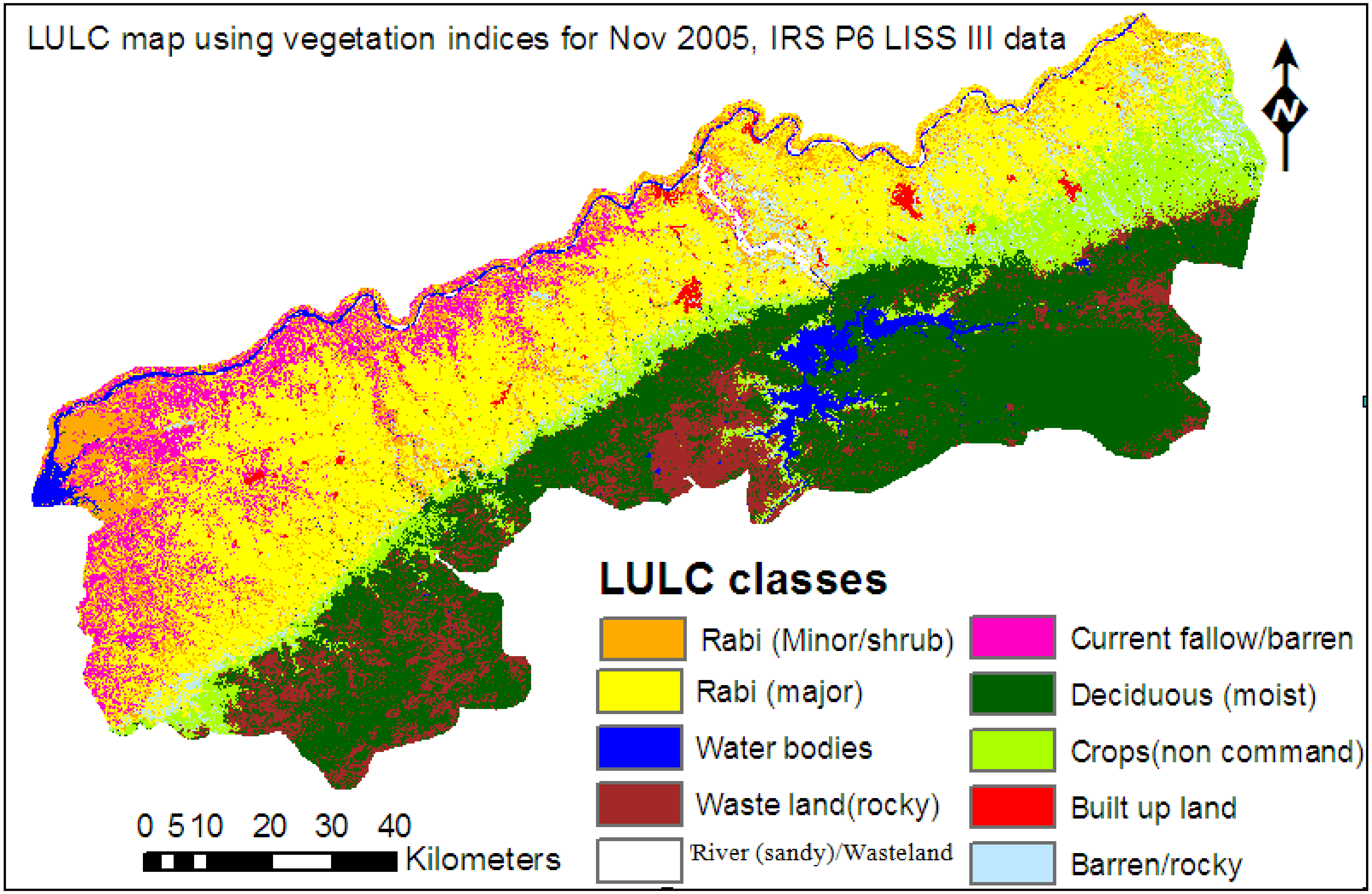


Figure 4.18 LULC map using vegetation indices for the year Nov 2005, IRS P6-LISS III data

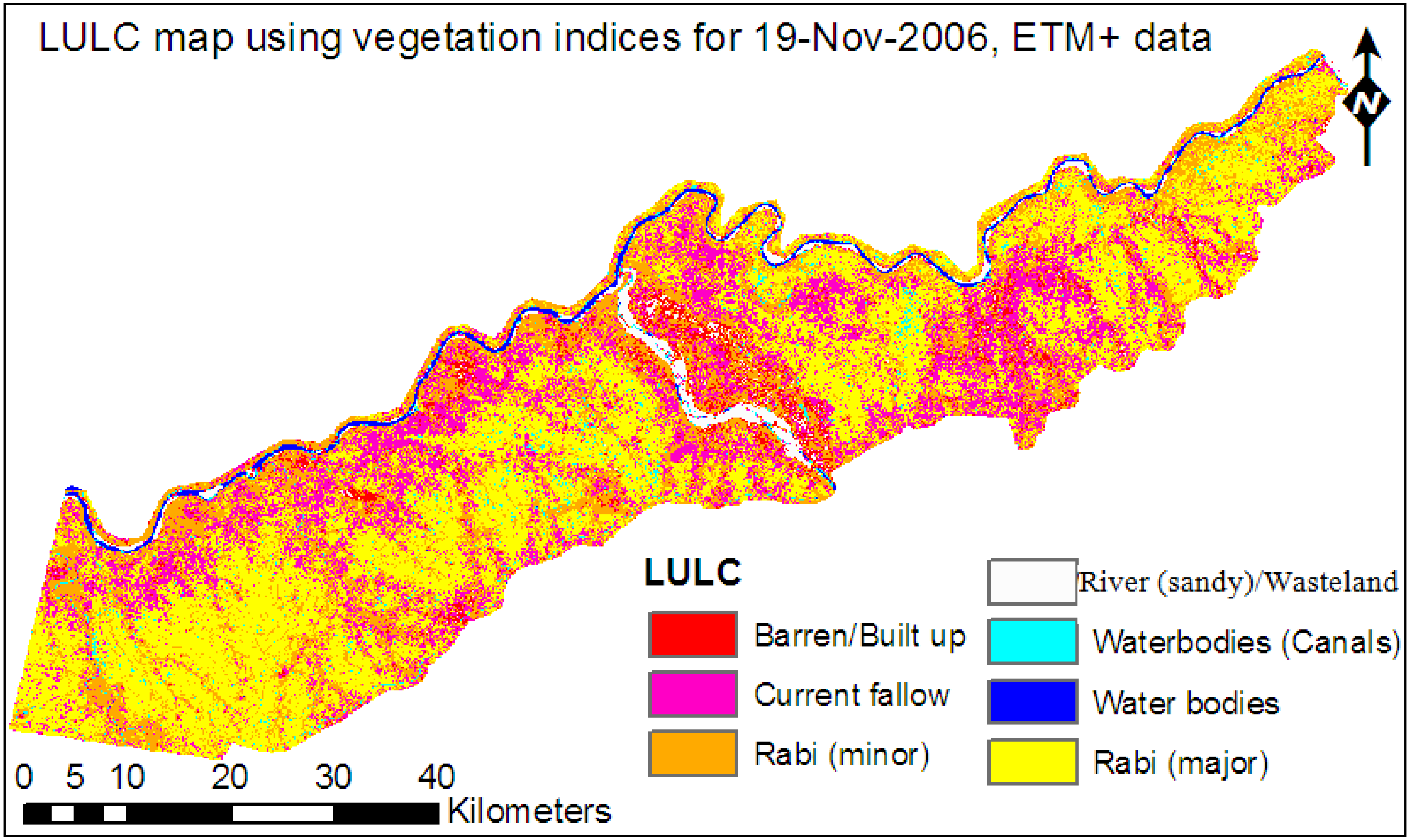
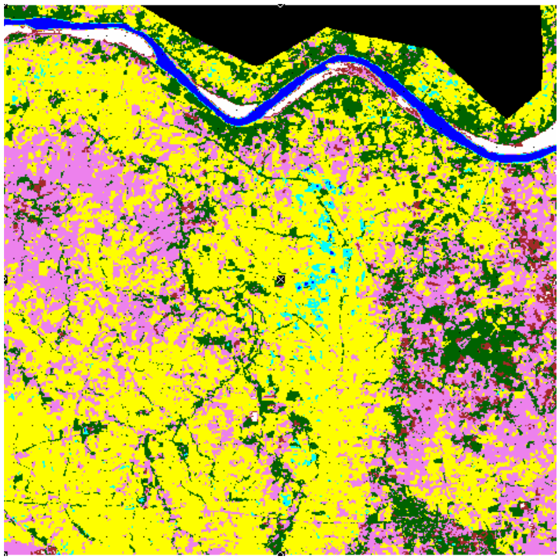
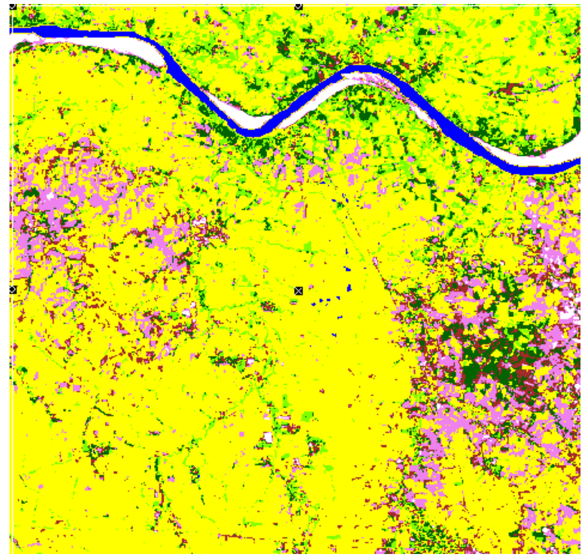
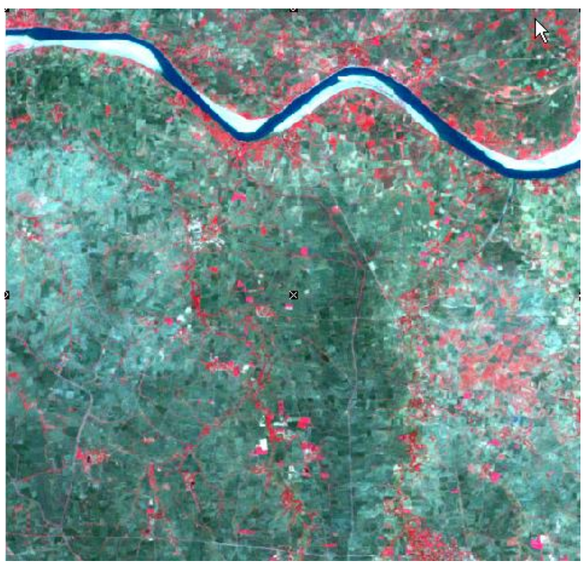


Figure 4.19 LULC map of the TCA using TCT For 19-Nov-2006, Landsat 7 ETM+





(a) (b)



(c)

Figure 4.20 Classified image showing (a) with TCT, (b) with raw data, and 9c) Raw image

It is seen from Fig 4.20 (a) water bodies (canal, pond) has come up as separate class and built up area has been identified more clearly as compared to classified images other raw data. And also there is clear distinction between fields with irrigation (wet fields) and with no irrigation (current fallow) were separated without mixing with other classes by using TCT. Table 4.4 shows the area under different land use/land cover classes. Major crop on October image is Soyabean as it is kharif season. Figure 4.21 shows the classified image of this data.

Table 4.4: Area under different land use/land cover for 1st Oct, 2000 ETM Data

Date	1-Oct-00
Sensor	ETM+
Land Use/Land Cover	Area in ha
Water Bodies	5993
Kharif (minor) crops	59905
Kharif (Major) crops	142106
Current fallow/waste land/built up	76028
River (sand)	5655
Barren	4599

Method of classification is based on data availability and type of information to extract from the images. LULC map is very useful as a basic data in any application based studies. So care has been taken to separate classes accurately with the above methodologies for different datasets. This is important input for calculating recharge and evapotranspiration (ET).

After observing the supervised classification with raw data and using vegetation indices and DEM as an additional information, classification accuracy has been enhanced using vegetation indices and DEM. Forest class is totally separated from command area. More number of water pixels have been identified on 18-Nov-2005 image as a result of NDWI. Similarly with ETM data water pixels in command have been separated from water bodies. Current fallow land fields having moisture content have been separated more clearly in ETM + data. However in 1st Oct, 2000 ETM+ data there is a mixing between built up, barren and current fallow. Built up class is mixed with current fallow in case of IRS P6 data also. So built up class is recoded manually to represent as a separate class. This LULC maps are useful while conceptualization of ground water modeling for boundary conditions like recharge etc. Fields under water stress have been identified by TCT wetness component and NDWI.

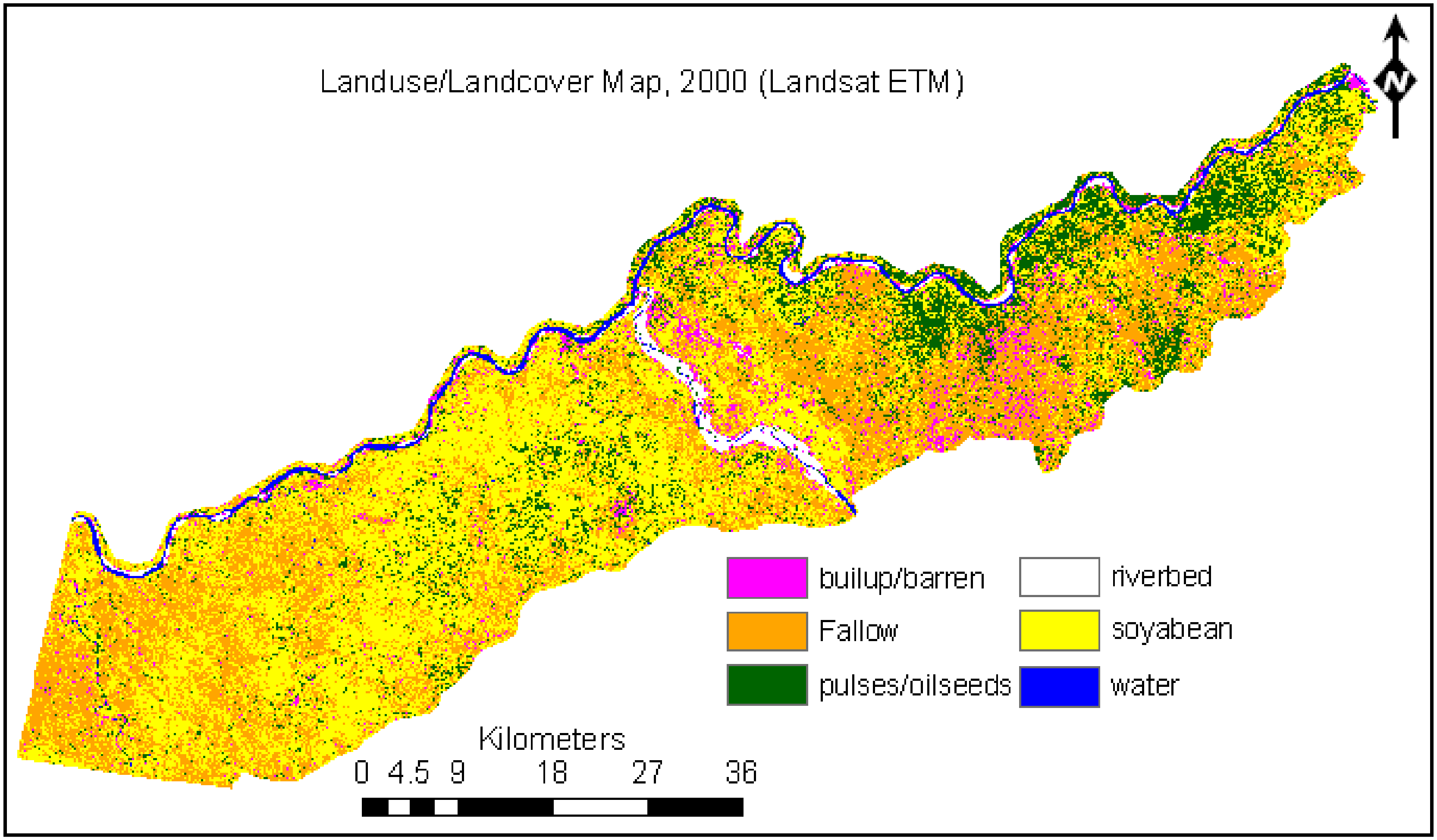


Figure 4.21 LULC map for the year 2000 delineated from Landsat ETM+

CHAPTER 5
LANDUSE MAPPING AND CHANGE DETECTION

5.1 GENERAL

A common aspect in many water management studies is the location of problem, position within the command area and the spatial inter-relationship between physical characteristics of system (i.e. topography, land use, soil type etc.) and other natural parameters. The success of application based research depends upon qualitative and quantitative aspects of datasets. Remote sensing along with GIS tools can provide critical spatio-temporally distributed data and inputs for parameterizing many hydrological, hydraulic and water management models to be used for water resources management in irrigated command area. This can be accomplished through creation of a geographic database which incorporates both spatial and non-spatial data. The spatial data consist of thematic information generated from topographic maps, remotely sensed images, literature and conventional surveying, while non-spatial data comprises of attribute information derived from various sources, such as field visits, census records and meteorological records.

Remote sensing technique can be used for the generation of land use land cover information and land use change detection in the command area of irrigation projects. While GIS can help in creation of geographical database and to store, retrieve and analyse both spatial and non-spatial data/information.

Land use mapping in command area of irrigation project requires spatial and temporal data. Remote sensing data satisfy both these requirements. A large number of sensors with varying spatial, temporal and radiometric resolutions are available presently to capture the data regarding earth surface all over the world. One of the best approaches to organize, manage and analyze remote sensing data is to integrate it with GIS. A GIS data generally refers to digital formats comprising primary and derivative layers. The important primary layers include geology, soil, land use land cover, contour, drainage, canal network and administrative boundaries etc. These primary layers are synthesized to create the derivative layers, such as hydrogeology, land capability, digital elevation model etc.

The non-spatial data include socio-economic data, agricultural productivity data and ground based observation related to natural resources, which act as collateral data to spatial data. The spatial and non-spatial data if used conjunctively provide meaningful information that can be used for various resources management related applications. Presently, Remote sensing and

GIS are the basic tools along with conventional modelling techniques to assess natural resources for planning and management which requires huge volumes of datasets.

In this chapter, methodology of GIS database generation and preparation of various spatial and non-spatial information layers is discussed followed by derivation of land use land cover information through image processing of satellite data. The methodology adopted for the study starting from data collection to final analysis is diagrammatically represented in Figure 5.1

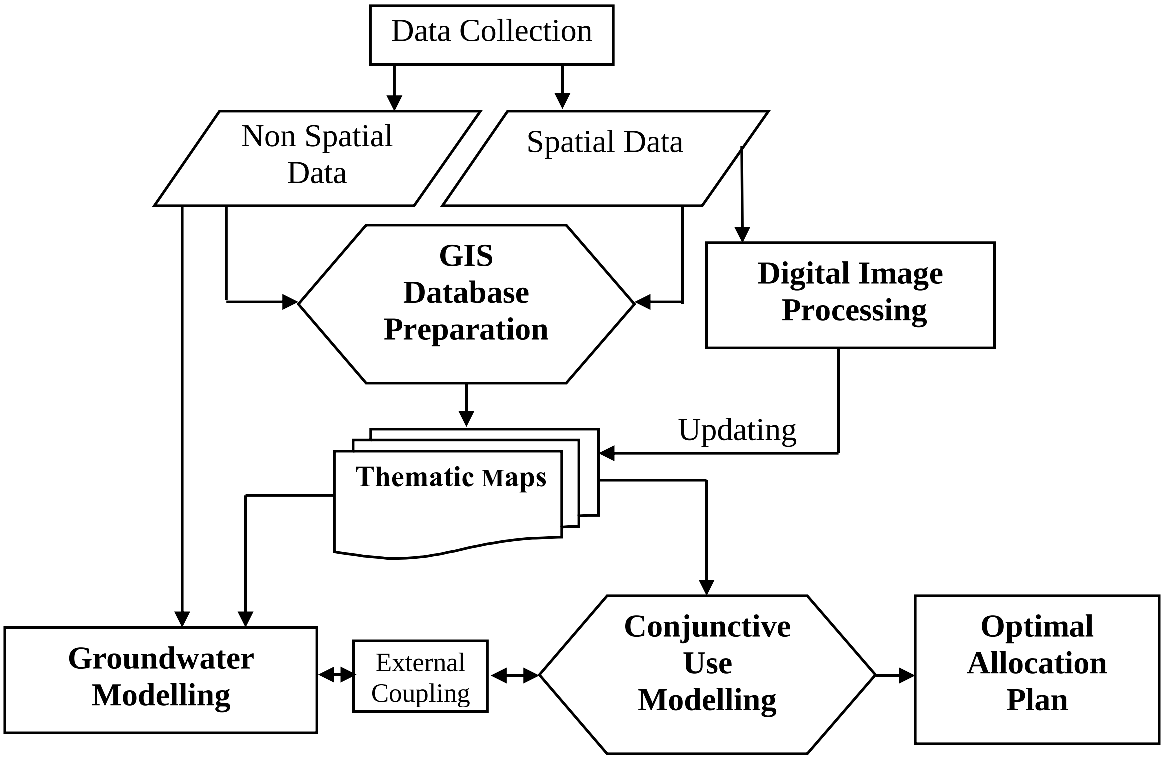


Figure 5.1 Flowchart of the adopted methodology for conjunctive use modelling

5.2 PREREQUISITE OF GIS DATABASE GENERATION

After identification of the problem, data collection is the prerequisite step before going for database generation and further analysis. Reliable and authentic data is important to carry out application based research as the outcome of the study largely depends upon the spatial and thematic completeness of the data. Before carrying out any analysis, the data collected needs to be thoroughly examined and checked in order to have an error free analysis. The method of checking errors for each dataset is different. Water table data has been checked with rise and fall analysis for each well. Location of observation wells has been checked with village name as well as with latitude and longitude to prepare spatial map. Litholog data has been compared with reference to geology maps obtained from Geological Survey of India (GSI), Survey of India (SOI) and literature from different sources. Similarly, stage discharge data has been checked with rise and fall analysis on a monthly basis. Finally, tabular database has been prepared in excel spread sheets. Types of data collected and steps before GIS database creation is explained sequentially in Figure 5.2.

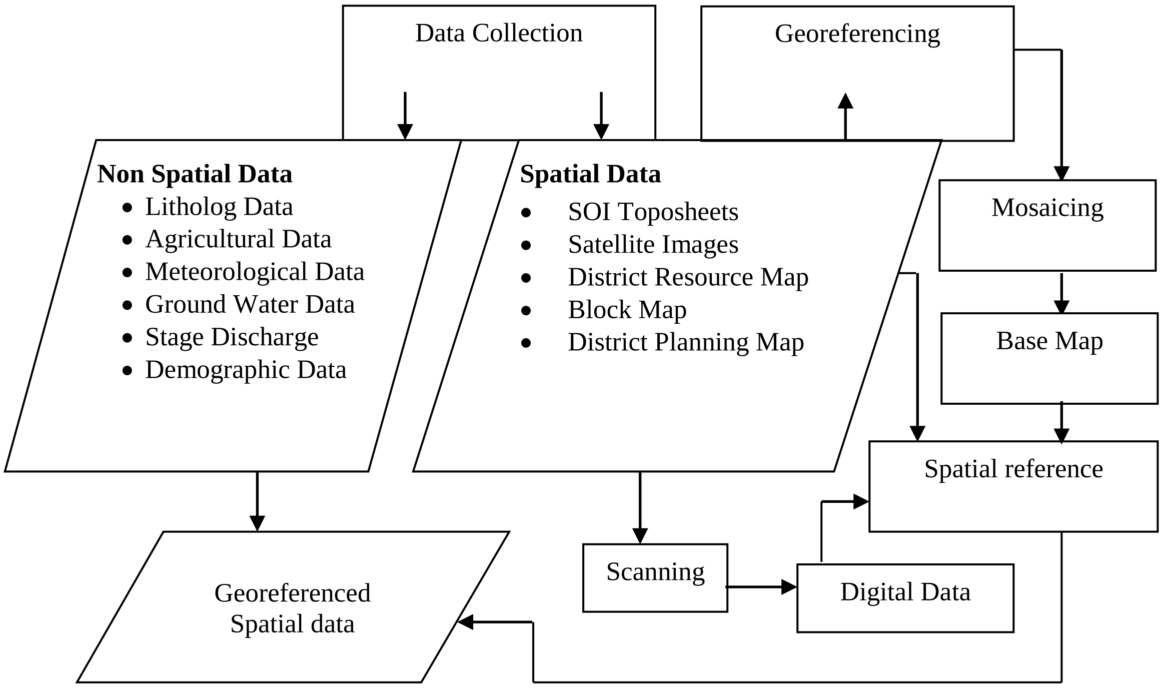


Figure 5.2 Flowchart showing data collection for the study

5.3 GIS DATABASE GENERATION

Database generation is one of the foremost and indispensable steps for any task related to planning, management and assessment of natural or manmade resources. It is a huge and challenging task as it involves geo-referencing of different datasets, generation or compilation, processing and analysis, formatting and structuring, storing and retrieval of spatial (maps) and non-spatial (tabular and attribute) data. It is important that the data should be presented in the form of maps to facilitate spatial analysis. In this context, standard scales and format of map is essential. To ensure uniformity, the base maps are prepared with the help of topographical map sheets. The prepared base maps will be utilized in the preparation of thematic maps for transferring the thematic details as derived from the satellite data analysis. The steps involved in GIS database generation are described below.

5.3.1 Geometric Correction

Remotely sensed images captured by a satellite are representations of the irregular surface of the Earth. Even, images of seemingly flat areas are distorted due to Earth's curvature and the physical limitations of sensors being used. Rectification is necessary for remotely sensed data to project it in planer coordinate system. Rectification is the process of transforming the data from one grid system into another grid system using a geometric transformation. Though the scanning and digitization of hard copy maps produces images that are planar, but these images do not contain any map coordinate information. These images need to be georeferenced.

Geo-referencing refers to the process of assigning map coordinates to image data. The image data may already be projected on the desired plane, but not yet referenced to a proper coordinate system. Rectification, by definition, involves geo-referencing, since all map projection systems are associated with map coordinates. Image-to-image registration involves geo-referencing only if the reference image is already georeferenced. Registration is the processes of making an image conform to another image.   In many cases, images of one area that are collected from different sources may need to be used together. To compare separate images pixel by pixel, the grids of each image must conform to the other images in the data base. After rectification, pixels of the new grid may not align with the pixels of the original grid, thus the pixels have to be resampled. Resampling is the process of extrapolating data values for the pixels on the new grid from the values of source pixels. Mostly researchers prefer the nearest neighbour resampling method, as very small amount of spectral integrity is lost in this technique. Figure 5.3 shows the steps involved in geometric correction.

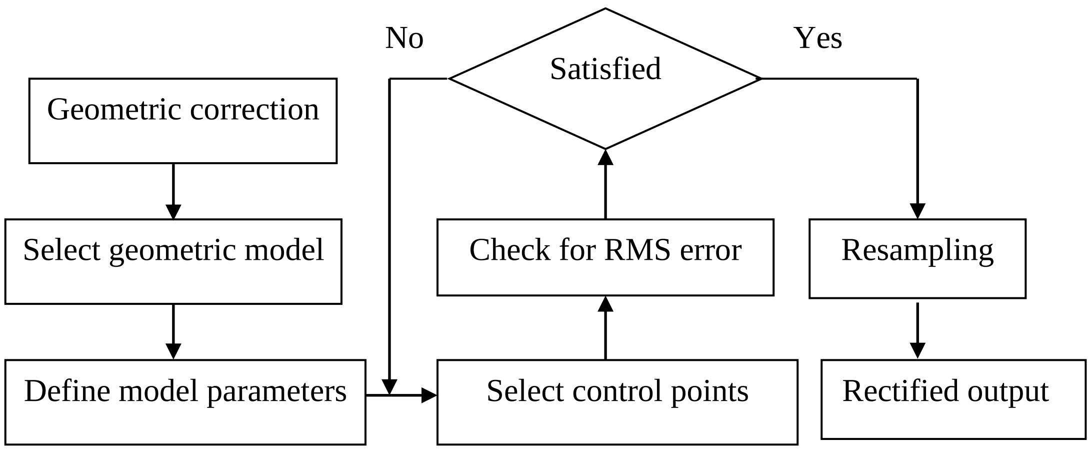


Figure 5.3 Steps for geometric correction of spatial data

Survey of India (SOI) topographical map sheets use Polyconic projection and the same has been adopted for georeferencing and image to image registration. Georeferencing parameters adopted here are given in Table 5.1. While giving reference coordinates for georeferencing of topographical map sheets latitude and longitude values should not be given as it is a spherical coordinate system which is not associated with map projection. These latitude and longitude values have been converted into linear units. Conversion has been done with the available softwares by providing the input and output projection parameters.

Table 5.1 : Geo-referencing parameters for the present study

Parameter	Method
Projection	Polyconic
Longitude of central meridian	77°45'E
Latitude of origin	22°N
Transformation	2nd order polynomial
Ellipsoid	Modified Everest
Datum	Indian-1954
Resampling	Nearest Neighbour
Cell Size - topo sheets	6 m
Cell size for satellite data	24 m

Mosaicing has been done for all the topographical map sheets to get a master image or base map, since study area is spread over 20 topographical map sheets of 1:50000 scale. This base map has been used as a reference image to register all other spatial data. Image to image registration has been carried out for remote sensing datasets, district resource map, district planning map, canal network map, command boundary map and block maps covering the whole study area with reference to base map. While doing registration; well defined road cross sections, canals, railway lines and other prominent and permanent points have been chosen as ground control points (GCP) to avoid distortion. Care has been taken to bring the root mean square error (RMSE) to a minimum and within permissible limit. In this study, since the topographical map sheet at 1:50000 scale has been scanned at 300 dpi, the default pixel size will be 4.23 m. Therefore, RMSE in registration process should be less than this pixel size. Geometric correction and mosaicing has been done in ERDAS Imagine 8.6. The RMSE for the above maps while carrying geo-referencing is given in Table 5.2.

5.3.2 GIS Data Format

Relational database in GIS framework has generated using the Personal Geodatabase model available in ArcGIS 9.2. The geodatabase model defines a generic model for geographic information. This generic model can be used to define and work with a wide variety of different user or application specific techniques. Geodatabases contain feature classes and tables, and supports a model of topologically integrated feature classes, similar to the coverage model. However, it extends the coverage model with support for complex networks, topologies, relationships among feature classes, and other object-oriented features.

Table 5.2 : RMSE in geo-referencing of different datasets

Topographical maps				Other Data sets		
No	RMSE (m)	No	RMSE (m)	Data Set	Date	RMSE (m)
55B/16	0.36	55F/13	0.19	IRS IB LISS I	18-11-95	0.766
55B/15	0.25	55F/14	0.19		10-12-95	0.724
55/F2	0.17	55F/15	0.42		23-01-96	0.593
55/F3	0.43	55J/1	0.09		29-03-96	0.824
55/F4	0.38	55J/2	0.14	Resourcesat LISS III	22-02-05	0.436
55/F6	0.17	55J/3	0.27		13-11-05	0.579
55/F7	0.27	55J/5	0.08		27-02-05	0.478
55/F9	0.14	55J/6	0.11		18-11-05	0.518
55/F10	0.12	55J/9	0.20	Tawa Index Map	-	1.45
55/F11	0.16	55J/10	0.06			

Feature classes can be organized into a feature dataset or they can also exist independently in the geodatabase. Feature classes store geographic features represented as points, lines, or polygons, and their attributes; they can also store annotation and dimensions. All feature classes in a feature dataset share the same coordinate system. Once spatial reference for feature dataset is given there is no need to define spatial reference for each feature class separately. Thus, it becomes easy and simple to edit and manage GIS data in geodatabase format. For the present study, in personal geodatabase, one feature dataset has defined with spatial reference and in this dataset point, line and polygon feature classes have been generated to store different geographic features.

Figure 5.4 shows the methodology for preparing GIS database for the present study.

5.3.3 Digitization of Features

The data collection has been carried out in different phases and sources and was a time consuming task. First available data set was SOI toposheets. So, digitization has been done for various features which are available on these maps. Point, line and polygon feature classes were digitized to prepare various thematic maps. A point has been used to represent those features that are too small to be represented as areas (e.g. groundwater observation wells, pumping wells, points where litholog data is available, etc.). A line has been used to represent features that are linear in nature (e.g. canal network, transport network, contours or rivers). Since the project was commissioned during year 1975 to 1978 and available SOI toposheets were updated before 1978, some of the new canals of Tawa project were not visible on toposheets, hence, these canals have been digitized using Tawa index map and georeferenced remote sensing images of the area. Features like district boundary, geology of the area and soil type have been digitized as polygons

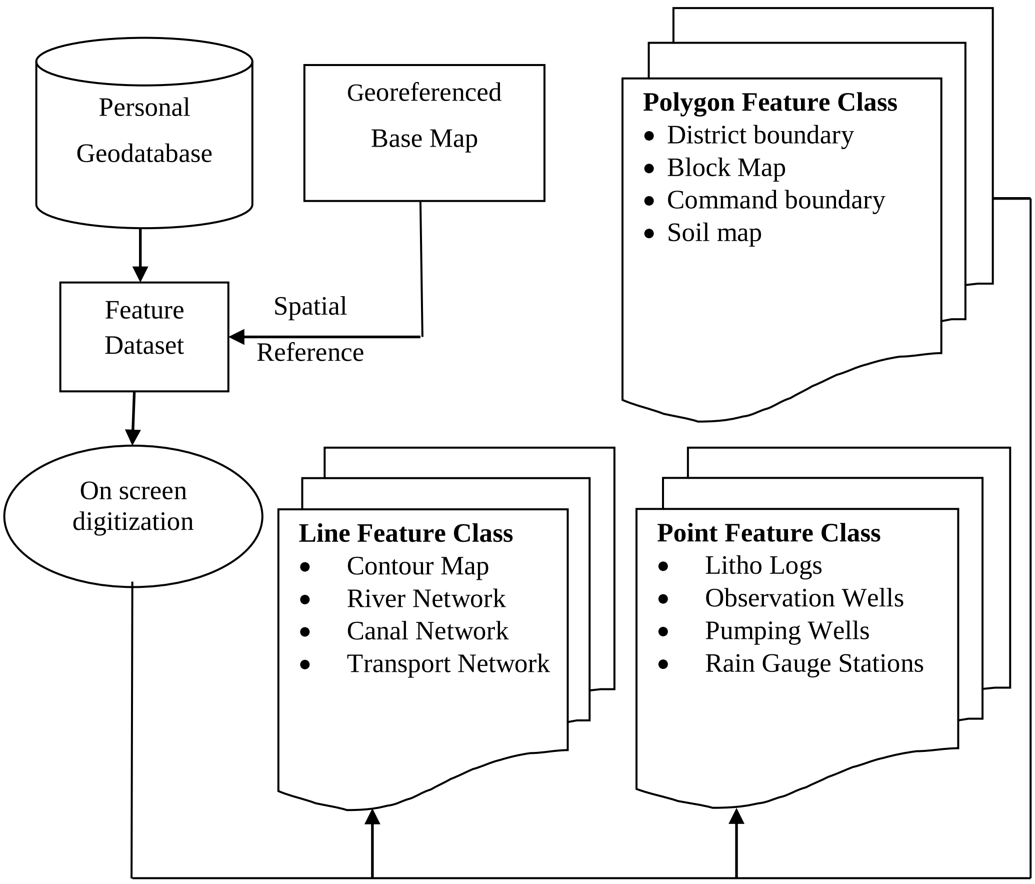


Figure 5.4 Flowchart for basic GIS database preparation

5.3.4 Generation of Thematic Layers

Various thematic maps prepared with the help of topographical map sheets, geological data and satellite images are described below.

5.3.4.1 Digital elevation model

Digital Elevation Model (DEM) is one of the important layers to study any aspect of water resources. The NASA's Shuttle Radar Topography Mission (SRTM) consisted of a specially modified radar system that flew onboard the Space Shuttle Endeavour during an 11-day mission in February of 2000, obtained elevation data on a near-global scale to generate the most complete high-resolution digital topographic database of Earth. NASA-JPL (Jet Propulsion Laboratory) provides global DEM of around 90 m spatial resolution and about 10 m accuracy in X, Y and Z direction (Rodriguez et al., 2005). This DEM (Figure 5.5) has been used in the present study to define the surface elevation in groundwater model and as ancillary data in land use land cover mapping of the command area.

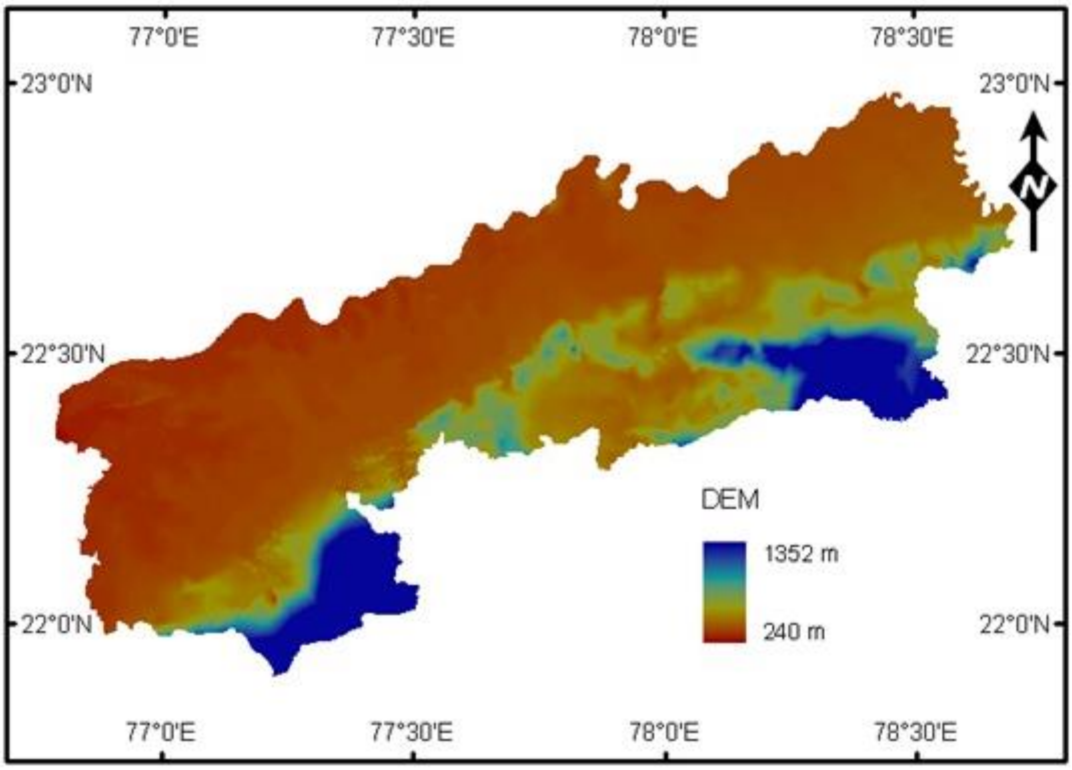


Figure 5.5 SRTM DEM of Hoshangabad district

5.3.4.2 Phreatic aquifer thickness map

Aquifer thickness map has been prepared from lithological data for the purpose of defining the hydrogeological boundary in groundwater model. Kriging (Oliver, 1990) interpolation method has been used to create the continuous surfaces of aquifer thickness. Further, this map is subtracted from DEM to get the elevation values with respect to mean sea level (msl).

5.3.4.3 Hydraulic conductivity

Hydraulic conductivity has been calculated by dividing transmissivity with saturated thickness of aquifer. Hydraulic conductivity varies from 1 to 64 m/day in Tawa Command Area (TCA). Figure 5.6 shows the hydraulic conductivity distribution for the TCA.

5.3.4.4 Location of observation wells

Observation wells in the TCA are shown in figure 5.7. Location of observation wells and location of Lithologs has been prepared by exporting tabular data to GIS format. All the thematic maps for the TCA are prepared in a GIS environment. This database is an input to remote sensing data interpretation, groundwater modelling and in conjunctive use modelling.

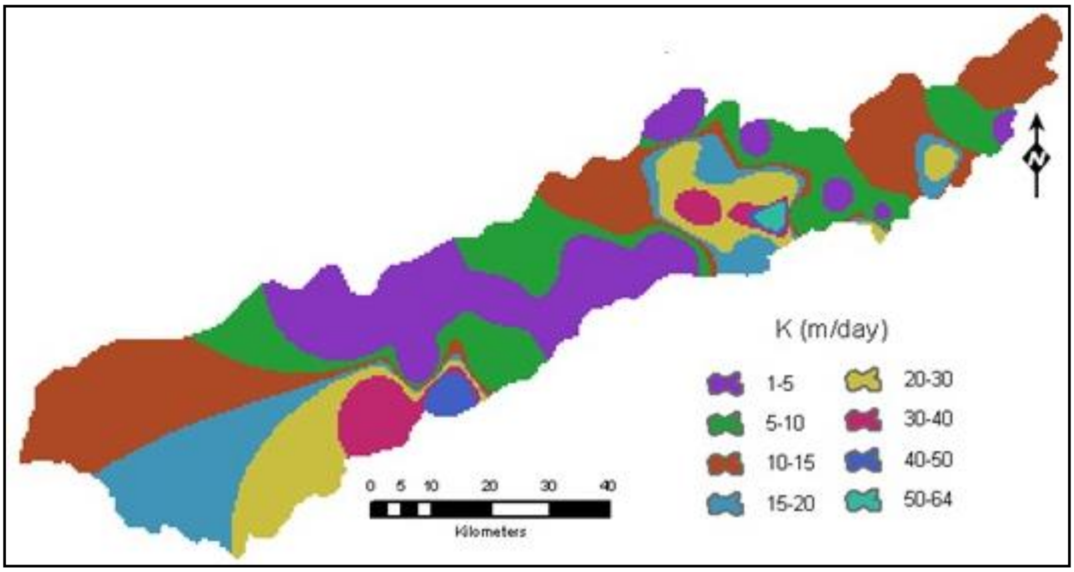


Figure 5.6 Spatial distribution of hydraulic conductivity of Tawa alluvial aquifer

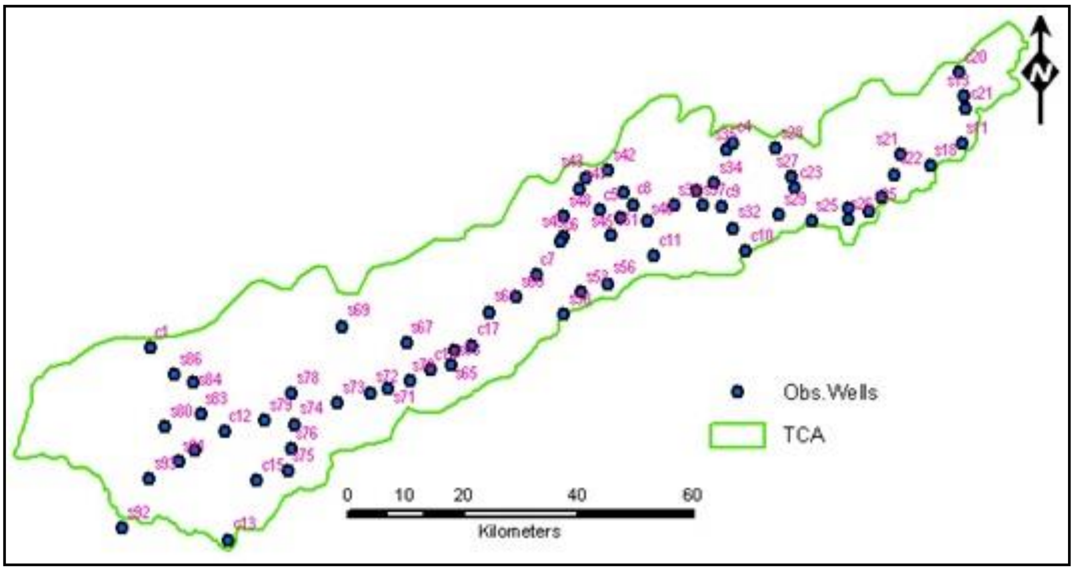


Figure 5.7 Location of observation wells in the TCA

5.4 REMOTE SENSING DATA PREPROCESSING

Digital image analysis is very important part of the present study. Remote sensing data is used to map the present/past state of the Tawa command. From satellite image analysis, one can estimate changes in land use land cover spatially and temporally. However, remote sensing data available is in generic format and needs some pre-processing before extracting useful information or parameters. Pre-processing functions involve those operations that are normally required prior to the main data analysis and extraction of information, and are generally grouped as radiometric or geometric corrections. Radiometric corrections include correcting the data for sensor irregularities and unwanted sensor or atmospheric noise, and converting the data so they accurately represent the reflected or emitted radiation measured by the sensor. Geometric corrections include corrections for geometric distortions due to Sensor-Earth geometry variations and conversion of the data to real world coordinates on the Earth's surface.

5.4.1 Atmospheric Corrections and Image Enhancement

First step after extraction of data is to examine the quality of the datasets before going for further analysis. One can assess this by looking the initial statistics of the datasets by examining minimum and maximum value of the Digital Number (DN), mean and standard deviation of the dataset. High minimum value indicates atmospheric interaction with the dataset and will require atmospheric correction. Similarly, low maximum value indicates improper distribution of DN values with low contrast of the images, and requires contrast enhancement for better identification of features on the images.

Initial statistics, covariance and correlation matrix for the remote sensing images used in present study are given in Tables 5.3 and 5.4 respectively. It can be observed from Table 4.3, IRS 1B LISS-I data require no atmospheric correction as minimum values are within the acceptable limits. For IRS P6-LISS III data, visible green band is mostly affected by atmospheric scattering as compared to other bands, whereas infrared band is having less interference. Maximum value in these datasets indicates that full scale brightness values have not been utilized. Image quality is based on scale of brightness values. High minimum and low maximum values indicate poor quality of images and require atmospheric correction and contrast enhancement for visual interpretation of images.

Table 5.3: Univariate statistics of various satellite dataset used

Statistics	IRS 1B LISS I											
	18-November-1995				10-December-1995				23-January-1996			
	B1	B2	B3	B4	B1	B2	B3	B4	B1	B2	B3	B4
Min	14	20	30	9	12	18	28	8	12	18	28	8
Max	69	63	58	67	65	59	56	70	65	59	56	70
Mean	29.8	31.4	37.5	37.2	21.9	27.3	33.7	36.4	21.9	27.3	33.7	36.4
Std. Dev	5.3	3.9	2.7	6.1	5.5	3.7	2.7	6.8	5.5	3.7	2.7	6.8
	IRS 1B LISS I				IRSP6 LISS III							
	29-March-1996				27-February-2005				18-November-2005			
	B1	B2	B3	B4	B1	B2	B3	B4	B1	B2	B3	B4
Min	14	21	29	10	68	32	22	23	56	23	11	14
Max	72	63	59	74	218	165	198	178	218	160	169	165
Mean	24.1	29.9	36.4	42.7	94.4	53.7	105.9	72.2	88.5	60.4	69.8	76.9
Std. Dev	6.5	4.2	3.1	7.3	14.1	17.1	20.1	19.6	12.59	13.9	18.8	16.4

Note: 'B' stands for Band

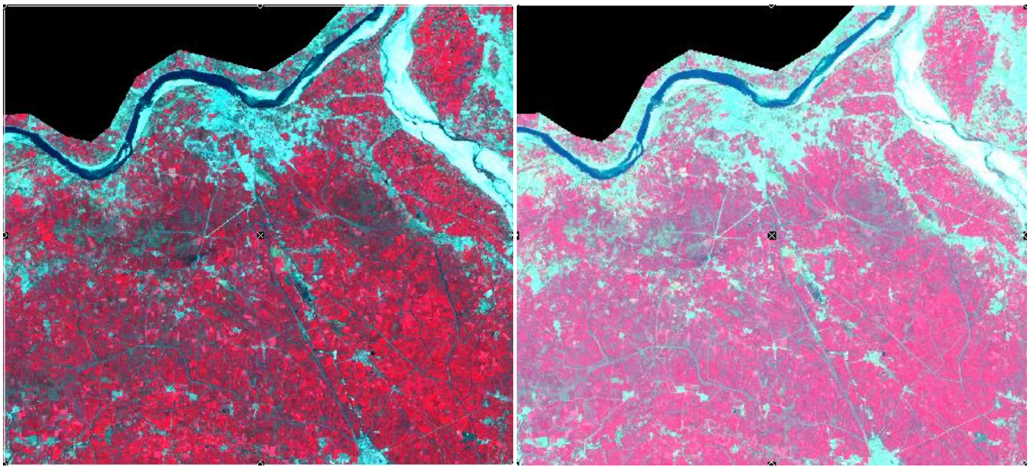
Table 5.4 Multivariate statistics for different datasets

IRS 1B, LISS-I Data																
	18-Nov-95				10-Dec-95				23-Jan-96				29-Mar-96			
COVARIANCE																
	B1	B2	B3	B4	B1	B2	B3	B4	B1	B2	B3	B4	B1	B2	B3	B4
B1	28.1				37.6				30.6				41.7			
B2	19.1	15.2			7.3	6.9			19.0	13.6			25.5	17.6		
B3	13.2	9.9	7.3		11.9	9.6	15.0		13.9	9.4	7.4		18.6	12.2	9.5	
B4	11.7	8.6	4.7	37.2	16.7	12.5	18.6	26.7	-1.6	2.9	0.1	45.5	-9.3	-2.9	-4.2	52.7
CORRELATION																
	B1	B2	B3	B4	B1	B2	B3	B4	B1	B2	B3	B4	B1	B2	B3	B4
B1	1				1				1				1			
B2	0.93	1			0.45	1			0.93	1			0.94	1		
B3	0.92	0.94	1		0.50	0.94	1		0.93	0.93	1		0.93	0.94	1	
B4	0.36	0.36	0.29	1	0.53	0.92	0.93	1.00	-0.04	0.12	0.01	1.00	-0.20	-0.09	-0.19	1.00

COVARIANCE									
	IRS P6 LISS-III Data								
27-Feb-05					18-Nov-05				
	B2	B3	B4	B5		B2	B3	B4	B5
B1	198				B2	159			
B2	234	292			B3	168	194		
B3	-58	-104	404		B4	96.6	98	353	
B4	242	302	-53	383	B5	153	183	206	271
CORRELATION									
	B2	B3	B4	B5		B2	B3	B4	B5

B1	1				B2	1			
B2	0.97	1			B3	0.96	1		
B3	-0.2	-0.3	1		B4	0.41	0.37	1	
B4	0.88	0.9	-0.1	1	B5	0.74	0.8	0.67	1

Atmospheric correction has been done by using dark pixel subtraction method for IRS P6 LISS III datasets, but did not yield good result as compared to raw data. The possible reason might be nonuniformity of the atmosphere over the image. For comparison atmospherically corrected image and raw image for IRS P6 LISS III data are shown in Figure 5.8 Effect of atmospheric correction on IRS P6 LISS III data (27-Feb 2005). So, general contrast enhancement has been done for all the datasets after examining the histogram of DN values by using Lookup Table (LUT) stretch to enhance the tonal information with the help of histogram observation. This has been done using piece wise stretch based on distribution of histogram. Histograms of all the four bands of IRS P6 LISS III (27-Feb 2005) data is shown in Figure 5.9 Histograms for IRS P6 LISS III Data (27-Feb 2005)Enhanced image by LUT stretch for IRS P6 LISS III (27-Feb 2005) data is given in figure 5.8



(a) Raw image (b) Corrected image

Figure 5.8 Effect of atmospheric correction on IRS P6 LISS III data (27-Feb 2005)

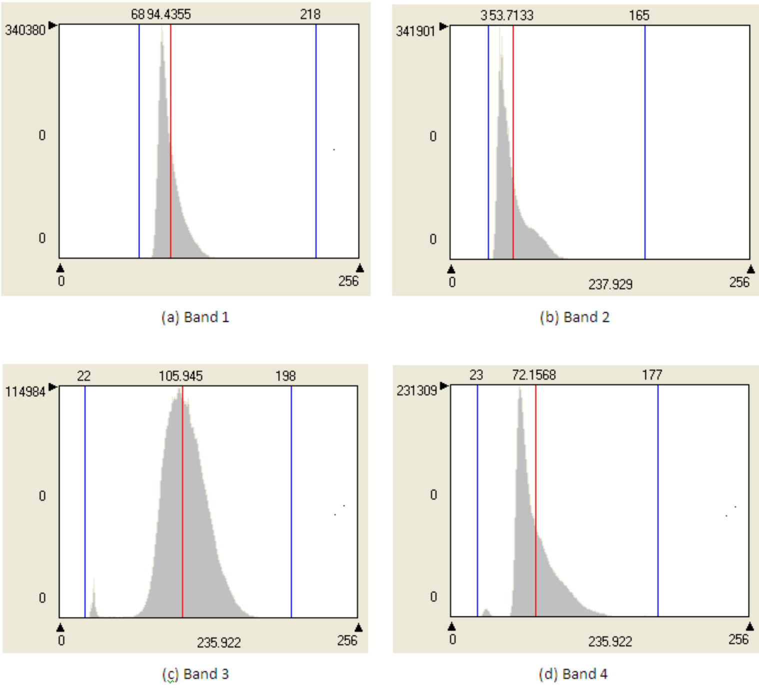
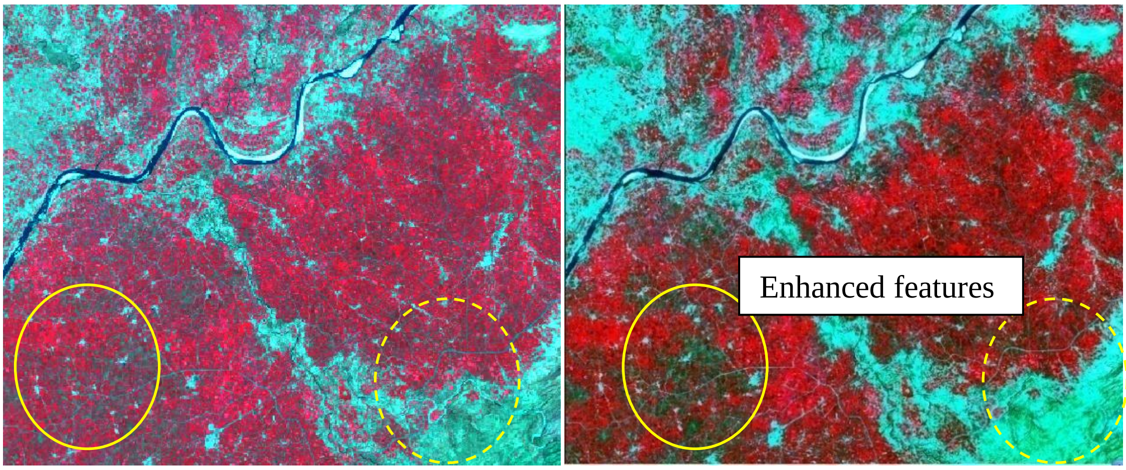


Figure 5.9 Histograms for IRS P6 LISS III Data (27-Feb 2005)



(a) Raw Image (b) LUT Stretch

Figure 5.10 Contrast enhancement using LUT stretch for IRS P6 LISS III data (27-Feb 2005)

On examining the histograms of Band 1 and 2 figure 5.9 data is stretched by piece wise LUT on left and right limb of histogram. Histograms of Band 3 and 4 are bimodal in nature with two peaks. Mean values are skewed from centre except for Band 3. Piece wise contrast enhancement has increased the contrast of the image.

On examining the variance of IRS 1B LISS I datasets, Band 1, December 1995 and March 1996 is having more information content as compared to other bands. Similarly, in case of the correlation matrix, it is found that Band 1 and Band 4; Band 2 and Band 4; Band 3 and Band 4 of all IRS 1B LISS I images are spectrally distinct. So Bands 1, 2 and 4 can be used for classification purpose to identify more number of classes.

In case of IRS P6 LISS III data, on examining the variance and covariance matrix, it is found that Band 4 and Band 5 are having more information content as compared to other bands for both images. Similarly, Band 2 & Band 4; Band 3 & Band 4; Band 4 & Band 5 are spectrally distinct for 27-Feb, 2005 image and for 18-Nov, 2005, Band 2 & Band 4 and Band 3 & Band 4 are spectrally distinct. It is preferable to take one band from each wave length region for better separability. After spectral enhancement images have been geometrically corrected as discussed in Section 4.3.1.

5.4.2 Land Use Land Cover Mapping

Land use land cover mapping is the main objective of remote sensing data analysis in present study. There are number of approaches available in literature for land use mapping using remote sensing data. Approach followed in present study is shown in figure 5.11 and the steps in LULC mapping are discussed subsequently.

5.4.3 Selection of Number of Classes and Training Data

Initially unsupervised classification has been performed to identify the number of land use classes and to understand their spatial variation and probable areas of misclassification. Further, supervised classification has been done with this experience. Total ten major classes have been identified through unsupervised classification and have been conformed from field knowledge. These are major crops (Wheat in Rabi and Soyabean in Kharif), minor crops (Pulses, Gram and other), fallow, water bodies, built-up, barren, forest, rock out crop and dry river bed.

In the present case, supervised classification approach has been used to train the Maximum Likelihood Classification (MLC) Classifier. Supervised training is user controlled and based on the experience of user and ground truth collected through field visits. Signatures are collected for training of MLC classifier for the major classes obtained through unsupervised classification, using parametric and non-parametric rules. Parametric signatures based on statistical parameters of the training sample while nonparametric, which are based on discrete objects in a feature space image. Parametric signatures are used to train statistically based classifiers like MLC. Parametric signatures have been collected from the FCC of the image by digitizing polygons, lines and points based on type of the class. Sufficient numbers of training pixels have been collected to satisfy the 10 n criteria (Congalton, 1991) for each land use class, where n is the number of bands used for the classification. Non parametric signatures have been collected from scatterplot or feature space images by linking FCC and scatterplot. Collected non parametric signatures have been converted to parametric signatures by generating statistics. Nonparametric signatures are helpful in improving classification accuracies of urban settlement and exposed rocky areas (ERDAS, 1994).

Representative signatures have been collected for each land use class all over the image. Signatures have been checked by examining the histogram whether it is unimodal or not. Further, signature separability has been verified using transformed divergence (TD).

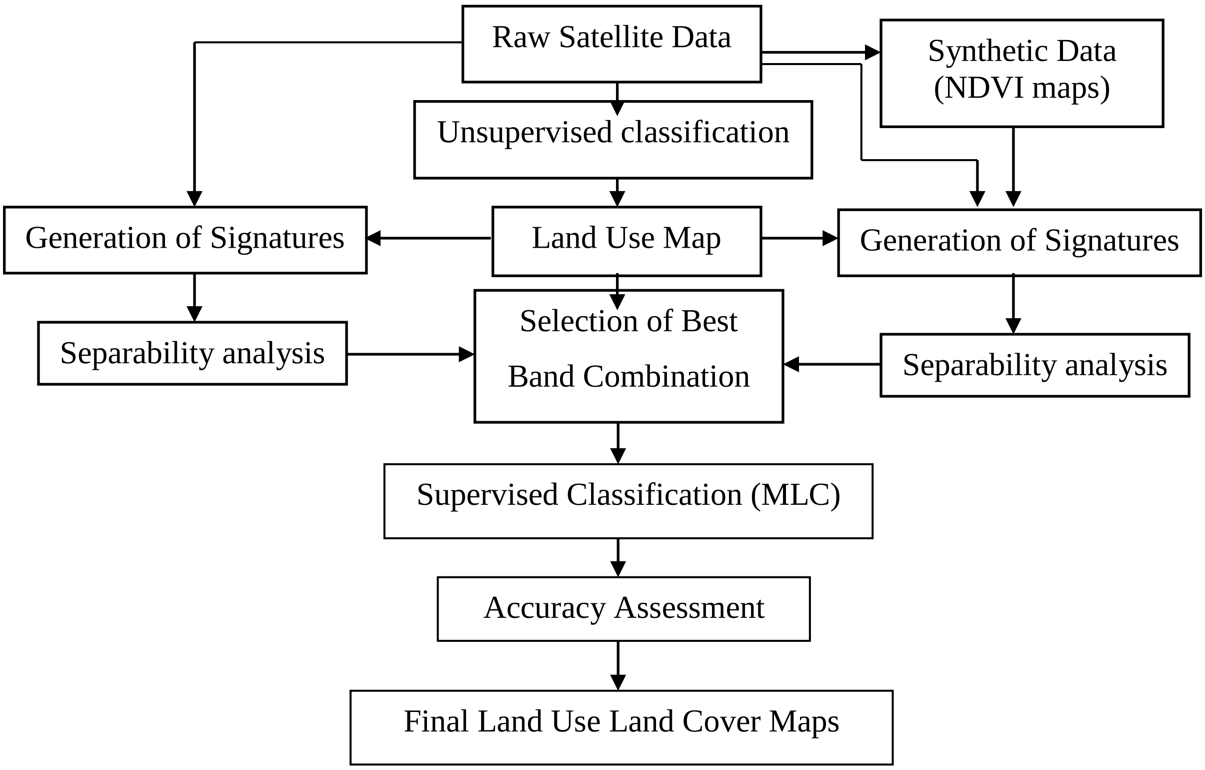


Figure 5.11 Flowchart of methodology for LULC mapping

5.4.3.1 Separability

Signature separability is a statistical measure of distance between two signatures and applicable only for the statistical classifiers. It can be calculated for any combination of the spectral bands. If the spectral distance between two samples is not significant for any pair of spectral bands, then they may not be distinct enough to produce an acceptable classification. In the present image analysis, Transformed Divergence (TD) is used to evaluate the signature separability. Swain and Davis (1978) defined TD as;

$$TD_{ij} = 2000\left(1 - \exp\left(\frac{-D_{ij}}{8}\right)\right) \tag{5.1}$$

$$D_{ij} = \frac{1}{2}tr((C_i - C_j)(C_i^{-1} - C_j^{-1})) + \frac{1}{2}tr((C_i^{-1} - C_j^{-1})(\mu_i - \mu_j)(\mu_i - \mu_j)^T)$$

where, i and j are the two signatures (classes) being compared, C_i is the covariance matrix of signature i, μ_i is the mean vector of signature i, tr is the truce function, and T is the transposition function. The TD gives an exponentially decreasing weight to increase distance between the classes. The scale of the divergence values can range from 0 to 2000. As a general rule, if TD values for all land use classes for a pair of spectral bands are greater than 1900, then the classes can be separated. If the value is between 1700 and 1900, the separation is fairly good. If values of TD are below 1700, separation is poor (Jensen, 1996). Minimum and average values of TD and number of spectral bands selected for different images are given in Table 5.5.

It can be seen from Table 5.5 that the values of TD for different pair of classes are not in acceptable limits. Though the maximum TD for different images varies from 1990 to 1998, which indicates good separability (TD > 1900) however, the minimum values of TD for different images are found to be between 1588 to 1719. These lower values of TD for some of the land use classes (built-up-rock outcrop-barren-fallow, forest-major crops) indicate poor separability. The main objective of land use classification in present study is to quantify the agricultural land and major crop in particular. The poor separability between major crops and forest is not acceptable in this case, so approach of ancillary data integration is adopted to improve the class separability

Table 5.5 Transformed divergence separability for various datasets

Date	Data	Best Separability Band Combination	TD	
			Average	Min
27 Feb 2005	IRS P6 LISS III	B2, B4, B5	1990	1719
18 Nov 2005	IRS P6 LISS III	B2, B4, B5	1998	1714

B2: Green band, B4: NIR band, B5: SWIR band

5.4.4 Ancillary Data to Improve the Class Separability

Normalized Difference Vegetation Index (NDVI) maps figure 5.12 and figure 5.13), derived using LISS III data and DEM map have been used as ancillary data in the present study to improve the accuracy of land use classification. To separate forest class from major crops DEM can be helpful as there is considerable elevation difference between TCA and forest region. Same training data (signatures) have been used except for built-up, barren fallow and dry river bed which are refined to reduce the error in classification. Class separability analysis has performed using refined class signatures and remote sensing data bands with ancillary data. In all the cases, built up has mixed with rock outcrops. Builtup, rock outcrops, dry river bed and barren are not important classes in present cases, as no surface water is supplied the area under these classes, so the builtup class has been merged with rock outcrop class and dry river bed and barren classes have been merged and again the separability has been evaluated. The TD values for 27-Feb 2005 indicate that Green, NIR, NDVI and DEM has got the maximum separability for the selected signatures. For 18-Nov 2005, Red, NIR, NDVI and DEM have got the maximum separability (Table 5.6). It was observed that Minor crops have been identified properly as compared to raw data classification.

Supervised classification has been done using the best band combination mentioned in Table 4.6 for all the datasets.

Table 5.6 Transformed divergence separability for various datasets using ancillary data

Date	Data	Best Separability Band Combination	TD	
			Average	Min
27 Feb 2005	IRS P6 LISS III	B1(Green), B3(NIR), DEM & NDVI	1997	1833
18 Nov 2005	IRS P6 LISS III	B2 (Red), B3(NIR), NDVI &DEM	1981	1890

5.4.5 Supervised Classification

Supervised classification is user controlled process. After the finalization of signatures, pixels in the image under study are sorted into user defined classes using any mathematical algorithm called as decision rule. Decision rules used in the supervised classification can be classified into two categories; (i) parametric decision rule, which is trained by the parametric signature, and (ii) nonparametric decision rule, which is trained by the nonparametric signatures. Parametric rules are based on statistical properties and every pixel is assigned to a class, since it is a continuous decision space (ERDAS, 1994). Nonparametric decision rule is not based on the statistical properties of the data.

In the present study, MLC a statistically based parametric algorithm is used for supervised classification of all the images. MLC is based on the probability that a pixel belongs to a particular class. This algorithm assumes that these probabilities are equal for all classes, and that the input bands have normal distributions. The basic equation of the MLC is;

$$D = \ln(a_c) - [0.5\ln(|Cov_c|)] - [0.5(X - M_c)T(Cov_c^{-1})(X - M_c)] \qquad (5.2)$$

where, D is the weighted distance (likelihood), c is a particular class, X is the measurement vector of the candidate pixel, M_c is the mean vector of the sample of class c, a_c is the percent probability that any candidate pixel is a member of class c, Cov_c is the covariance matrix of the pixels in the sample of class c, $|Cov_c|$ is determinant of Cov_c (matrix algebra), Cov_c^{-1} is inverse of the covariance matrix, and T is the transpose function. While doing classification, MLC assigns a particular pixel to the class 'c', for which weighted distance (likelihood) is lowest. In the present classification, initial probabilities of different land use classes have been taken as 1.0.

In present case, classification has been done using the best band combination mentioned in Table 5.6 for all the datasets. Classified output using ancillary data are shown in figure 5.14 and figure 5.15. Area under different land use classes derived using ancillary data for different datasets is given in Table 5.7.

The classification is not complete until its accuracy is assessed (Lillesand et al., 2004). The accuracy of the classified datasets is evaluated to know how well the classification and training data are in agreement.

Table 5.7 Area under different land uses using ancillary data

Land use	27-Feb 2005 IRS P6 LISS III	18-Nov 2005 IRS P6 LISS III
	Area (ha)	
Water	5300	5852
Minor crops (gram/pulses)	57397	41537
Major crops (wheat)	167575	182866
Fallow	27621	21458
Forest	16968	639
Rock outcrop/builtup	7433	6685
Riverbed/Barren	20533	28777
Agri. Non-command	-	6459

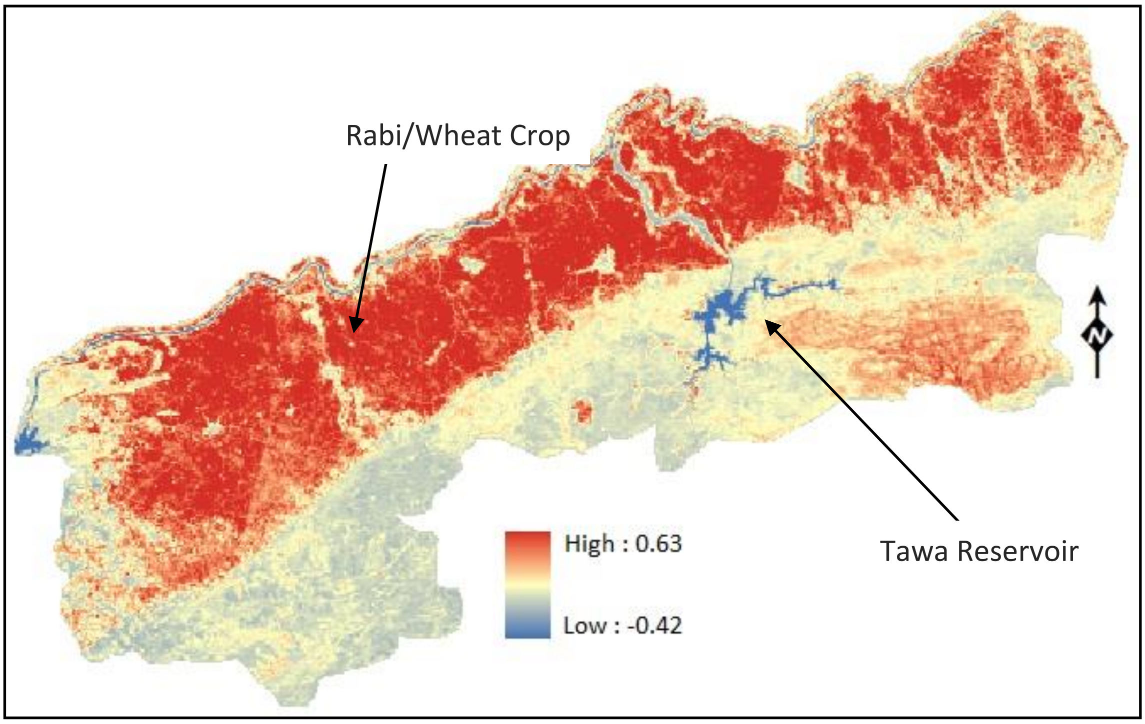


Figure 5.12 NDVI image of IRS P6 LISS III data, Feb 2005

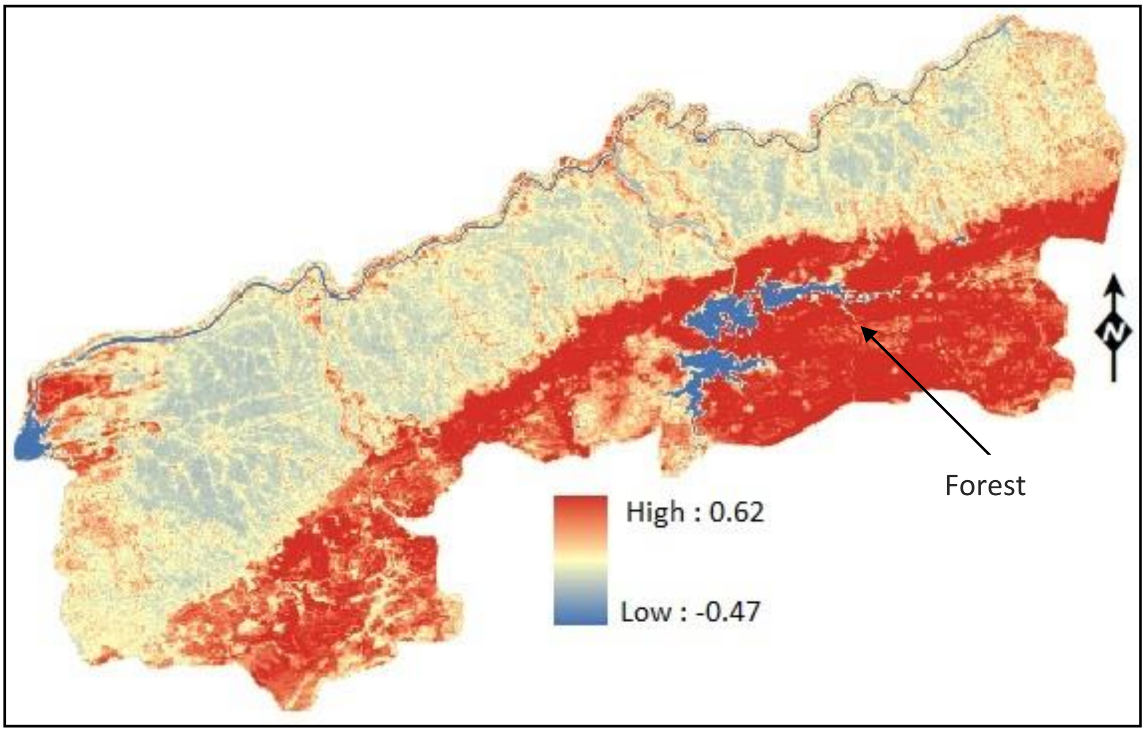


Figure 5.13 NDVI Image of IRS P6 LISS III data, Nov 2005

5.4.6 Accuracy Assessment

One of the most common forms of expressing classification accuracy is the preparation of a classification error matrix (confusion matrix or contingency table). Error matrix compares the relationship between known referenced data and the corresponding results of an automated classification for each class. In the present study, accuracy assessment has been done by using stratified random sampling method so as to represent the samples according to the number of pixels in each land use class. A general guideline for sample size is a minimum of 50 samples for each class category to be included in the error matrix (Table 5.8). Further, if the area is large (more than a million acres) or the classification has a large number of vegetation or land use classes (more than 12 categories), the minimum number of samples should be increased to 75 or 100 sample per category (Congalton, 1991; Congalton and Green, 1999). Table 5.8 shows the representative randomly selected sample pixels from the reference image and classified image. By observing the confusion matrix it can be concluded that the overall accuracy of the classification is higher than minimum acceptable limit (85%).

KHAT ($\hat{k}$) statistics is a measure of difference between the actual agreement between reference data and an automated classifier and the chance agreement between the reference data and a random classifier (Lillesand et al., 2004).

KHAT ($\hat{k}$) statistics can be defined as:

$$\hat{k} = \frac{\text{observed accuracy} - \text{chance agreement}}{1 - \text{chance agreement}} \tag{5.3}$$

The value of $\hat{k}$ equal to 0.88 (Table 5.8) reveals that the observed classification is 88 percent better than the one resulting from chance. Error matrix reveals that NDVI and DEM along with raw data have enhanced the classification accuracy. So, this classified image can be used to prepare a land use land cover (LULC) map for the study area.

Land use map is very important input in present study, not only in natural resources assessment but also in groundwater modelling. To improve the accessibility and utilization potential of land use maps, these maps are integrated in geodatabase by direct importing these classified maps in the database discussed in early part of this chapter.

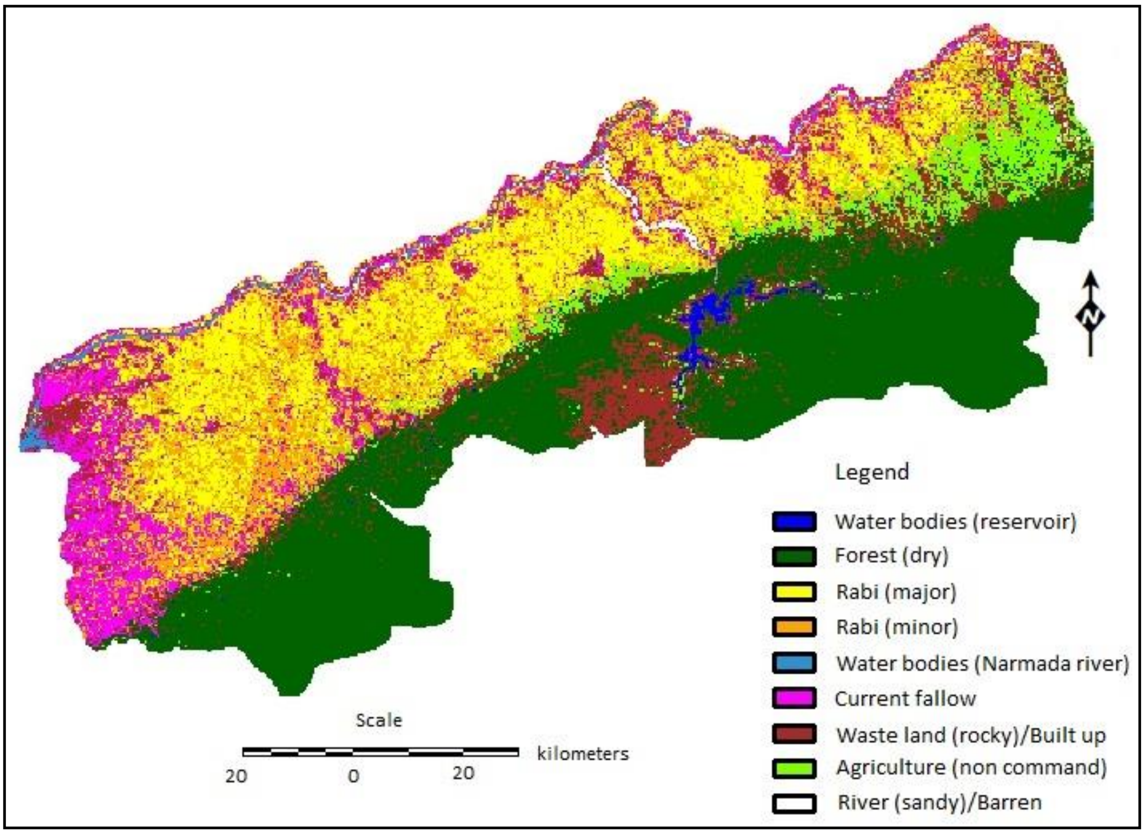


Figure 5.14 Classified image using ancillary data for Feb 2005, IRS P6 LISS III data

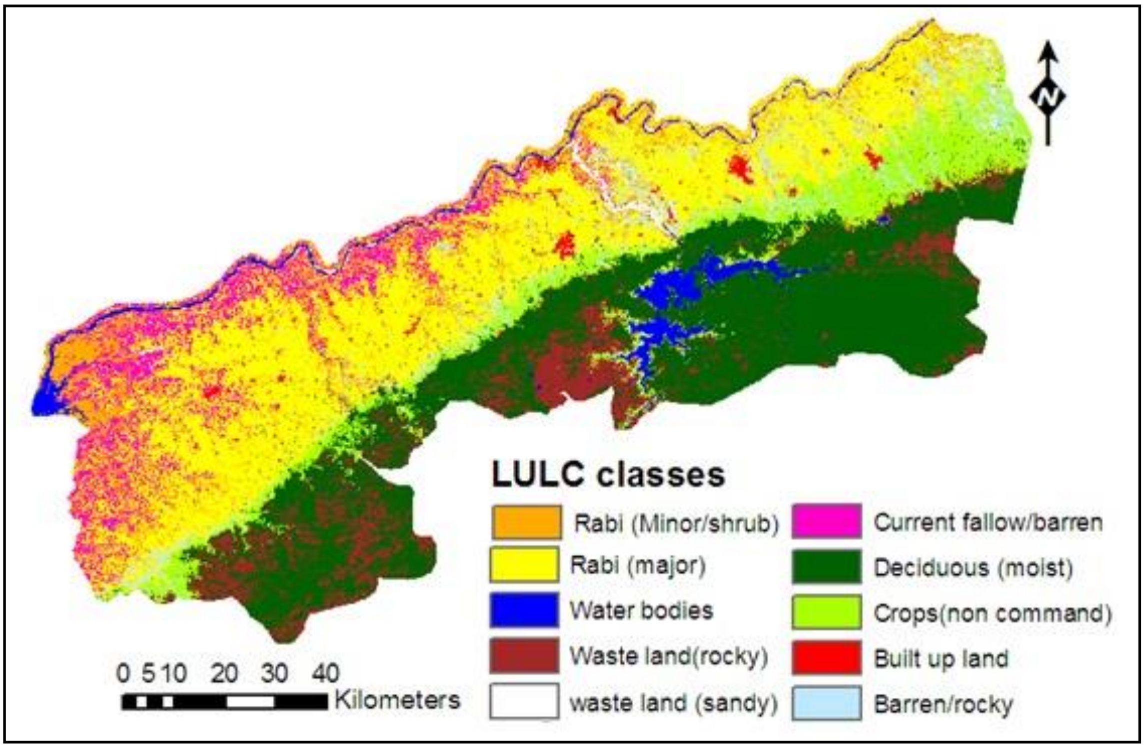


Figure 5.15 LULC map using ancillary data for Nov 2005, IRS P6 LISS III data

Table 5.8 Error matrix showing classification accuracy of Nov 2005, IRS P6 LISS III data

Classified Data	Reference Data									
	Water	Agri. Non-com	Minor Crops	Major Crop	Forest	Barren/dry river bed	built-up/rock outcrop	Fallow	Row Total	UA (%)
Water	87	0	0	0	0	0	0	0	87	100.00
Agri. non-command	3	11	1	0	0	0	0	0	15	73.33
Minor Crops	0	3	39	4	0	0	3	0	49	79.59
Major Crop	0	1	1	231	0	0	0	0	233	99.14
Forest	0	0	0	0	216	0	9	5	230	93.91
Barren/dry river bed	0	0	0	0	0	110	7	8	125	88.00
Built-up/rock outcrop	0	0	2	0	4	10	104	12	132	78.79
Fallow	0	0	2	0	0	13	12	100	127	78.74
Column Total	90	15	45	235	220	133	135	125	998	
PA (%)	96.67	73.33	86.67	98.30	98.18	82.71	77.04	80.00		
overall accuracy = 89.98%										
KHAT ($\hat{k}$) = 0.88										

5.5 CHANGES IN CROPPING PATTERN

The land use pattern/cropping pattern in command area of irrigation projects generally changes with the change in resources availability. These changes in most of the cases are gradual and may take five to ten years to reflect on larger scale statistics. To evaluate the change, if any, in cropping pattern of the Tawa command, land use of Rabi season of year 1995 has been mapped using temporal multiband data of IRS 1B LISS-I. Further, the land use in Rabi season of years 1995 and 2005 are compared based on major land use classes.

5.5.1 Land Use in Rabi Season of Year 1995

The land use land cover of last decade has been mapped using IRS 1B LISS I data. The temporal data was available for Rabi season of year 1995-96. After visual interpretation of different datasets, six classes have been identified on the image and cropping pattern has been identified on the images with temporal data. Figure 5.16 shows the IRS 1B LISS I temporal dataset for a part of the study area. Stages of standing crop over the area are clearly visible from the figure. In the month of November, Rabi season starts over the command area (Fig. 5.16 a). Initial stages of the field can be seen with field preparation which shows water in the fields and the next image (Fig. 5.16 b) shows the grown-up crop and the last image (Fig. 5.16 c) shows the fallow fields after crop cutting in most of the areas. Wheat and Gram are the main crops in Rabi season. Both of these crops have been identified visually as of staggered cropping pattern.

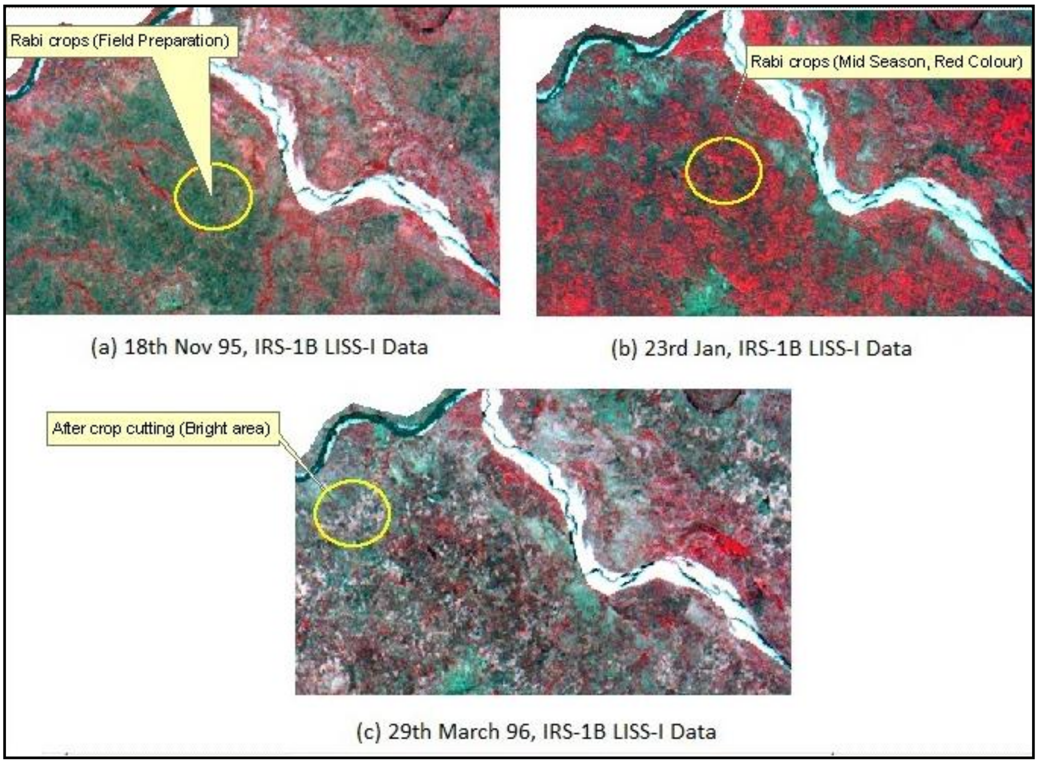


Figure 5.16 Different stages of crops

Based on visual interpretation training samples for supervised classification (MLC) are selected. It has been observed that in case of major crop (Wheat) there has not been much difference in DN values in all the temporal images in visible region but in NIR band there has been a marked difference between December and January images as high DN values of green vegetation in NIR band for January image. Low DN value in December image shows the moisture in the fields. This factor is important to delineate Rabi acreage and extent of Wheat crop. Band 4 is spectrally distinct with all visible bands as stated earlier. The change detection algorithm has been applied to separate crops under Rabi season using difference in DN values of November and January for the images in NIR band. Here it has been assumed that all other permanent land use land cover classes like forest, barren land, urban settlement etc will not have much of change in reflectance as compared to seasonal agricultural crops. Change detection has been done for these images using NIR band and the results are shown in figure 5.17. Signatures for all the land use classes have been refined using change detection layer and final supervised classification has been done using change image along with raw image data to delineate land use land cover classes. Final classified image for the year 1995-96 by using LISS-I data is given in figure 5.18

It is important to note that the whole Tawa command area is not covered in LISS-I datasets. Hence, common area from all the images has been taken for comparison of the results. Whole command area is considered using IRS P6 LISS-III, 2005 dataset only.

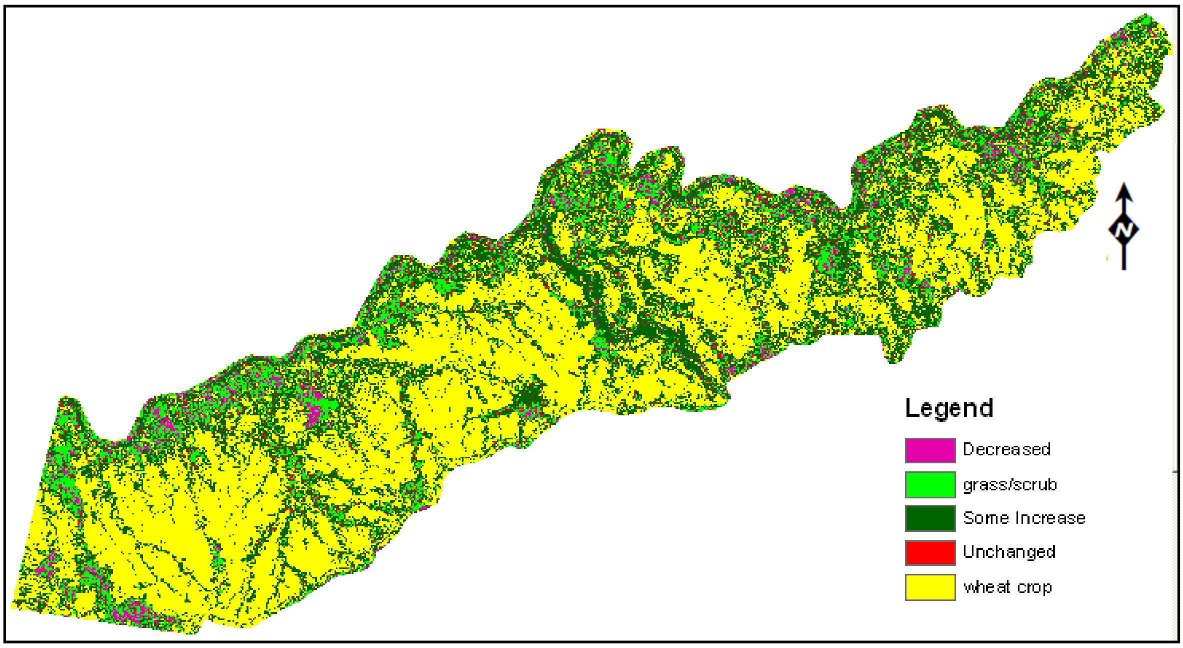


Figure 5.17 Change between Nov 95 and Jan 96 IRS 1B LISS-I Images

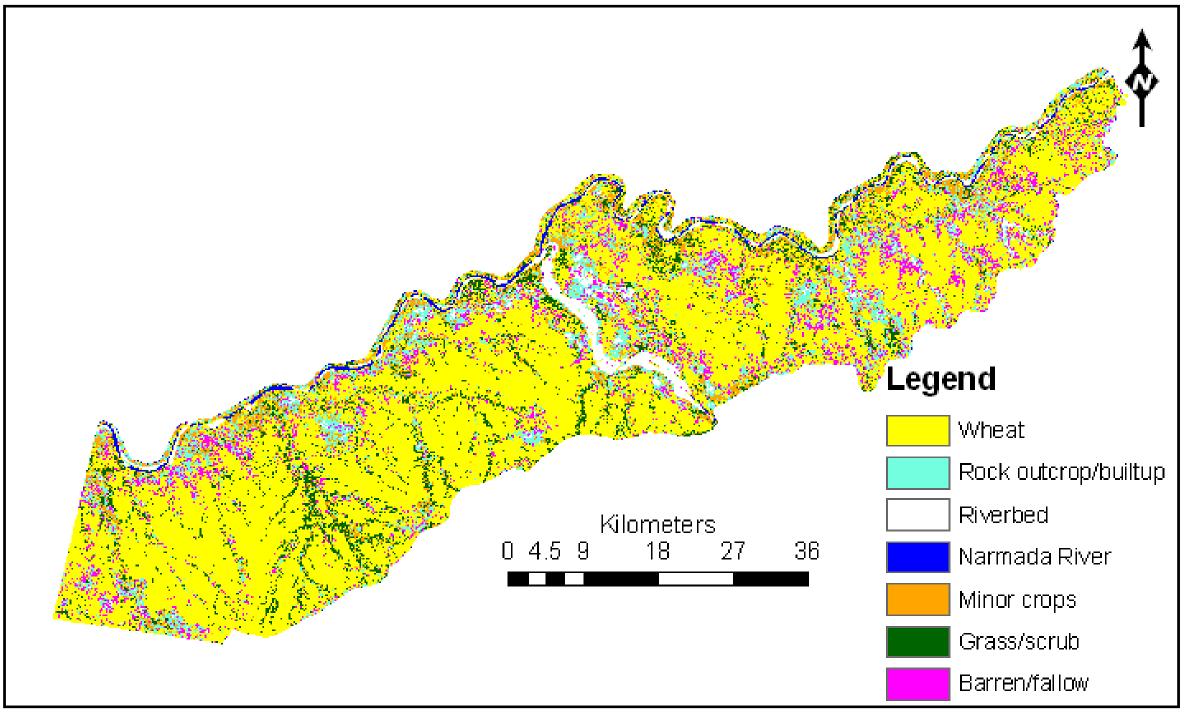


Figure 5.18 LULC map derived for Rabi season of year 1995-96

The comparison of temporal land use land cover data gives the information about insight changes, as land use change is a slow and continuing process. To know the pattern of land use in and change if any in one decade (i.e. from 1995 to 2005), the classified land use land cover maps of the part of TCA for Rabi season of years 1995-96 and 2005 have been compared. Only major land use classes are considered in this process. The area under these major classes in both the years is given in Table 5.9 and is also shown in figure 5.19

It is clear from figure 5.19 and Table 5.9 that the area under Wheat has increased from 124325 ha to 182866 ha. The increase in Wheat is compensated by decrease in fallow land and dry sand/barren land in the Rabi season. The increase in area under Wheat indicates the change in cropping pattern in the command. This change in cropping pattern might have taken place due to availability of surface water and increased availability of groundwater which is recharged by return flow from irrigation water. This increase in area under Wheat and trend of cropping pattern change must be considered while estimating the water requirement and deciding the optimal future plan.

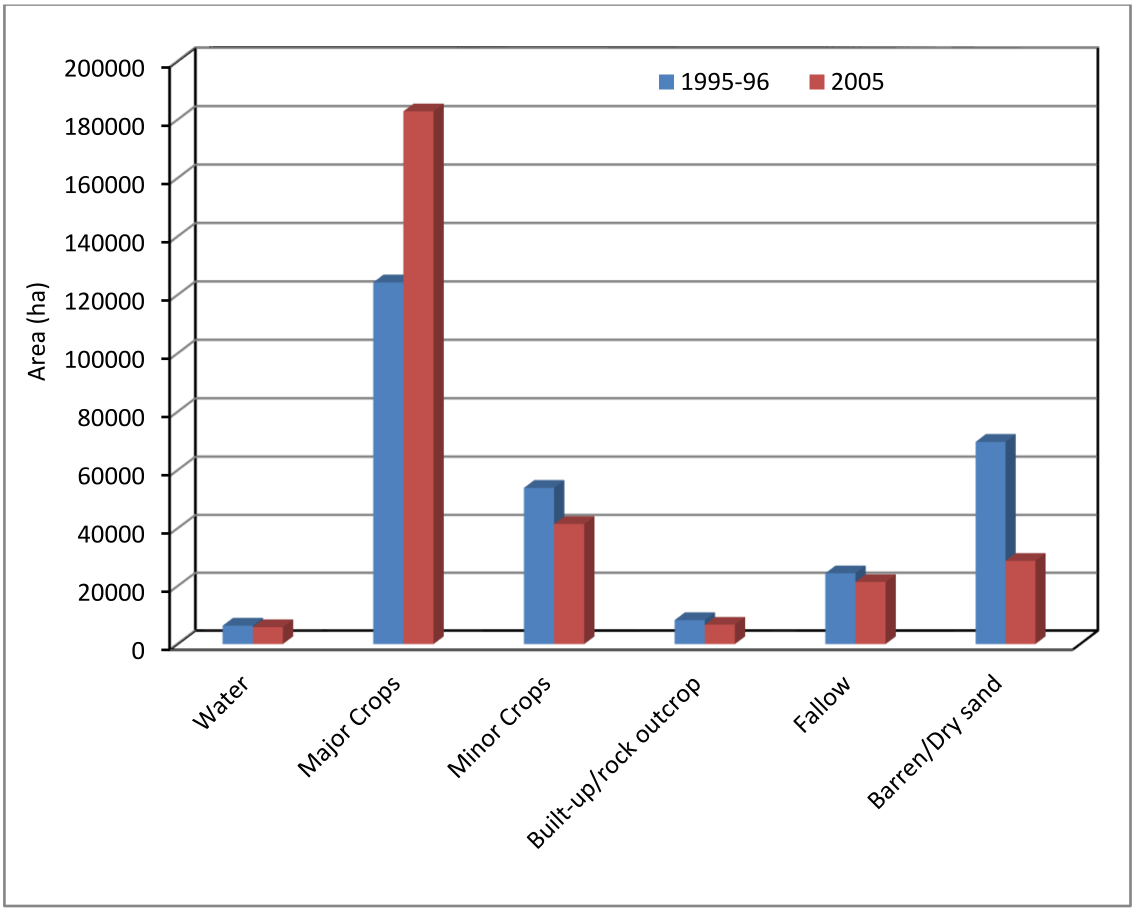


Figure 5.19 Area under different land uses in part of TCA in 1995-96 and 2005

Table 5.9 Land use land cover in Rabi season of 1995-96 and 2005

LULC class	LULC (ha)	
	1995-96	2005
Water	6379	5852
Major Crops	124325	182866
Minor Crops	53972	41537
Built-up/rock outcrop	8289	6685
Fallow	24483	21458
Barren/Dry sand	69727	28777
Total	287175	287175

5.6 CONCLUDING REMARKS

The database is a prerequisite component in water resources planning and management research. The spatial and non-spatial data are required for assessing water resource potential of command area as well as to determine the water requirement of the area. The spatial database generated in this chapter will be used for deriving parameters of groundwater model and water balance study. The procedure and tools used to generate this database are discussed in this chapter. Pre-processing and classification of remote sensing data are described in detail. Land use land cover of Tawa command for Rabi of year 2005 and 1995-96 has been generated and checked for classification accuracy. The comparison between land use of these two time periods indicates that the cropped area under major crop (Wheat) has increased, and this must be reflected in planning the future scenario.

CHAPTER 6
GROUNDWATER MODELLING

6.1 GENERAL

Any mathematical model is a conceptual description or approximations developed to replicate the physical systems using mathematical equations, which are not exact description of physical systems or processes. Groundwater modelling is the process of describing groundwater movement of an area through the mathematical equations. Groundwater is a dynamic system and its availability in irrigated agricultural area governs the production of agricultural crops. In the command area of any surface irrigation project, groundwater system cannot be considered in isolation, as it continuously interacts with surface water system. The irrigation return flow and seepage from canal along with rainfall recharge replenishes the groundwater system, while agricultural, urban and industrial systems extract groundwater for their use. In the present study, groundwater is considered as additional source for irrigation water along with canal supply. It is important to model the groundwater system of the Tawa Command Area, so that the present state and future condition of groundwater due to changes in management practices can be assessed.

Keeping this in consideration, the present chapter describes the development of groundwater model for the Tawa Command Area. Initially, general aspects of groundwater modelling are presented along with different assumptions involved and mathematical equations to be used. In the present case, Visual MODFLOW, version 4.1 (Guiger and Franz, 1996), developed by Waterloo Hydrogeologic Inc., has been used for the groundwater modelling of the area. Various aspects of model conceptualization in MODFLOW, parameterization, boundary conditions and integration with GIS are presented. Further, model calibration (estimation of aquifer parameters using an inverse problem) and validation aspects are discussed. Finally, sensitivity analysis and simulation results have been presented. Calibrated groundwater model is externally coupled with the conjunctive use model to predict the groundwater behaviour under different management decisions (optimum allocation of water).

6.2 GROUNDWATER MODELLING

Groundwater models are used to calculate the rate and direction of movement of groundwater through aquifers and confining units in the subsurface. These calculations are referred to as simulations. The outputs from the model simulations are the hydraulic heads and groundwater flow rates which are in equilibrium with the hydro-geologic conditions (hydrogeologic framework, hydrologic boundaries, initial and transient conditions, hydraulic properties, and sources or sinks) defined for the modeled area. Through the process of model calibration and verification, values of different hydro-geologic conditions are varied to reduce any disparity between the model simulations and field data, as well as to improve the accuracy of the model. The model can also be used to simulate the possible future changes to hydraulic head or groundwater flow rates as a result of change in stresses on the aquifer system. The success or failure of a model depends on the quality and completeness of field data and the type and quality of the mathematical tools (Sambiah et al., 2004; Gurunadha Rao, 2005; Inka et al., 2007; Gaur et al., 2008).

Groundwater models describe groundwater flow using mathematical equations that are also based on certain simplifying assumptions. These assumptions typically involve the direction of flow, geometry of the aquifer and the heterogeneity or anisotropy of bedrock within the aquifer. Due to simplified assumptions embedded in the mathematical equations and uncertainties in the data required by the model, a model must be viewed as an approximation and not an exact duplication of field conditions.

In general, the following features and assumptions are usually incorporated in the groundwater models (Willis and Yeh, 1987).

i) A single aquifer system is modeled using a single storage coefficient in vertical direction,
ii) The aquifer is bounded at the bottom by an impermeable layer,
iii) Ratio of horizontal and vertical conductivity is 10.00,
iv) The upper boundary of the aquifer is either an impermeable (confined aquifer), or a slightly permeable layer (semi-confined aquifer) or a free water table (unconfined aquifer),
v) Darcy’s law (head loss varying linearly with apparent velocity of flow) and Dupuit’s assumptions (negligible vertical flow) are applicable,
vi) The aquifer has head-controlled, flow controlled, and/or zero-flow boundaries: the first two of these boundaries may vary with time, and
vii) The process of infiltration and percolation of rain water, surface water and of capillary rise and evaporation, taking place in the unsaturated zone of aquifer (above water table), cannot be simulated. This means that net recharge to the aquifer must be calculated separately and assigned in the model.

6.2.1 Types of Groundwater Models

A model simulates the aerial and temporal properties of a system in either physical or mathematical way. Depending upon the nature of equations involved, these models can be: empirical, probabilistic, and deterministic. Empirical models are site specific in nature and are derived from experimental data that are fitted to some mathematical function. Probabilistic models are based on law of probability and statistics and these models require large data sets and unsuitable in hydro-geologic practice for future prediction. Deterministic models assume that the stage or future reactions of the system studied are predetermined by physical laws governing groundwater flow. Most traditional problems in hydrogeology are solved using deterministic models which can be as simple as the Theis equation or as complicated as a multiphase flow through a multilayered, heterogeneous, anisotropic aquifer system. There are two large groups of deterministic models depending basically upon the type of mathematical equations involved: analytical, and numerical (Todd, 1980).

The analytical models are used to solve the equations that describe very simple flow conditions in groundwater system, while numerical model approximates the equations for very complex conditions. In selecting a model for use at a site, it is necessary to determine whether the model equations account for the key processes occurring at the site. Analytical models provide an exact solution of a specific but simplified groundwater flow equation. Analytical models are typically steady-state and one-dimensional groundwater flow models. However, due to the simplifications inherent with analytical models, it is not possible to account for field conditions that change with time or space.

Numerical models are capable of solving the equations, representing more complex groundwater system. These models use approximations (e.g., finite differences, or finite elements) to solve the differential groundwater flow equations. The model domain and time is discretized to support these approximations. In discretization process, the model domain is represented by a network of grid cells or elements while the time of the simulation is represented by time steps. The accuracy of a numerical model depends upon the accuracy of the input data, size of the space and time discretization and the numerical method used to solve the model equations. In addition to complex three-dimensional groundwater flow problems, numerical models may be used to simulate very simple flow, which can easily be simulated using an analytical model. However, numerical models are generally used to simulate problems which cannot be accurately described using analytical models.

Since the process of describing and solving a numerical groundwater model is problem independent, many commercial and public domain software are available for this purpose, like Visual MODFLOW, FEFLOW, FLOWPATH, 3DFEMFAT etc. (McDonald and Harbaugh,1988; Kumar 1992; Guiger and Franz, 1996). The simulation of groundwater flow using any model requires a thorough understanding of hydro-geologic characteristics of the aquifer. The hydrogeologic investigations should include a complete characterization of the following:

i) Sub-surface extent and thickness of aquifers and confining units (hydro-geologic framework),
ii) Hydrologic boundaries (also referred to as boundary conditions), which control the rate and direction of movement of groundwater,
iii) Hydraulic properties of the aquifers and confining units,
iv) A description of the horizontal and vertical distribution of hydraulic head throughout the modelled area for beginning (initial conditions), equilibrium (steady-state conditions) and transitional conditions, when hydraulic head may vary with time (transient conditions), and
v) Distribution and magnitude of recharge, pumping or injection of groundwater, leakage to or from surface-water bodies etc. (sources or sinks, also referred to as stresses). These stresses may be constant (not varying with time) or may change with time (transient).

In the present study, MODFLOW 4.2 is used to formulate groundwater model for alluvial aquifer of Tawa Command Area (TCA).

6.2.2 Groundwater Flow Equation

There are two basic equations which governs the flow through porous media. These are (a) Darcy's law and (b) Continuity equation (law of mass conservation). Various partial differential equations, which themselves may be models for various situations of groundwater flow, are a combination of Darcy's law and Continuity equation. The equation representing the piezometric head distribution in a three-dimensional flow through non-homogeneous and anisotropic medium is expressed as (Bear, 1979)

$$\frac{\partial}{\partial x}\left(K_{xx}\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(K_{yy}\frac{\partial h}{\partial y}\right)+\frac{\partial}{\partial z}\left(K_{zz}\frac{\partial h}{\partial z}\right)=S_0\frac{\partial h}{\partial t} \qquad (6.1)$$

Where, Kxx, Kyy and Kzz are permeabilities of the medium (L/T) measured along the principal axis X, Y, and Z respectively and vary with space coordinates (x, y, z), h is the piezometric head which is a function of both space and time i.e. h = f(x, y, z, t); and S_0 is the specific storativity of the porous medium (L-1).

Specific storativity of the porous medium of an aquifer is defined as the volume of water released from storage (or added to it) in a unit volume of aquifer per unit decline (or rise) in the piezometric head.

6.2.2.1 Flow in a confined aquifer

The groundwater flow in an anisotropic and non-homogeneous, non-leaky confined aquifer is expressed by the following partial differential equation (Bear, 1979)

$$\frac{\partial}{\partial x}\left(T_{xx}\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(T_{yy}\frac{\partial h}{\partial y}\right)=S\ \frac{\partial h}{\partial t}+q(x,y,z,t) \quad (6.2)$$

Where, Txx and Tyy are the aquifer transmissivities in the principal directions X and Y (L2/T), Txx = Txx(x,y); Tyy = Tyy(x,y); q(x, y, z, t) represents the distributed sink function and is defined as the excess of outflow over inflow per unit area per unit time (L/T), S is the storativity of confined aquifer (dimensionless).

Aquifer transmissivity is defined by the rate of flow per unit width through the entire thickness of an aquifer per unit hydraulic gradient.

6.2.2.2 Flow in an unconfined aquifer

In the case of a confined aquifer, although the potentiometric surface declines, the saturated thickness of the aquifer remains constant. In an unconfined aquifer, the saturated thickness can change with time. Under such conditions, the ability of the aquifer to transmit water changes as it is the product of the conductivity and the saturated thickness (Elango and Sivakumar, 2007).

Unconfined aquifer groundwater flow problems are generally analyzed using the Dupuit-Forchheimer assumptions. The Continuity equation and Darcy’s law are combined with free surface boundary condition to obtain the partial differentiation equation of groundwater flow in an unconfined aquifer. The governing differential equation for a two-dimensional transient flow in an anisotropic, heterogeneous unconfined aquifer may be written as (Willis and Yeh, 1987)

$$\frac{\partial}{\partial x}\left(K_{xx}h\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(K_{yy}h\frac{\partial h}{\partial y}\right)=S_y\frac{\partial h}{\partial t}+q(x,y,z,t) \tag{6.3}$$

Where, Sy is the storativity of the unconfined aquifer, which is nothing but specific yield of the aquifer medium i.e. S = Sy. This equation is also called as Boussinesq Equation. In the present work, aquifer of the study area is, in general, unconfined in nature.

6.3 Aquifer Condition of Tawa Canal Command

Tawa Command Area is geologically (as already shown in Fig. 3.12, Chapter 3) divided into alluvium, Deccan traps, Gondwanas, Bijwa¬ras and Archeans. The north western part of the TCA comprises of archean, granites and geneisses and crystalline limestone of bijwaras. In this region, groundwater occurs mostly under phreatic condition and in confined nature below the crystalline lime zone. Northern part of the Hoshangabad district, adjoining the Narmada River is covered with alluvium which makes for more than 50% of the entire district area and almost covers total Tawa Command Area except a few patches of granite on North-West. It is reported that all the alluvial aquifer zones constitute a single aquifer system. The unconfined aquifer along the southern fringe adjacent to gondwana passes laterally to the north into a number of aquifer zones separated by thick clay zones. The thickness of alluvial ranges between 15 m at Pathrai to 160 m at Tinsari (Fig. 3.13, Chapter 3). The top phreatic aquifer ranges in thickness from 2 to 10 m and is encountered in the depth range of 4 to 20 meters below ground level (mbgl) (Fig. 3.14, Chapter 3). The phreatic alluvial aquifer mostly comprises of fine to medium grained sand with intercalations of clay and silt, and at places also of coarse sand or gravel.

All the aquifer zones constitute a single aquifer system in unconfined nature. The aquifer is principally recharged by lateral flow from the south and North, and also by direct vertical percolations of rain/irrigation water/seepage from tanks/canals. Specific Yield data, available for few locations, varies between 0.0001 to 0.32 over the Tawa Command Area (Table 3.3, Chapter 3).

6.4 The MODFLOW

The MODFLOW is a Modular Three-Dimensional Ground-Water Flow Model developed by the USGS (McDonald and Harbaugh, 1988). Fundamental equation which has been used in the MODFLOW to simulate the groundwater flow is

$$\frac{\partial}{\partial x}\left(K_{xx}\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(K_{yy}\frac{\partial h}{\partial y}\right)+\frac{\partial}{\partial z}\left(K_{zz}\frac{\partial h}{\partial z}\right)-W=S_0\frac{\partial h}{\partial t} \quad (6.4)$$

where, W is the volumetric flux per unit volume representing source and/ or sinks of water (T-1). The above equation together with definition of initial head conditions, flow and or head conditions at the boundaries of an aquifer system constitutes a mathematical representation of a groundwater flow system.

Visual MODFLOW software, version 4.2 (Guiger and Franz, 1996), is a commercial version of original USGS's MODFLOW package, developed by Waterloo Hydrogeologic Inc. (WHI). The Eq 5.1 with finite difference numerical approximation has been used in the MODFLOW for the solution of groundwater flow problem. In the present study, MODFLOW–2000 numerical engine and WHS solver is used to solve the numerical model. WHS solver is an algorithm developed by the WHI. The WHS solver uses a Bi-Conjugate Gradient Stablised (Bi-CGSTAB) acceleration routine implemented with some incomplete decomposition for preconditioning of the groundwater flow partial differential equations. This solver approaches the solution of large set of partial differential equations iteratively through an approximate solution. Two levels of factorization; level 0 and level 1, are used in WHS solver. Factorization level 1 requires less iteration as compared to factorization level 0, but requires more memory for the convergence of a groundwater flow problem (Guiger and Franz, 1996). The WHS solver works on a two-tier approach, outer iteration and inner iteration to a solution at one time step. Outer iterations are used to vary the factorized parameter matrix in an approach toward the solution. An outer iteration is where the hydro-geologic parameters of the flow system are updated (i.e. transmissivity, saturated thickness, storativity) in the factorized set of matrices (Guiger and Franz, 1996). Different levels of factorization allow these matrices to be initialized differently to increase the efficiency of the solution and model stability. Inner iterations are used iteratively to solve the matrices created in the outer iteration. Maximum number of inner iterations can be 500 (Guiger and Franz, 1996). After the outer iteration is completed, solver checks for the maximum change in the solution at every cell. If the maximum change in the solution is below the set convergence tolerance than the solution has converged and the solver stops, otherwise a new outer iteration starts. Solver uses two convergence/termination criteria; (i) change in head, and (ii) mean residual between consecutive iterations and at convergence of the problem. Change in head criteria is used to judge the overall solver convergence, while the residual criterion is used to judge the convergence of the inner iterations of the solver. If the change in successive inner iterations is less than the defined tolerance then the solver proceeds with the next outer iteration (Guiger and Franz, 1996), otherwise it terminates the solution.

6.5 Groundwater Model for Tawa Command Area

The objective of the groundwater modelling in TCA is to know present state and probable change in groundwater system due to change in water allocations through conjunctive use modelling. Step wise procedure followed for the present study is shown in Figure 6.1 and there after a brief discussion on the conceptualization of the groundwater model for a canal command area is given.

6.5.1 Conceptualization of Groundwater Model

Model conceptualization is the process of assembling data that describes the field conditions in a systematic method to represent the groundwater flow processes. The first step in developing the groundwater model is to define the study area and the boundary conditions. GIS tools and remote sensing data are valuable in conceptualization of groundwater modelling as this data gives the real conditions of the site spatially and temporally. The aquifer geometry of a groundwater model is defined using the geological and hydrological data collected for the study area. A land use land cover map (as described in Section 4.5) is used to calculate the recharge over the study area. Aquifer thickness is derived using DEM and Litholog data available in geodatabase discussed in Chapter 4.

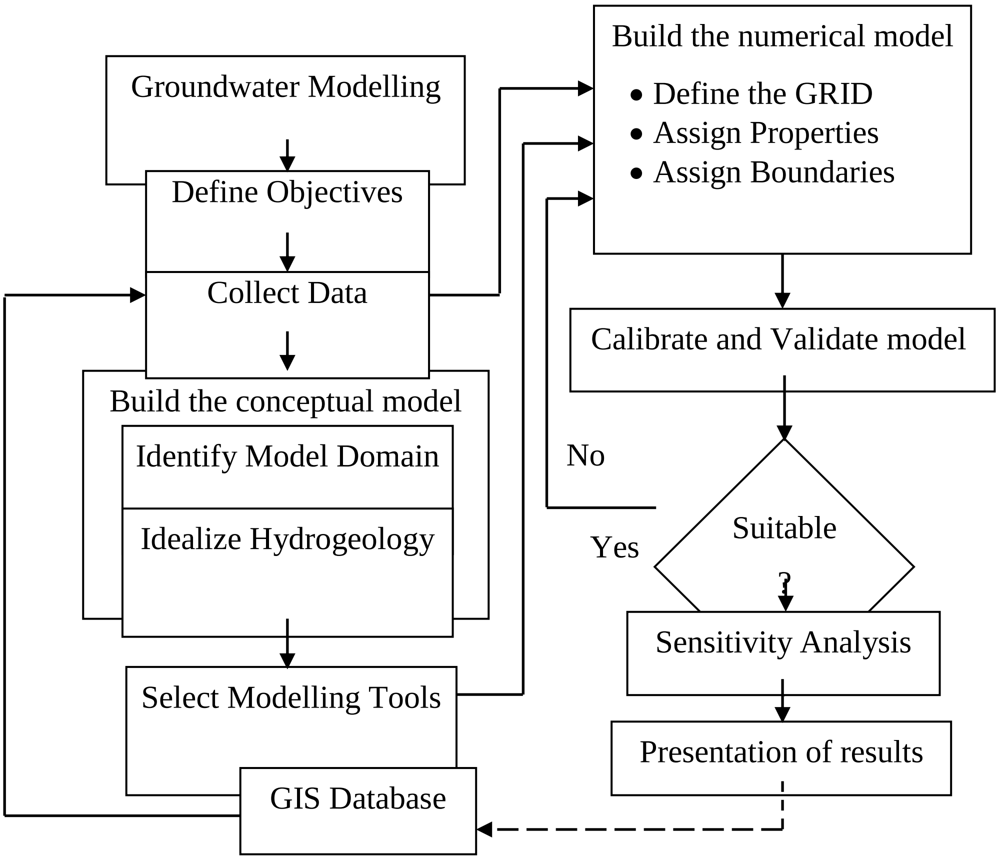


Figure 6.1: Steps in groundwater modelling

6.5.2 Model Grid Design

The continuous model area is divided into square or rectangular regions called cells. Head computed at discrete points are called nodes. The network of cells and nodes are called grid or mesh. The nodal grid forms the framework of the mathematical model. A finite difference approximation method will have either block centered or mesh centered grid blocks. The name of the technique refers to the relationship of the node to the grid lines. Head is computed at the centre of the rectangular cell in the block centered approach whereas it is computed at the intersection of grid lines in the mesh centered technique.

In the present study, block centered approach has been adopted. This grid is prepared by importing Tawa Command boundary file from geodatabase, to define boundary in X-Y domain. A finite difference grid is designed by manipulating rows, columns and layers of cells. A series of cells oriented in the x-direction is called a row and a series of cells aligned along the y-direction is called column. A horizontal two-dimensional network of cells is called layer. Cells are designated using row and column coordinates, with the origin in the upper left corner of the mesh. The upper left cell is designated as row 1 and column 1. The upper layer is layer 1 and layers increase in number downwards. The size of the grid depends on the availability of data, the size of the area and the spatial resolution requirement of final results. For the current groundwater model, 500 m ×500 m grid is adopted with 244 rows and 406 columns. In the Tawa Command Area, most of the water available is from unconfined aquifer system, so the top phreatic aquifer is conceptualized for groundwater modelling in this study.

Model domain in the vertical direction is defined in the form of two surfaces (layers). First layer is represented by the ground surface. Second layer is represented by the bottom of the alluvial aquifer. ESRI GRID files, DEM (Fig. 4.5, Chapter 4) and aquifer thickness map are imported from geodatabase into MODFLOW framework to define the model boundary in Z- direction. The model grid in X-Y and X-Z domain are shown in Figure 6.2 and Figure 6.3 respectively.

6.5.3 Time Discretization

Time discretization is the time step adopted in the simulation of groundwater. In the present investigation, one year period has been divided into two seasons starting from May to October, and November to April. Seasonal time step has been adopted for defining the initial and boundary conditions, whereas monthly time step has been used for River Narmada. Monthly time step, starting from May has been used throughout the groundwater simulation.

Model has been calibrated for a 4 year time period (May 1997 to May 2001) and validated for a period of two year (2002 to 2003). Time discretization for the different input parameters are presented in Table 6.1.

Table 6.1: Time discretization adopted for different parameters and groundwater simulation

Parameter	Time discretization
Recharge (Rainfall, Irrigation return Flow, Canal seepage)	Seasonal
Narmada River (River boundary)	Monthly
Specified head boundaries	Seasonal
Groundwater withdrawal	Seasonal
Simulation time step	30 days
Water zone budget	Seasonal
Piezometric head	Seasonal
Calibration period	4 Years
Validation period	2 Years

6.5.4 Hydraulic Parameters of Groundwater Model

Two hydraulic parameters, saturated hydraulic conductivity (K) and specific storativity (specific yield (Sy) for unconfined aquifer) are defined on a cell basis. Hydraulic conductivity map has already been given Fig. 4.6 (Chapter 4). Initial values of hydraulic parameters have been used in the present study have already been presented in Table 3.3 (Chapter 3).

6.5.5 Groundwater Levels

Observed data of groundwater levels from 70 observations wells was available for the TCA. Water levels have been obtained for all the wells for a period of 8 years (1996 to 2003). Rainfall data was available from 1997 to 2003. So the groundwater model has been simulated for the period of 8 years (1997-2003). Pre monsoon water levels have been recorded at the end of May and post monsoon water levels have been measured at the end of November by Central Ground Water Board (CGWB), Bhopal. Pre-monsoon water levels of year 1997 have been used to define the initial head distribution (initial condition). Observation wells have been defined as point data in ESRI shape file by specifying the respective field to generate a water level surface in the model. Location of observation wells have been shown in Fig. 4.7 (Chapter 4).

6.5.6 Groundwater Recharge

Groundwater recharge takes place in three ways; (i) rainfall recharge, (ii) irrigation return flow (IRF), and (iii) canal seepage. Season-wise recharge values have been obtained from CGWB, Bhopal and Khare (2003). For initial conditions, these values are used for calibration. Rainfall data was available on block basis and season wise, and 50 year normal rainfall distribution on monthly basis. So block basis rainfall has been distributed monthly with reference to monthly 50 year normal rainfall over monsoon and non-monsoon periods. Table 6.2 shows the distribution monsoon and non monsoon rainfall of Hoshangabad block on monthly basis. In the similar way for all the years and all the blocks the rainfall has been calculated. According to GEC (1997), 12 percent of rainfall goes as recharge to groundwater. Irrigation return flow has been taken from CGWB report (Anonymous 1996) and is given in Table 6.3.

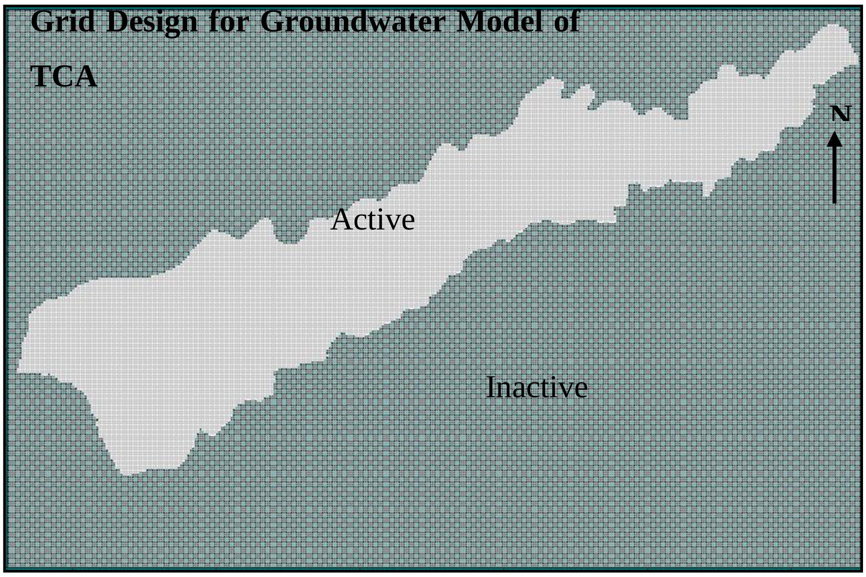


Figure 6.2 Space discretization of aquifer in MODFLOW

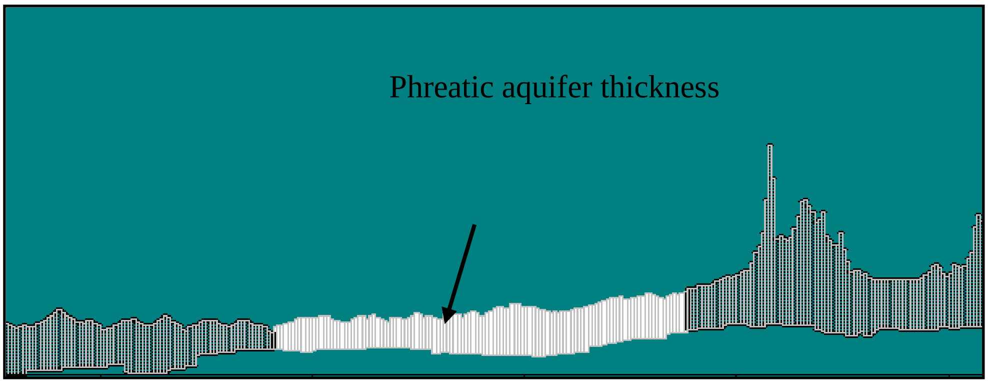


Figure 6.3 Lithological sections of the aquifer in North-South direction

Table 6.2: Rainfall distribution for Hoshangabad block on monthly basis

Hoshangabad	Jan	Feb	Mar	Apr	May	June	Jul	Aug	Sep	Oct	Nov	Dec	Monsoon month -total (mm)	Non Monsoon month -total (mm)
50 yr. Normal Rainfall (mm)	11.00	6.30	3.30	11.40	143.30	430.20	396.50	396.50	215.40	28.50	21.30	10.70	1438.60	235.80
% distribution	4.66	2.67	1.40	4.83	60.77	29.90	27.56	27.56	14.97	12.09	9.03	4.54		
Year-1997 (mm)	11.06	6.33	3.32	11.46	144.03	317.58	292.70	292.70	159.01	28.65	21.41	10.75	1062.00	237.00
Rainfall Recharge @12% (mm)	1.33	0.76	0.40	1.38	17.28	38.11	35.12	35.12	19.08	3.44	2.57	1.29		

Table 6.3: Irrigation return flow

Blocks covered	Area (Km^2)	Irrigation return flow				Total		Total Recharge (mm)	
		Surface		Groundwater					
		ha-m							
		Monsoon	Non Monsoon	Monsoon	Non Monsoon	Monsoon	Non Monsoon	Monsoon	Non Monsoon
Seonimalwa	864	1914	574	6	54	1920	628	22	7
Hoshangabad	398	1770	5310	17	152	1787	5462	45	137
Itarsi	301	804	2412	1	13	805	2425	27	81
Babai	529	870	2610	33	293	903	2903	17	55
Sohagpur	420	1740	5220	19	169	1759	5389	42	128
Pipariya	160	930	2790	4	40	934	2830	58	177
Bankheri	28			1	7	1	7	0.4	3

Canal seepage has been calculated according to GEC (1997). For unlined canals in normal soils with some clay content along with sand, the value of canal seepage is 1.8 to 2.5 m3/s per million m² of wetted area (Choudhary and Chahar,2007; Chahar,2009). In this study, latter value has been adopted. Wetted perimeter has been taken from the CGWB report (Anonymous, 1996), Canal length has been obtained from GIS database. For Tawa Left Bank main Canal (LBC), Barga Branch Canal (BBC), and Pipariya Branch Canal (PBC) recharge is assigned individually. For all other canals, canal seepage is distributed over the command area on cell basis. Table 6.4 gives the details of canal seepage. Total canal running days are taken to calculate the total seepage. Around 10% of total seepage has been allotted in monsoon season while assigning canal recharge to groundwater model as in the monsoon season, the canal runs only for 12 to 23 days. In the MODFLOW, recharge has been converted in mm/year by dividing the total seepage with respective area. Land use land cover maps prepared, have been converted into vector format (ESRI shape files) to define spatial extent of land use classes to define recharge for May and November time step.

Table 6.4: Canal seepage in the TCA

Canal length (km)	Canal length (km)	Wetted perimeter (m)	No. of canal running days	Seepage factor (m^3/million m^2 of wetted area)	Total seepage (MCM)
LBC	120.12	34.14	155	2.5	54.91
BBC	30.02	13.9	155	2.5	5.58
PBC	61.23	14.05	155	2.5	11.52
Other canals over command area	1029.37	1712.6	155	2.5	380.64

6.5.7 Groundwater Draft

Groundwater draft of TCA is given in Table 3.6 (Chapter 3). Representative pumping wells have been given in the model according to population of wells in the command area. 30% of total draft is taken for monsoon and remaining for non monsoon period. Block wise pumping per well is given in Table 6.5. Year wise pumping is not available therefore pumping and number of wells are kept constant for total period. Total groundwater withdrawal has been simulated in the form of pumping wells.

6.5.8 Boundary Conditions

Boundary conditions are mathematical statements which specify the dependent variable at the boundaries of the problem domain. Selection of appropriate boundary conditions is an important step in the model design. The flow pattern in the whole flow domain for steady state simulation is determined by the boundary condition. Any wrong selection of boundary conditions will affect the transient simulation and thereby one will lose the realistic solution of groundwater model.

Table 6.5: Block wise groundwater draft in TCA

Name of Block	No. of wells	Draft				
		Per well	Monsoon	Non monsoon	Monsoon	Non monsoon
		ha-m			m^3/day	
Piparia	13	598	179	419	9802	22997
Sohagpur	30	90	27	63	1470	3449
Babai	32	62	19	43	1013	2376
Hoshangabad	24	148	44	103	2420	5678
Kesla	11	561	168	393	9195	21573
Seonimalwa	40	133	40	93	2180	5114
Timarani	20	148	45	104	2432	5706
Harada	32	75	22	52	1223	2869

In broad categories, boundaries can be classified in two aspects viz. physical and hydraulic. Water level contours drawn from field data will help to some extent to delineate the boundaries. End point of flow regime, outcrops (impermeable), water body viz. sea, big lakes, and perennial rivers encountered in the model area. In the present study, northern boundary is Narmada River which is a perennial river and has been taken as a physical boundary. In many applications, it may not be possible to assign the boundary of the model as the physical boundary of the system. In that case, one has to resort to the hydraulic conditions as the boundary conditions at the boundary.

Hydraulic boundaries are represented by:

i) specified head boundaries or constant head boundary, wherein this type of boundary, head is constant throughout the simulation period,

ii) specified flux boundary where zero flux specifies for no flow boundary. In the present study, the eastern side of the TCA, near Dudhi river, the boundary has been defined as no flow boundary and

iii) Head dependent boundary wherein flux is calculated for variable head and assigned accordingly. This type of a condition is called a Cauchy or mixed boundary condition as it relates the boundary flows to the boundary head. The simulation of river-aquifer interaction, general head and stream are called head dependent boundaries.

Figure 6.4 shows the boundaries for the present groundwater model. Other major tributaries of Narmada River in the command area have been given as river boundary condition to simulate the influence of these surface water bodies on the groundwater system. Machak reservoir has been given as recharge boundary due to non-availability of reservoir water level data. From the satellite imagery reservoir boundary has been delineated and used in groundwater model.

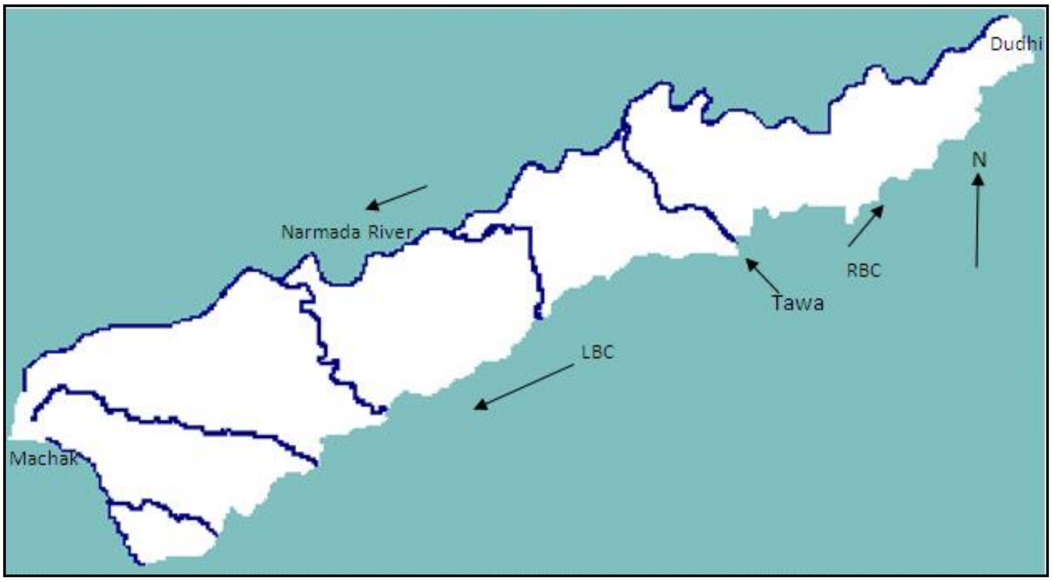


Figure 6.4 Location of different boundaries

6.5.9 Tolerance Criteria

The selection of tolerance level (convergence and model termination) depends on the acceptable standards of the accuracy in the results. The adoption of large convergence thresholds leads to relatively less accurate results. On the other hand, small thresholds will increase the computational time. In the present study, WHS solver has been used for solving the governing partial differential equations. Maximum number of inner and outer iterations, head change in successive iterations, residual, and relative residual criterions have been used as the convergence thresholds. Details of the criteria are given in Table 6.6.

Table 6.6: Convergence thresholds adopted in WHS solver

Tolerance Criteria	Threshold value
Maximum number of outer iterations	50
Maximum number of inner iterations	100
Head change between successive iterations	0.01 m
Residual	0.01 m
Relative residual	0.0 m

6.6 INVERSE AND DIRECT PROBLEM OF GROUNDWATER MODEL

Simulation of the response of aquifer to a deterministic pattern of stresses is known as direct problem (Fig. 6.5a) in groundwater hydrology. To simulate the aquifer response, appropriate initial and boundary conditions are imposed with known aquifer parameters. The data requirement for carrying out such a study includes the spatially distributed estimates of transmissivity (T) and storage coefficient (S)/ specific yield (Sy). Pumping test is one of the popular methods of estimating these parameters. It involves generating the aquifer response to the pumping in a single well. The generated data are analyzed to arrive at the estimates of aquifer parameters. The aquifer parameters so obtained represents only that portion of the aquifer which lies within the radius of influence of the well used for the pumping test.

Another approach for estimating S and T, known as inverse problem, is to employ the historical data of aquifer response and the corresponding aquifer excitations (Fig. 6.5 b). The aquifer excitations can be either of the form of vertical acceleration (pumping or recharge) or change in boundary conditions. The model is first calibrated against historical data. The calibration process invariably requires adjustments in the aquifer parameters. The estimation of these parameters is thus, an inverse process wherein these parameters are calculated from the historical excitation response and the associated initial and boundary conditions data.

6.7 Calibration of Groundwater Model

Model calibration consists of changing values of model input parameters in an attempt to match field conditions within some acceptable criteria after proper characterization of field conditions. This process is an inverse modelling problem which involves aquifer parameter estimation through matching of simulated and historical data of hydraulic heads. The calibration process typically involves calibrating to steady-state and transient-state conditions.

In the present groundwater model, model calibration has been done using parameter optimization module, which is called PEST, of Visual MODFLOW 4.2. Visual MODFLOW have an interface for parameter estimation module developed by Dr. John Doherty (Doherty, 1998).

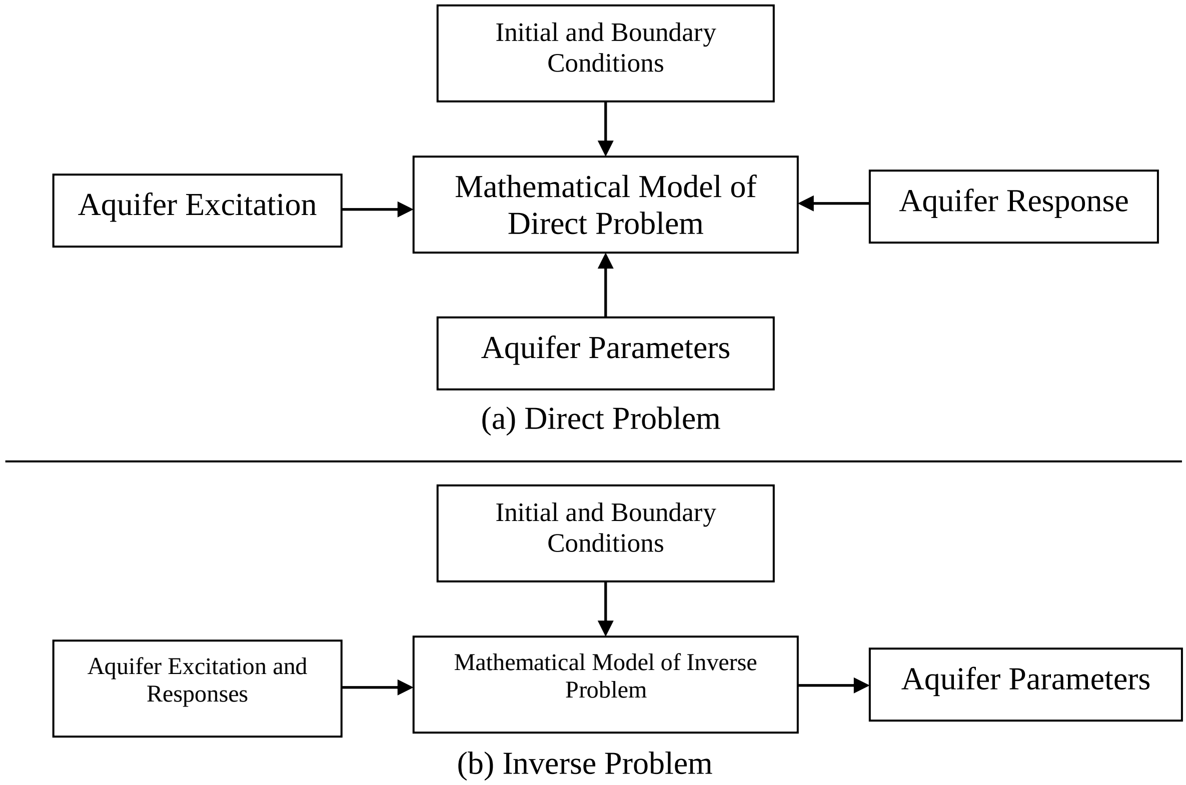


Figure 6.5: Direct and inverse problems in groundwater hydrology (Khare, 2003)

6.7.1 Parameter Optimization using PEST

The PEST is a non-linear parameter estimation program, which can be used for parameter estimation as well as for the prediction (Doherty, 1998). The PEST minimizes the weighted sum of squared differences between calculated and observed values. This sum of weighted squared model to measured discrepancies is called an objective function. In parameter estimation mode, PEST adjusts the model parameters and disturbances until the fit between calculated hydraulic heads and observation heads is optimized. The Gauss-Marquardt-Levenberg algorithm (Levenberg, 1944; Marquardt, 1963) has been used in the PEST for parameter optimization.

For linear models, optimization can be achieved easily. However, for distributed non-linear problems parameter estimation is an iterative process. Most of the cases of groundwater models are non linear in nature. At the beginning of each iteration n, the relationship between model parameters and model-generated observations is linearized using Taylor series expansion about the current best parameter set. This "linearized" problem is then solved for a better parameter set, and the new parameters have to be tested by running the model again.

The PEST compares the changes in parameters with improvement in the objective function and decides whether it is worth doing optimization iteration again, based on the defined convergence criteria adopted. If so, the whole process is repeated. At the beginning of a PEST run, a set of initial parameter values is to be defined. The PEST uses these values at the start of its first optimization iteration. Derivatives of observations with respect to parameters are calculated using finite differences. The model is run once for each adjustable parameter for each optimization iteration.

While estimation process, PEST writes a detailed run record to a (*.REC) file. While calculating derivatives, PEST records the sensitivity of each parameter with respect to the observations. At the end of the parameter estimation process (at convergence) PEST records the optimized value of each adjustable parameter together with its 95% confidence interval. It tabulates the set of field measurements, their optimized model-calculated counterparts, and the difference between each pair. Then, it calculates the parameter covariance matrix, the parameter correlation coefficient matrix and the matrix of normalized eigenvectors of the covariance matrix (Doherty, 1998).

6.7.2 Calibration Parameters

Calibration parameters for a groundwater model may include hydraulic conductivity and storage capacity of the aquifer material. In the present study, hydraulic conductivity (Kxx, Kyy, Kzz), specific yield (Sy) and recharge (from rainfall, irrigation return flow and canal seepage) factors have been considered as calibration parameters. Rainfall recharge has been calibrated in the form of recharge factor, which is the ratio of calibrated recharge to initially supplied recharge. The study area has been discretized into different spatial zones of homogeneous hydraulic parameters and recharge. A set of chosen parameters (Kxx, Kyy, Kzz, Sy & recharge factors) are calibrated for each defined zones (Fig. 4.7, Chapter 4). Calibration has been performed in several trials with different initial values of selected parameters. Initial values of aquifer hydraulic parameters have been selected from the data obtained from various sources as mentioned in Chapter 3. Initial values of rainfall recharge and canal seepage have been estimated using the GEC methodology (GEC, 1997). Irrigation return flow has been taken from technical reports of Tawa Command Area (Anonymous, 1996).

Range of initial values, lower and upper limit of calibration parameters used in the present study are given in Table 6.7. Initial value of recharge factor has been adopted as 1.0, and the range of 0.25 to 2.5 times of initial value fixed in calibration process.

6.7.3 PEST Control Parameters

Calibration process is controlled in the PEST by defining the different parameters related to Marquardt lambda, parameter change constraints and termination criteria. Limiting values of these parameters have been adopted as suggested by Doherty (1998). Different controlling parameters adopted in the present study for the calibration of groundwater model are presented in Table 6.8.

Finally, the model has been calibrated in transient state from year 1997-2001 using the narrow range of aquifer parameters obtained from various agencies and verified from steady state calibration. Further, model results have been validated corresponding to observed data of two years (2002-2003). Validated hydraulic parameters have been used for further analysis.

Table 6.7: Range of initial values of hydraulic parameters used in the calibration process

Formation	Hydraulic conductivity (Kxx and Kyy), m/day				Specific yield (for initial, lower and upper limits)	
	Initial		Lower limit	Upper limit		
	From	To			From	To
Alluvium	1	65	1	100	0.001	0.12

Table 6.8: PEST control parameters used in the calibration

Marquardt lambda		Parameter change constraint		Termination criteria	
Controlling parameter	Limiting value	Parameter	Limiting value	Criteria	Limiting value
Initial lambda	10	Maximum relative parameter change	10	Overall iteration	50
Adjustment factor	2			Negligible reduction	0.01
Sufficient Phi ratio	0.3	Maximum factor parameter change	10	Max. no reduction iterations	3
Limiting relative Phi reduction	0.02			Max. unsuccessful iterations	3
Maximum trial lambdas	10	Use-If less friction	0.001	Negligible relative change	0.01
				Max. "no change" iterations	3

6.7.4 Statistical Approach for Error Criteria

Calculation of the error associated with each target (head, drawdown, concentration or flux) and then computing simple statistics on the population of targets will be useful in evaluating the merit of the calibration. The error is called residual and it is the difference between the computed and observed target values. Negative residuals indicate that the model is calculating the dependent value too high and a positive residual, where the model value is too low.

The type of statistics computed could include the following (Hill and Tiedeman, 2007):

i) Sum of square residuals: Squaring all the residuals and adding them together compute the sum of squared residuals. This statistics is useful tool to plot on sensitivity curves and also used by inverse models in automated calibration process like PEST.

ii) Residual mean: the residual mean is computed by dividing the sum of residuals by the number of residuals. Because both positive and negative residuals are used in calculation, this value should be close to zero for good calibration. It means the positive and negative errors should balance each other.

iii) Residual Standard deviation: The residual standard deviation is a measure of overall spread of residuals. It is a ± value. The residual standard deviation can be compared to the overall range in target value as further comparison. Normally this value should be less than 10 to 15 percent for a good calibration.

iv) Absolute mean error: the absolute mean error is calculated using absolute value of the error and is measure of the average error in the model.

v) Root mean squared (RMS) error: The root mean squared error is the average of the squared differences in measured and simulated heads.

All the above statistical error measures mentioned, quantify the average error only and nothing could infer about the distribution of error. The comparison of computed and observed head provides only a qualitative and subjective indication of the spatial distribution of error. It is therefore recommended to have a quantitative analysis of error distribution in all calibration process.

6.7.5 Steady State Simulation

Steady state solution is often used as starting conditions since the real steady state conditions rarely exist in practice. The steady state model presumes a balance of input and output quantities of an aquifer so that the water head remain invariant. This means there is no change in the storage and thus, it is only the hydraulic conductivity, in the case of unconfined aquifers and the spatial distribution of input/output quantities, which are modified in the steady state calibration. The modification of parameters should be in small steps keeping in view the hydro-geological information. Once a reasonable match is obtained between observed and computed water levels, the hydraulic conductivity values and the spatial pattern of the input/output quantities can be used for the second stage transient calibration.

In the present study, initially the model has been calibrated for steady state to know the stability of the model conceptualization and to verify the given range of aquifer parameters and their spatial distribution. Initial steady state calibration has been done manually to know the modeling mechanism and afterwards PEST has been used by considering the above mentioned criteria for calibration.

Calibration has been done for a one year period from May 1997 to April 1998, pre monsoon 1997 water levels have been used for initial condition. Initial calibration has been done for aquifer parameters. Recharge factors have been adjusted afterwards. Initially, hydraulic conductivity in X and Y directions (Kx and Ky) has been assumed to be same, while in Z direction, it has been assumed as one tenth of the horizontal conductivity in X direction. During the calibration process, it has been observed that hydraulic conductivity in Y and Z directions is relatively insensitive. Therefore, in later trials hydraulic conductivity in Y and Z directions has been tied with the hydraulic conductivity in X direction i.e. their ratio with hydraulic conductivity in X direction remains same. Figure 6.6 shows the computed water level contours and topographical contours. In general, it has been observed that the water level contours follows the topography. This should be achieved while steady state calibration to go further for transient state simulation. Trend of water level contours has been found satisfactory with reference to topographical contours. Figure 6.7 shows the computed and observed hydraulic heads. Root Mean Square (RMS) error for steady state simulation has been around 3.579 m which is acceptable as trend of contours follow the topography which is important for steady state simulation.

6.7.6 Transient State Simulation

After checking the stability of the model and ascertaining the range of hydraulic parameters, one can proceed for transient state simulation. Transient simulation involves the change in hydraulic head with time. These simulations are required to narrow down the range of variability in model input data since there are numerous choices of model input data values which may result in similar steady-state simulations. Model calibration should include comparisons between model-simulated conditions and field conditions for hydraulic heads, groundwater flow directions, and water mass balance. Further, calibration process can be judged using various criteria, which include residual mean, absolute residual mean, RMSE, normalized root mean square error (NRMS) and correlation coefficient determined for the simulated versus observed hydraulic heads.

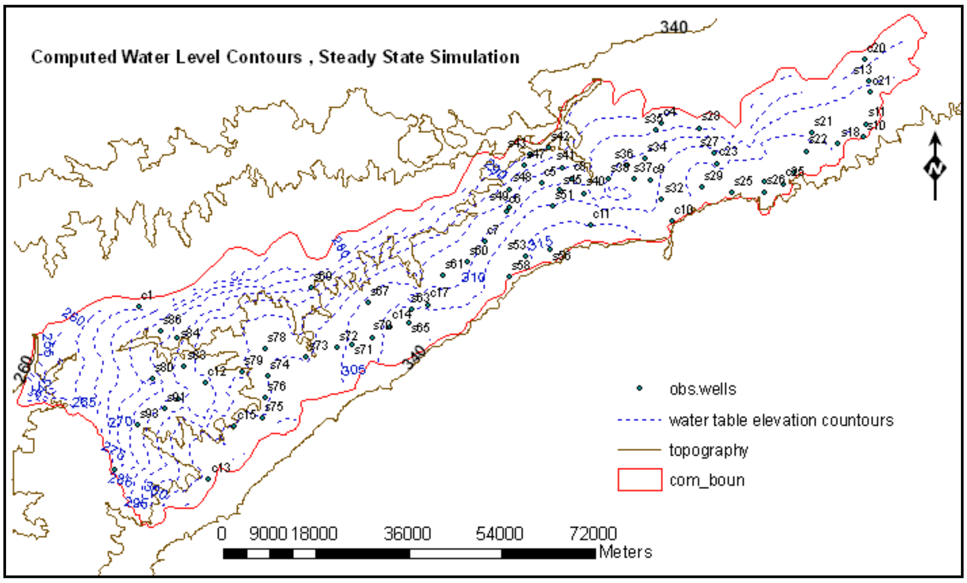


Figure 6.6 Computed water level contours under steady state simulation

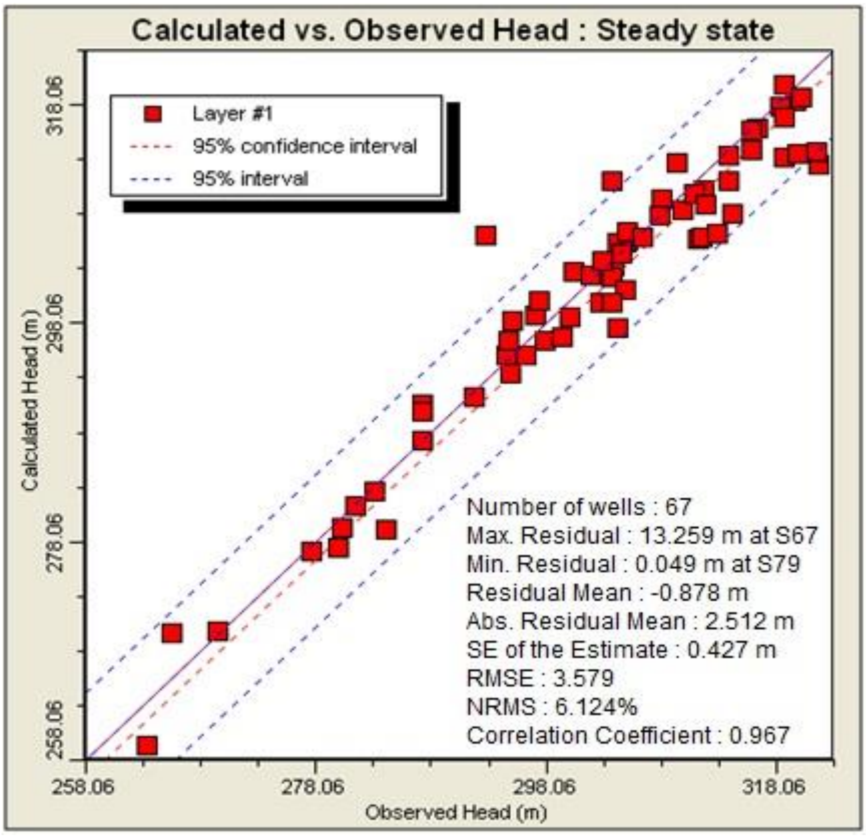


Figure 6.7 Computed vs. observed head in steady state simulation

Groundwater model has been calibrated in transient state for a period of 4 years (1997-2001). PEST algorithm has been run several times with different set of initial, lower and upper bounds of calibration parameters (Table 6.7) to check the consistency of the calibration process and to eliminate the chances of over calibration. The over calibration is such a stage at which results in a model appears to be calibrated but are based on a dataset that is not supported by field data i.e. not within the range of reported field values (Hill and Tiedeman, 2007). In the present study, over calibration has been restricted by placing the lower and upper bounds of the calibration parameters for each zone separately. Accuracy of calibration has been judged by comparing, NRMS, RMS, absolute mean value of the differences between the calculated head and observed heads and NRMS.

At the end, calibration statistics has been generated, which includes different criterions to judge the calibration quality. Calibration statistics includes calibration residual, RMS in m, NRMS in %, mean residual in m (difference of calculated and observed head), absolute mean residual and standard error of estimate (SE),which are determined for monthly and seasonal time steps. These are also called calibration errors and frequently used to assess the success of calibration.

The calibrated and validated statistics for different time steps (Fig. 6.8) shows that the residual mean varies from -0.1.65 to 1.18 m which is slightly high, absolute residual mean varies from 1.6 to 2.375 m, it is the average error in the model and in acceptable limits. NRMS varies from 3.27% to 5.248 %, which should be less than 10 to 15% for a good calibration and RMS varies from 1.88 m to 3.05 m which is acceptable (Thangarajan, 2004) for the calibration period (0-1643 days) and validation period (1643-2190 days).

6.7.7 Validation of Groundwater Model

The calibrated groundwater model has been verified by historical data matching over a period of two year (2002 to 2003) in all the observation wells and for six years in some of the selected wells which have not been used in calibration process, to check model consistency. History matching uses the calibrated model to reproduce a set of historic field conditions. The most common historical matching scenario consists of reproducing an observed change in the hydraulic head over a different time period, typically one that follows the calibration time period.

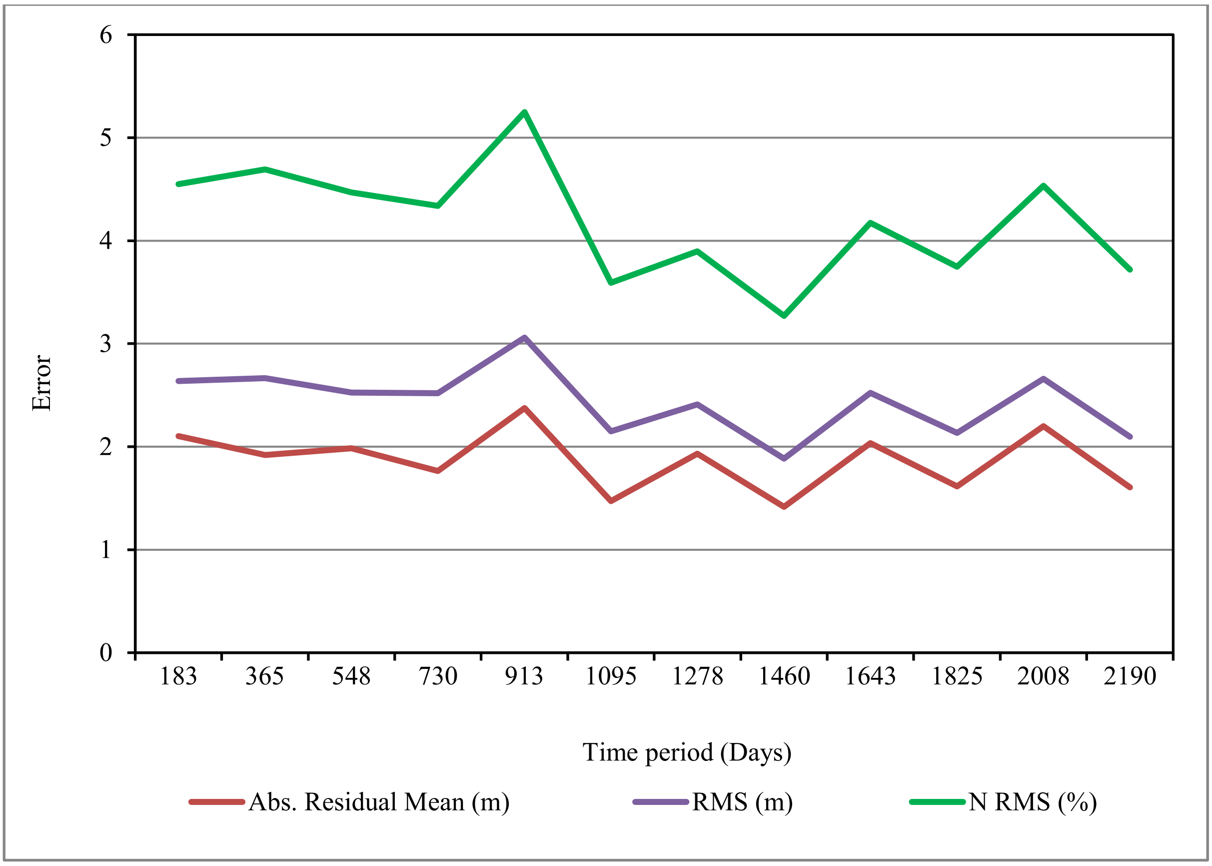


Figure 6.8: Errors in transient calibration (0-1643) and validation (1643-2190)

In the present study, calibrated model has been used to simulate the aquifer under stressed conditions i.e. with new set of data (stresses and boundary conditions). Aquifer parameters and recharge factors have been kept same during this process. Further, various errors statistics have been generated along with the simulated groundwater levels. NRMS error has been found between 3.72 to 4.5%, which is within acceptable limits (<15%). Absolute mean residual has been found to be 1.66 to 2.3 m. The simulated groundwater levels have been compared with observed levels. Matching of simulated and observed groundwater levels are shown in Fig. 6.9 to Fig. 6.13 for different blocks in the TCA. Validation results reveals that there has been an acceptable match between simulated and observed groundwater levels and it can be noted that the model has successfully reproduced the measured changes in field conditions for both the calibration and validation (history matching) time periods, the calibrated groundwater model is ready for use in conjunctive use model.

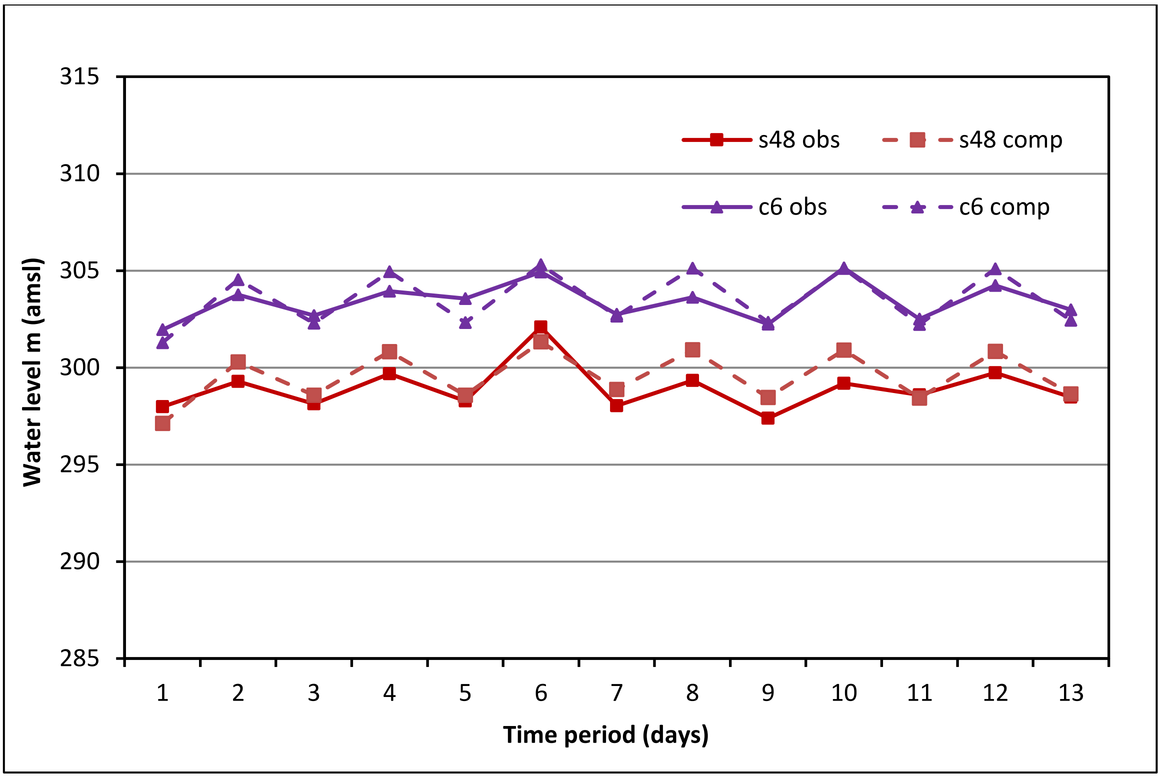


Figure 6.9 Computed vs. observed well hydrographs in Hoshangabad block

(calibration and validation period)

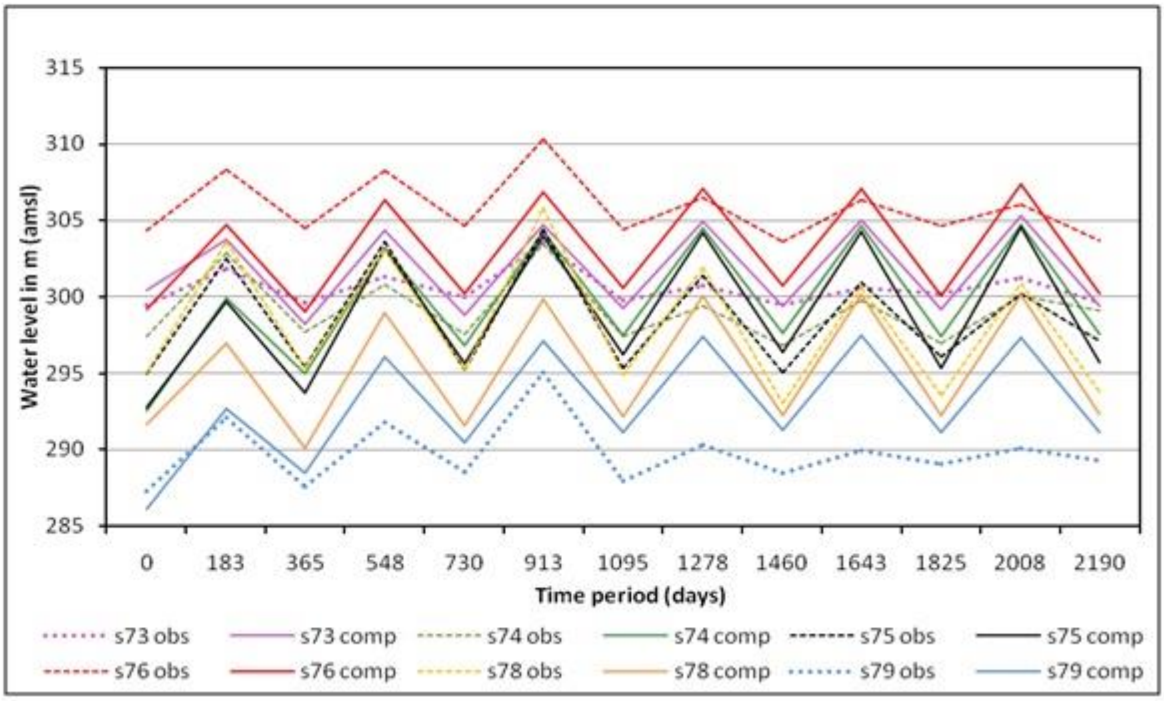


Figure 6.10 Computed vs. observed well hydrographs in Timrani block

(calibration and validation period)

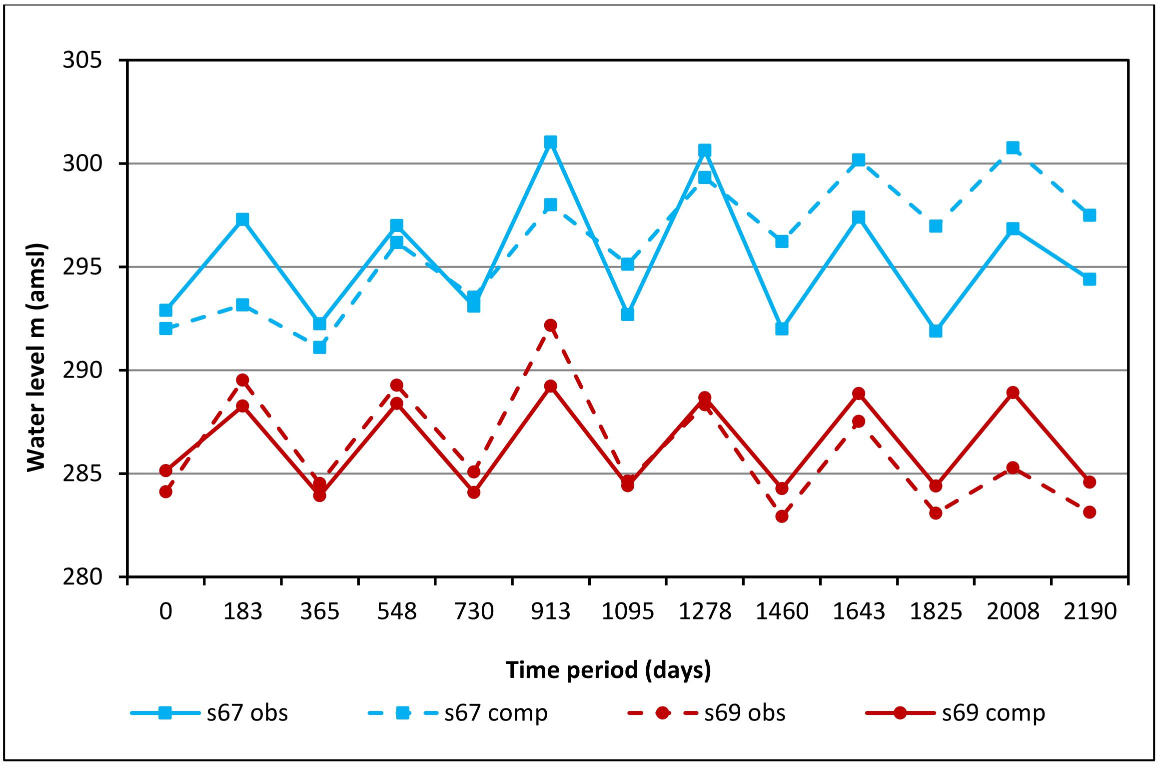


Figure 6.11 Computed vs. observed well hydrographs in Seonimalwa block

(calibration and validation period)

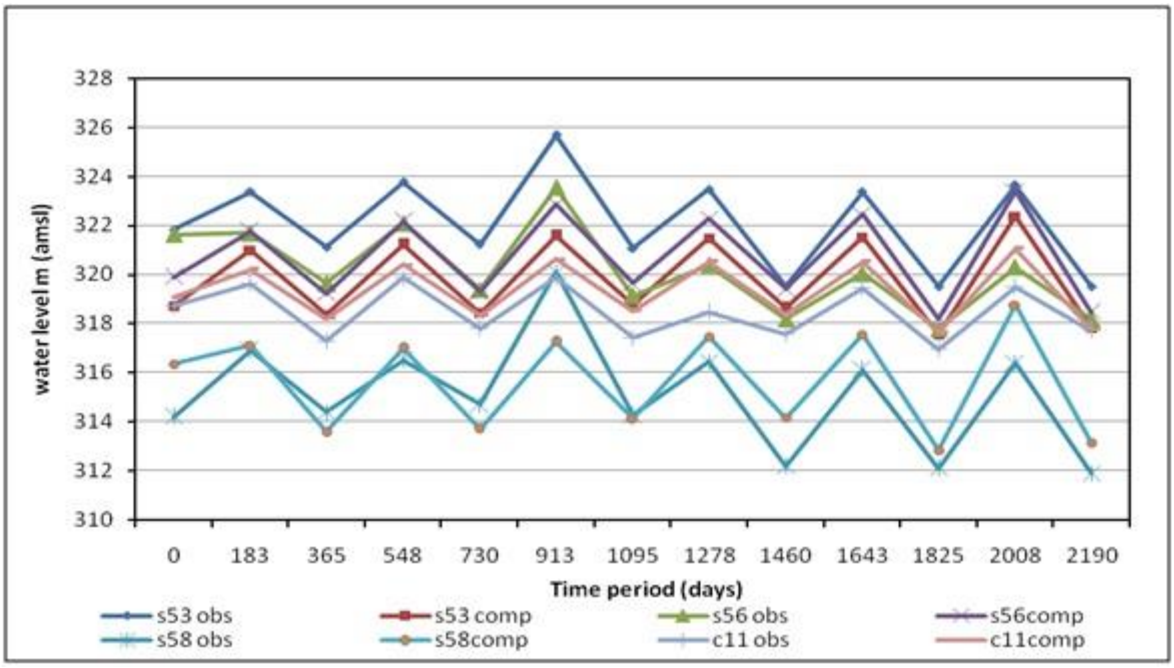


Figure 6.12: Computed vs. observed well hydrographs in Itarsi block

(calibration and validation period)

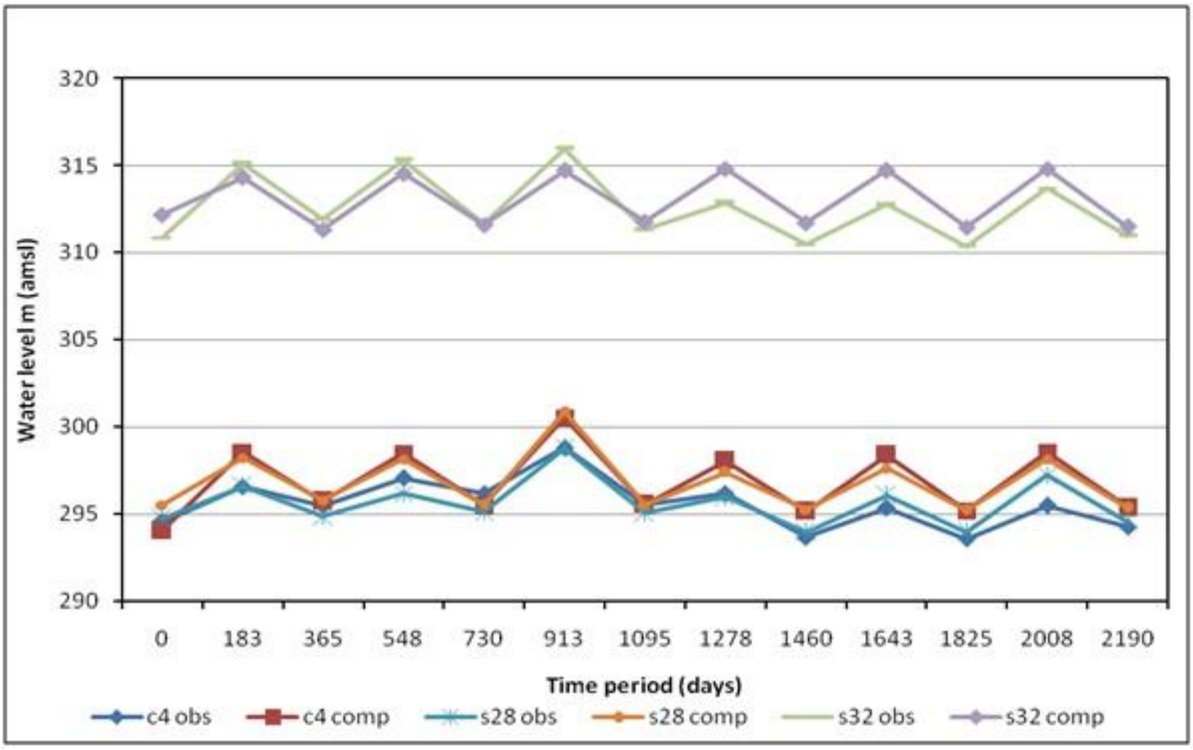


Figure 6.13: Computed vs. observed well hydrographs in Babai block
(calibration and validation period)

6.8 SENSITIVITY ANALYSIS

A sensitivity analysis has been performed for the calibrated aquifer parameters and recharge and the corresponding changes have been observed in the model. The purpose of the sensitivity analysis was to demonstrate the behaviour of the model simulations to uncertainty in values of model inputs. In the present study, the sensitivity analysis has been performed for hydraulic conductivity 'K', specific yield (Sy), and recharge (RCH). Model is run for the different values of parameters considered for sensitivity analysis and changes in errors (NRMS, RMS, Absolute mean residual) have been recorded.

The model has been found to be more sensitive to recharge and hydraulic conductivity as compared to specific yield. This trend has also been indicated by the relative mobility in the value of mean errors between the value of mean error corresponding to calibrated parameters and value of mean error obtained due to percent change in input parameters with respect of calibrated parameters. The normalized errors are tabulated in Table 6.9. It can be seen that the NRMS error (%) increases by 2.49 times with a 30% decrease in hydraulic conductivity, whereas it increase by 2.07 times with a 30% increase in hydraulic conductivity (Fig. 6.10a). In case of recharge, the model is more sensitive as compared to conductivity. NRMS error increases by 4 times for a 20% decrease in calibrated recharge values. For a

20% increase in recharge, the error is 2.8 times the base value (Fig. 6.16). Error in all model output has increased by percentage change in base values of aquifer parameters and recharge. In case of specific yield it has been observed (Fig. 6.15) that the small change occurs in error as compared to recharge and conductivity.

Table 6.9: Sensitivity analysis for calibrated aquifer parameters and recharge

% Change	Errors due to % change in K (times)				Errors due to % change in RCH (times)				Errors due to % change in Sy (times)			
	NRMS	SEE	RMS	ARM	NRMS	SEE	RMS	ARM	NRMS	SEE	RMS	ARM
-30	2.94	2.92	3.04	3.01	6.47	3.95	6.46	6.42	1.36	1.24	1.36	1.31
-20	1.88	1.52	1.88	2.12	4.44	2.58	4.44	4.44	1.17	1.12	1.17	1.12
-10	1.12	1.09	1.12	1.23	2.15	1.19	2.15	2.19	1.07	1.05	1.07	1.04
0	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
10	1.16	1.02	1.16	1.17	1.39	0.73	1.39	1.48	1.01	1.12	1.11	1.05
20	1.59	1.14	1.59	1.68	2.81	1.44	2.81	3.00	1.16	1.17	1.20	1.19
30	2.07	1.32	2.07	2.24	4.11	2.06	4.10	4.40	1.19	1.19	1.23	1.24

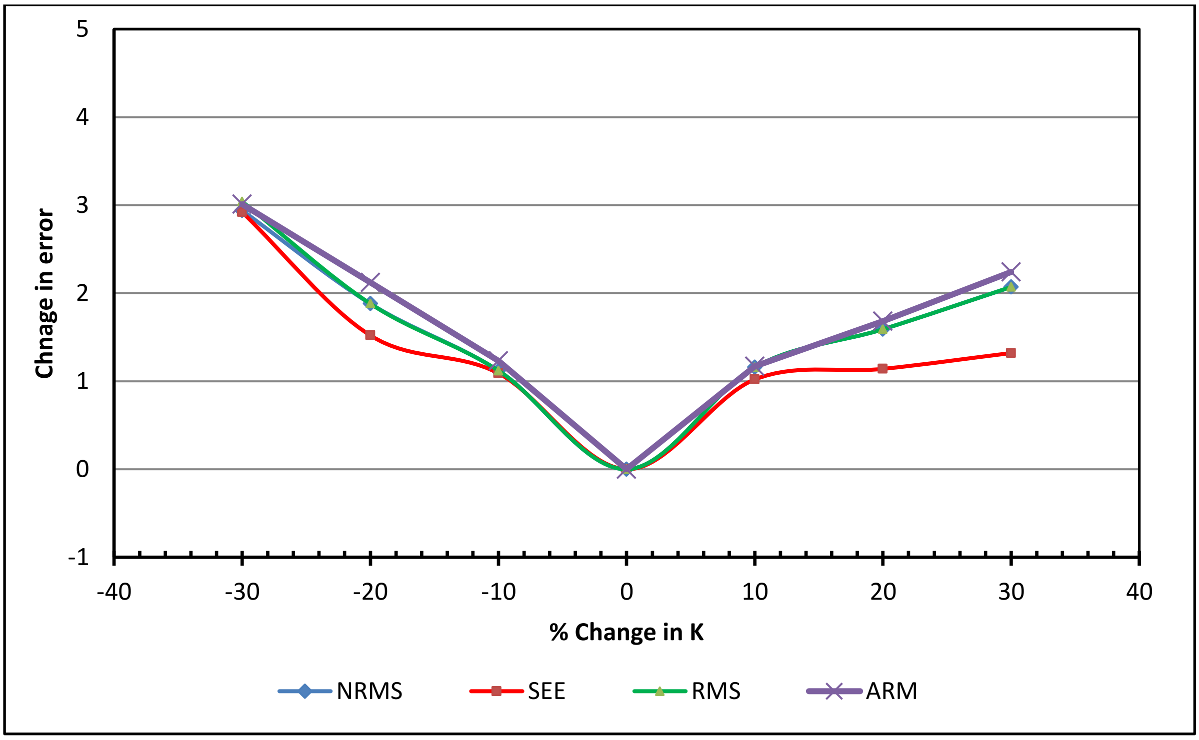


Figure 6.14 Sensitivity of hydraulic conductivity

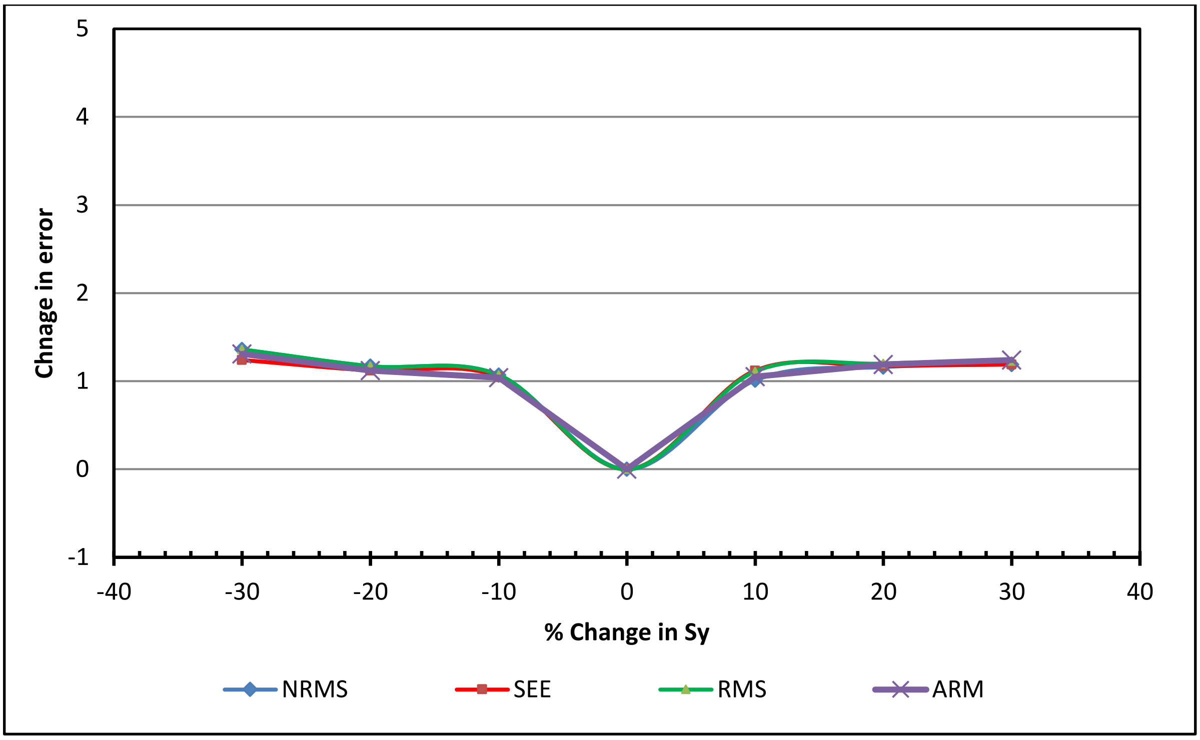


Figure 6.15 Sensitivity of specific yield (S_y)

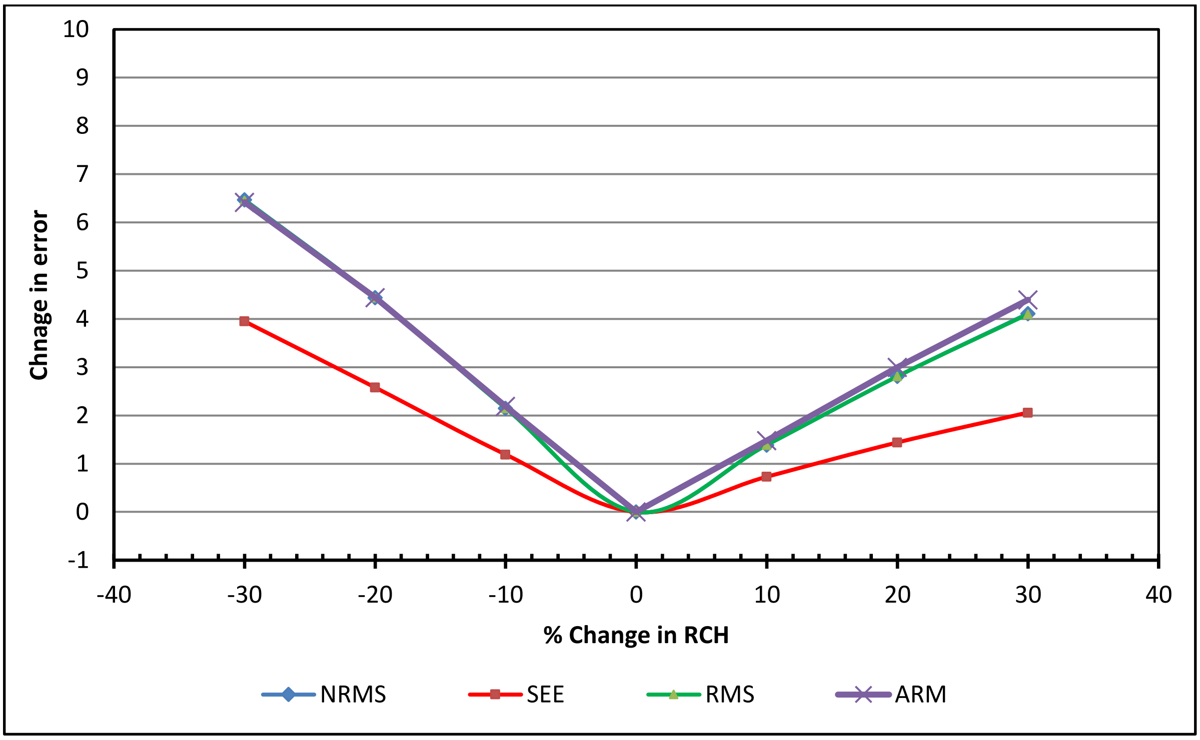


Figure 6.16 Sensitivity of total recharge (RCH)

6.9 Modelling Results

6.9.1 Calibrated Aquifer Parameters and Recharge

After calibration and validation of the groundwater model it can be seen that the Hydraulic conductivity (Kx and Ky) varies from 4 to 51 m/day in the Tawa Command Area (Fig. 6.17). It has been observed that isolated patches having low conductivity in between high conductivity zones. Calibrated parameters have been found to be within the range of values reported in various studies. Specific yield (Sy) has been in the range of 0.001 to 0.11 in different zones of the command area.

Calibrated recharge zones and recharge rate are given in Fig. 6.18 and Table 6.10 respectively. Recharge rate is high in Babai and Itarsi zones. In the command area of RBC rate of recharge is found to be high in Pipariya block. It might be due to the leakage from the Tawa reservoir as there is much elevation difference between Right Bank Canal and natural topography. Machak reservoir also has been given as recharge boundary in groundwater model. This zone cannot be compared with other zones in the command, for Machak reservoir recharge rate has been taken around 2000 mm/year in the initial stage due to lack of water level data for the reservoir. The groundwater level maps are prepared form the interpolated values obtained from groundwater model as shown in Fig. 6.19.

Table 6.10: Calibrated recharge in TCA

Zone	Recharge (mm/year)	
	Pre monsoon	Post monsoon
LBC	500.204	1000.409
PBC, BBC	371.13	742.26
Machak reservoir	3179.91	3179.916
Khirkiya	181.15	78.41
Harda	156.57	67.76
Timrani	186.82	431.62
Seonimalwa	765.99	333.83
Hoshangabad1	645.84	552.24
Hoshangabad2	333.833	285.45
Itarsi	809.22	691.51
Babai	1361.46	555.42
Sohagpur	426.88	407.06
Pipariya	583.87	521.31
Bankhedi	118.45	4.17
Built-up	143.24	26.52

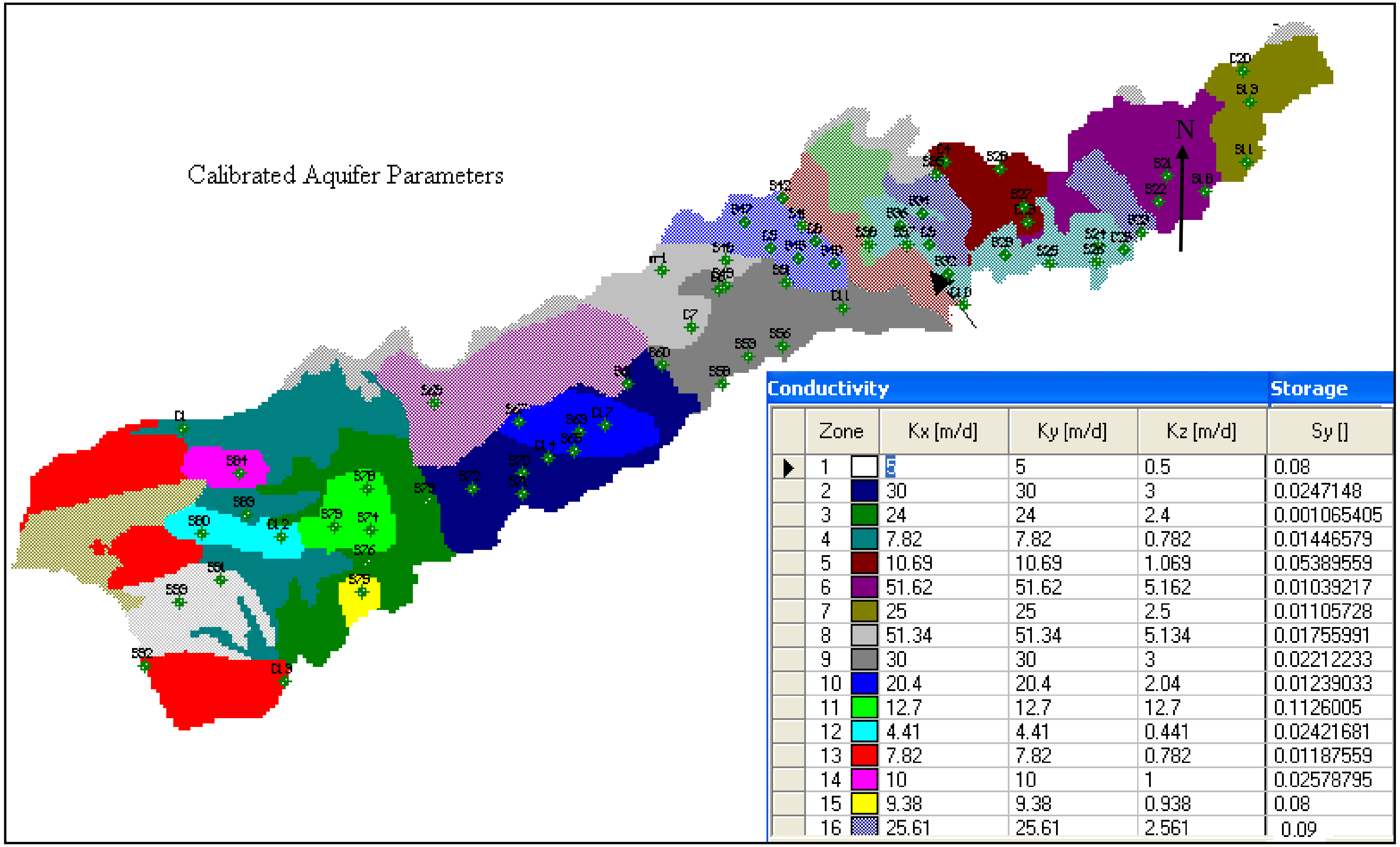


Figure 6.17 Calibrated aquifer parameters in TCA

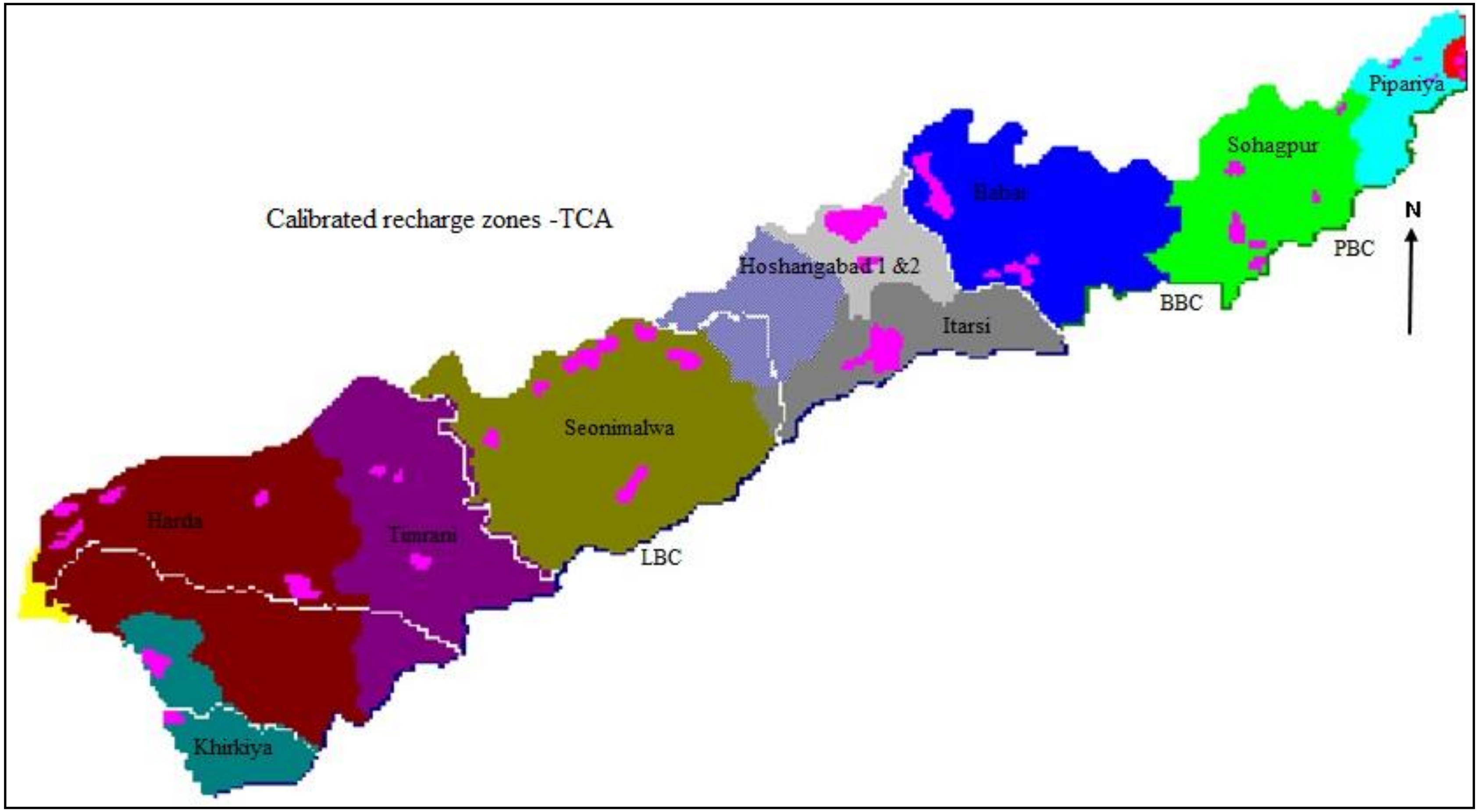


Figure 6.18 Recharge boundaries in the Tawa Command Area

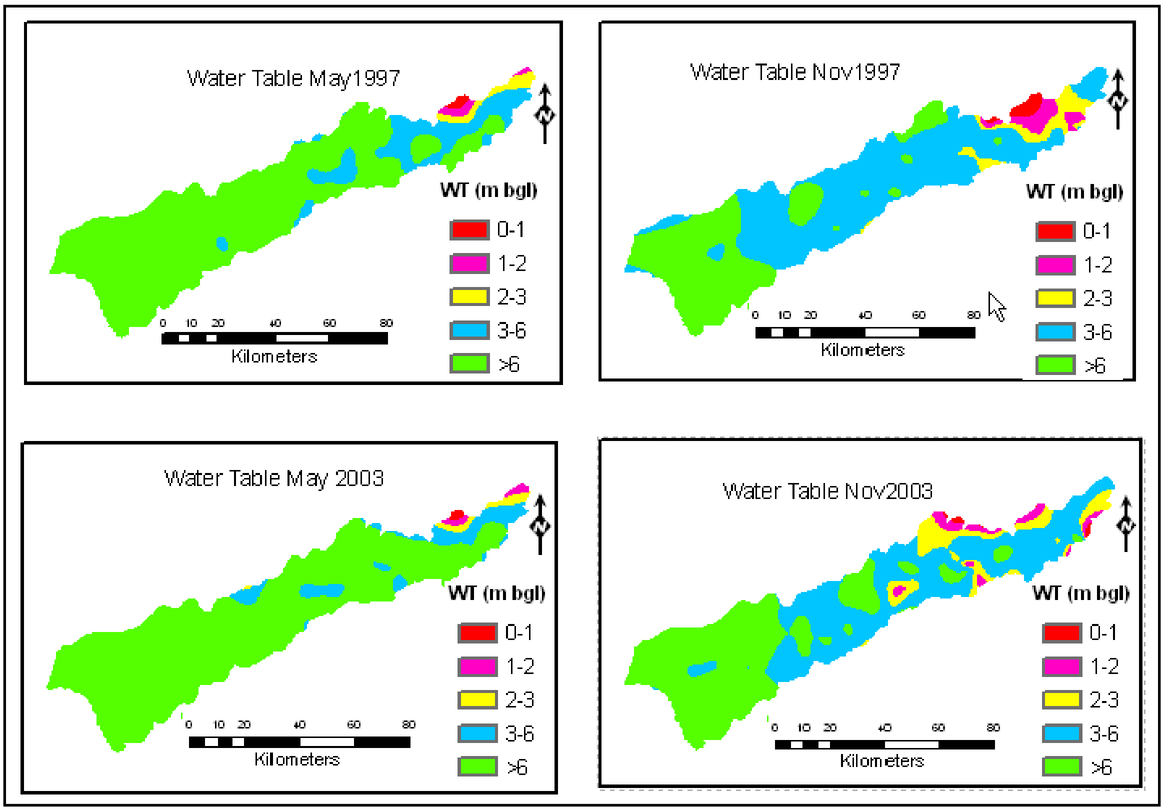


Figure 6.19 Water table maps of TCA for years 1997 and 2003

6.9.2 Zone Budget

Zone budget calculates sub-regional water budget using results from steady-state or transient-state MODFLOW simulations. It calculates budgets by tabulating the budget data that MODFLOW produces using the cell-by-cell flow option. The user simply has to specify the sub-regions for which budgets needs to be calculated. These sub-regions are entered as 'zones' analogous to the way that properties, such as hydraulic conductivity, have been entered in groundwater model. Following a simulation flow observations, such as base flow to a stream, or flux across a boundary, are very useful for calibrating a groundwater model against data other than just head measurements. The utilization of flow observations provides a stronger line of evidence to verify the model predictions, and is particularly useful in models where the water table is relatively flat. In this study, block wise zone budget has been generated for the study area and it is very helpful to know the available groundwater resources in a particular region. Season wise water budget on block basis is tabulated in Tables 6.11 to 6.20. Table 6.21 shows the yearly water budget for entire study area on bock basis. The calculated water budget for the year 2003 has been around 2712 MCM which is matching with the reported values in the recent report (Anonymous, 2009).

Table 6.11: Season wise water budget in Khirkiya block

Time (days)	Inflow (m^3/day)							
	Storage	RCH	River leakage	Harda	Syani	Machak	LBC	Total
183	5994	99772		159150	2922	29522	8551	305911
365	12477	42117	142	123720	7812	35680	17018	238967
548	431	98972	30	158870	3131	31932	8553	301918
730	10428	41557	212	124850	7973	36329	16997	238346
913	469	102170	27	159900	3057	31869	8512	306004
1095	10215	41717	203	125940	7958	36358	16981	239373
1278	613	98253	37	160930	3172	32223	8510	303737
1460	10200	41637	208	125990	7972	36545	16981	239533
1643	594	99772	34.27	160770	3129	32170	8510	304979
1825	15176	41797	232	125300	8125	36086	9472	236188
2008	608	99772	48	160430	3116	32311	15738	312023
2190	16122	41797	221	125490	8051	36257	9635	237574

Table 6.12: Season wise water budget in Harda block

Time (days)	Inflow (m^3/day)										Total
	Storage	RCH	River leakage	Timrani	Khirkiya	Machak river	Machak Reservoir	Ajnal river	LBC	Narmada	
183	99908	389960	516	115350	21293	19590	161970	94393	13012	823	916815
365	226050	167740	1011	67605	20114	24757	169900	105360	19111	834	802482
548	66019	388250	827	128720	20558	24389	174170	93947	13148	869	910897
730	201130	166550	1111	74014	19585	25176	176530	108420	19192	836	792544
913	49916	395090	3877	131770	20524	24340	178910	94545	13245	5017	917234
1095	198380	166890	1085	76092	19426	24995	179740	109860	19248	821	796537
1278	49509	386720	826	134180	20328	24257	181340	96836	13299	800	908095
1460	189700	166720	1097	77070	19627	25010	181280	112220	19273	821	792818
1643	68874	389960	825	135030	20492	24258	182310	97772	13310	836	933667
1825	190350	167060	1278	72166	19571	24339	181940	113270	13483	811	784268
2008	36067	389960	690	139920	20616	23819	182770	98709	19127	867	912545
2190	181580	167060	1226	72715	19822	24677	182230	114450	13570	831	778161

Table 6.13: Season wise water budget in Timrani block

Time (days)	Inflow (m^3/day)									Total
	Storage	RCH	River leakage	Seonimalwa	Harda	Ajnal	Ganjal	LBC	Narmada	
183	411	583090		4262	20035	2787	25823	20277	149	656833
365	55178	251710	2730	10052	28133	5918	51126	39024	186	444057
548		582580		4146	18875	3106	26302	22776	156	657941
730	67160	251350	1440	9949	27854	6228	51206	39630	187	455003
913		584610		4806	15958	3141	25966	23104	166	657751
1095	71342	251450	1197	10309	27859	6294	51975	39735	183	460344
1278	132	582120		4397	19295	3147	27453	23156	143	659843
1460	72084	251400	1270	10746	27602	6302	52886	39769	183	462242
1643	1445	583090		4580	19224	3147	27673	23166	153	662478
1825	79071	251500	2772	11127	26657	6665	53033	23621	181	454627
2008		583090		4818	18619	3113	28036	38351	155	676182
2190	79688	251500	2477	11496	26080	6529	53407	23861	186	455224

Table 6.14: Season wise water budget in Seonimalwa block

Time (days)	Inflow (m^3/day)										
	Storage	RCH	River leakage	Hoshangabad	Itarsi	Timrani	Ganjal	Indra	LBC	Narmada	Total
183	15351	1545700	495	47729	29953	20499	81770	20358	37020	3410	1802284
365	293120	666290	1631	50280	34872	8345	102980	22869	85178	4835	1270400
548		1543000	545	49014	30845	22492	81442	19850	54176	3817	1805181
730	285870	664360	1742	50769	34925	8695	103350	22586	93269	5233	1270799
913		1554000	369	47713	30685	22610	66872	18193	61623	5512	1807577
1095	321150	664910	1822	51296	34892	8798	103160	22605	98024	4871	1311528
1278	11298	1540500	848	49656	30725	22653	83501	19754	67057	3244	1829236
1460	323280	664640	2012	51326	34904	8873	104550	22412	102570	4945	1319511
1643	28140	1545700	796	49117	30568	22534	82769	19301	71468	3519	1853912
1825	368710	665190	1972	50336	33181	7197	101260	20260	88982	4644	1341732
2008		1545700	443	49353	31724	24039	81178	20495	90580	3661	1847173
2190	372550	665190	1819	50526	33314	7209	100310	20208	91918	4777	1347821

Table 6.15: Season wise water budget in Itarsi block

Time (days)	Inflow (m^3/day)								
	Storage	RCH	River leakage	Hoshangabad	Seonimalwa	Indra	Tawa	LBC	Total
183		530290	63	24272	8844	16513	855	34213	615050
365	28261	445920	206	22754	7943	20362	117	62980	588543
548		528710	97	24984	9472	17213	890	34542	615907
730	30063	444810	206	22993	8535	20442	159	63141	590350
913		535030	54	25382	10071	17097	909	34324	622867
1095	31002	445130	185	23242	8989	20421	178	63177	592324
1278		527290	13	25059	10968	16978	943	34483	615734
1460	30952	444970	179	23086	9810	20366	189	63258	592810
1643		530290		25112	11489	16879	926	34284	618980
1825	38014	445280	206	22808	9199	17995	221	38210	571933
2008		530290		25302	12663	18727	866	59069	646917
2190	39964	445280	200	22906	9560	18103	215	38448	574676

Table 6.16: Season wise water budget in Hoshangabad block

Time (days)	Inflow (m^3/day)								
	Storage	RCH	River leakage	Itarsi	Seonimalwa	Indra	Tawa	Narmada	Total
183	13950	450900	2219	270510	52753	301380	47775	5406	1144893
365	71698	375660	1150	243330	35845	257830	51611	5511	1042635
548		449080	2268	272370	50885	294730	44702	5817	1119852
730	60445	374390	1198	244880	36559	257810	51643	5543	1032468
913		456350	2193	275420	49869	270120	22674	6044	1082670
1095	73701	374750	1238	246720	38235	265770	54982	5426	1060822
1278	18936	447450	2179	274460	54095	311050	58821	5131	1172122
1460	60143	374570	1359	247590	39671	265850	54528	5467	1049178
1643	7213	450900	2165	275680	54566	306280	52105	5635	1154544
1825	73142	374930	1389	238610	39766	265000	56443	5343	1054623
2008		450900	2124	283380	55498	300710	45609	5638	1143859
2190	71074	374930	1268	240280	40230	264730	53734	5442	1051688

Table 6.17: Season wise water budget in Babai block

Time (days)		Inflow (m^3/day)						
	Storage	RCH	River leakage	PBC	Sohagpur	Tawa	Narmada	Total
183	16471	1780900		13305	64037	6055	11889	1892657
365	315670	725030		29897	59885	40144	12327	1182953
548		1779200		14979	64852	4874	12325	1876230
730	287430	723870	57	30798	61249	39431	12507	1155342
913		1785800	1626	15527	62565	1901	19017	1886435
1095	345720	724200		30904	62180	37596	12447	1213047
1278	43017	1777700		16007	67029	7339	10412	1921504
1460	284220	724040	322	31477	62524	40977	13285	1156845
1643	81779	1780900		15814	66369	5834	8923	1959619
1825	334800	724370		24190	59189	39165	12726	1194440
2008	10	1780900		20110	67576	5115	11090	1884801
2190	342660	724370		24317	59686	38338	12021	1201392

Table 6.18: Season wise water budget in Sohagpur block

Time (days)	Inflow from (m^3/day)						Total
	Storage	RCH	PBC	Pipariya	Babai	Narmada	
183	27	454890	20213	56318	33667	1220	566335
365	41517	413530	40928	53833	31078	1090	581976
548		453690	19929	58622	35708	1110	569059
730	37960	412690	41142	54338	32573	1045	579748
913		458480	19584	51012	33006	1384	563466
1095	47642	412930	41177	55982	33120	1065	591916
1278	1560	452610	20197	60728	37812	1128	574035
1460	37288	412810	41314	54446	33546	1068	580472
1643	21728	454890	19930	60807	37256	1025	595636
1825	55786	413050	26809	50909	32595	1079	580228
2008	17	454890	34183	61569	37179	1111	588949
2190	61303	413050	27041	51293	32458	1039	586184

Table 6.19: Season wise water budget in Pipariya block

Time (days)	Inflow from (m^3/day)						
	Storage	RCH	Bankhedi	PBC	Sohagpur	Narmada	Total
183		221690	8035	21274	19228	1797	272024
365	15529	197330	6456	33697	18542	1612	273166
548		221520	9447	22563	20211	1604	275345
730	11383	197220	6571	34145	18847	1561	269727
913		222180	2714	20458	16178	2127	263657
1095	18058	197250	7893	34451	19584	1575	278811
1278	134	221380	11513	23077	21548	1615	279266
1460	9359	197230	6357	34370	18944	1608	267868
1643	19129	221690	13610	22368	21907	1392	300096
1825	18070	197270	5339	25647	17862	1634	265822
2008	30	221690	11243	30745	21234	1580	286522
2190	22608	197270	5563	25859	18157	1551	271008

Table 6.20: Season wise water budget in Bankhedi block

Time (days)	Inflow from(m^3/day)				
	Storage	RCH	PBC	Pipariya	Total
183	0	9042	3665	10766	23473
365	2310	838	7164	16715	27026
548	0	8824	3827	10933	23584
730	2431	685	7204	16820	27140
913	0	9696	3426	12933	26055
1095	4132	729	7288	16280	28429
1278	0	8627	3891	10856	23375
1460	2015	707	7211	16993	26926
1643	664	9042	3838	10654	24199
1825	3708	751	5357	16307	26123
2008	0	9042	5609	11632	26283
2190	3987	751	5370	16241	26349

Table 6.21: Yearly block wise water budget (MCM)

Year	Khirkiya	Harda	Timrani	Seoni Malwa	Itarsi	Hoshangabad	Babai	Sohagpur	Pipariya	Ban khedi	Total command
1998	99.5	313.8	201.0	561.0	219.7	399.3	561.7	209.6	99.5	9.2	2674
1999	98.6	310.9	203.2	561.6	220.2	392.8	553.6	209.7	99.5	9.3	2659
2000	99.6	312.8	204.2	569.5	221.8	391.2	566.0	210.8	99.0	9.9	2685
2001	99.2	310.5	204.9	574.9	220.6	405.4	562.2	210.7	99.9	9.2	2697
2002	98.8	313.6	204.0	583.5	217.4	403.2	576.0	214.6	103.3	9.2	2724
2003	100.3	308.6	206.6	583.3	223.0	400.7	563.6	214.5	101.8	9.6	2712

6.10 CONCLUDING REMARKS

For the Tawa Command Area (TCA), groundwater model is prepared in Visual MODFLOW 4.2 to know the present state and behavior of groundwater with respect to aquifer parameters, recharge and withdrawals. By observing the calibrated aquifer parameters and sensitivity analysis results it is learned that the groundwater system of TCA is more sensitive to recharge as compared to other factors.

The calibration and validation results indicates that the groundwater model for TCA has been well calibrated and has capable of predicting future state of groundwater system as a response of changed water allocation plan. This model needs to be integrated in conjunctive use model as groundwater is the sources of water which will be used in conjunction with surface (canal) water. The use of groundwater model of TCA in conjunctive use modelling will be described in Chapter 7.

CHAPTER 7
FORMULATION OF CONJUNCTIVE USE MODEL

7.1 GENERAL

Distributed conjunctive use model for irrigation command area is a mathematical model, which has been formulated for the optimum allocation of surface water and groundwater supply to satisfy the crop water requirement along with various system and geometric constraints. In this chapter, a general mathematical model for conjunctive use of surface water and groundwater in command area of irrigation project, is formulated incorporating it's major elements.

The model selected for the present investigation includes surface water and groundwater as sources of irrigation, multiple users (the command area is divided into five zones as described in later part) and Crop Production Response Functions (CPRF), which defines the crop yield as intrinsic function of water supplied. The developed model has been applied over data from the Tawa Command to illustrate a practical application of distributed conjunctive use model. In the subsequent sections, mathematical formulation of model and it's solution have been discussed.

7.2 RESOURCES ASSESSMENT

The first and foremost part in the resources allocation/management studies, is to assess the present state of all available resources of the system. As discussed in earlier chapters the parameters governing water resources management problems are always spatially distributed in nature. However, the spatial scale at which the resources are to be assessed depends on the scale of final model output and the dimensionality constraints of the model framework. Tawa Command Area is facing problems of rising groundwater levels in head reach of LBC and water table depletion in tail reach of LBC. The spatial discretization of command area is prerequisite in applying developed conjunctive use model to solve the problems of groundwater system in Tawa Command, while optimizing the output from the command area.

The command area has been divided into five zones (Fig. 7.1) based on the groundwater conditions of the area. The administrative block boundaries have been considered as boundaries of new zones. The resources availability has been assessed for each zone using the geospatial techniques and information from literature.

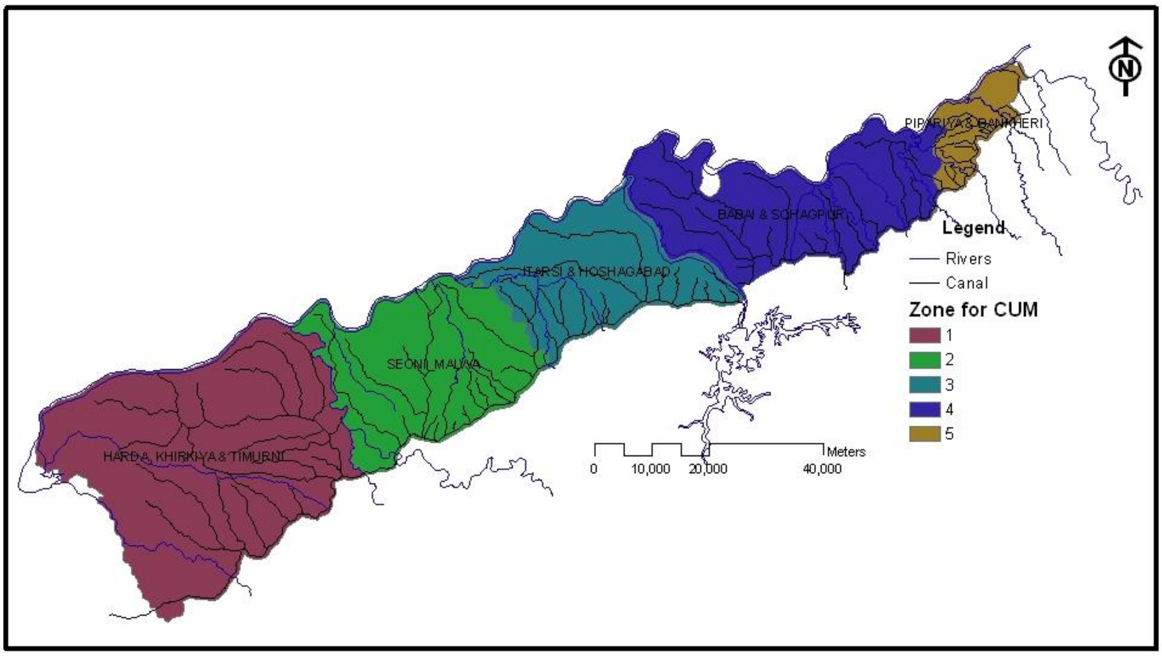


Figure 7.1 Different zones of Tawa Command Area for conjunctive use modelling

Total irrigable area in the Tawa Command has been divided into five zones. The block boundary map in geodatabase, described in Chapter 4, contains the information regarding CCA in each block along with surface water supply in each block, obtained from project reports. The new zone map has been generated using 'Merge' function in Arc GIS. The attribute values for new zones have been estimated using 'Aggregate' function available in 'Spatial Analysis Tools' of Arc GIS. The generated zone map provides the information regarding the CCA and surface water supply to each of the zone. The administrative block GCA and CCA under each zone is given in Table 7.1. Now onwards each zone will be considered as individual system.

Table 7.1: Zones of Tawa Command Area

Zone Number	Blocks under zone	GCA (ha)	CCA (ha)
1	Harda, Khirkiya & Timirani	146512.5	95233.15
2	Seonimalwa	109748.2	71336.36
3	Hoshangabad & Itarsi	48475.34	31598.97
4	Babai & Sohagpur	72983.94	47439.56
5	Pipariya & Bankheri	23964.94	15577.21

The monthly surface water availability in each zone of TCA is given in Table 7.2. The canal supplies water for Rabi season only, from April to September the canal remains closed, hence the canal supply for these months are not indicated in Table 7.2.

Table 7.2: Monthly surface water availability in each zone of TCA (ha-m)

Zone	Jan	Feb	March	Oct	Nov	Dec	Total
1	8239.3	8239.3	3570.3	4394.3	8239.2	8239.3	40921.6
2	9724.1	9724.1	4213.8	5186.2	9724.2	9724.2	48296.6
3	3135.6	3135.6	1358.7	1672.3	3135.6	3135.6	15573.4
4	3371.8	3371.8	1461.1	1798.3	3371.8	3371.9	16746.7
5	1895.6	1895.6	821.4	1010.9	1895. 6	1895.6	9414.6
Total	26366.4	26366.4	11425.3	14062.0	26366.4	26366.4	130952.9

(Source: Khare, 2003)

Groundwater availability mainly depends on the annual recharge from various sources like rainfall, irrigation return flow, seepage from canal and water bodies, and this cannot be ascertained exactly. Therefore, one has to assume suitable values for conveyance losses as well as recharge factors for different components of recharge. Khare (2003) has done an extensive exercise to estimate the annual groundwater availability in the CCA of Tawa project, the estimates are also confirmed by Uppalury (2010). Hence the annual groundwater availability for Tawa Command has been taken as 140809 ha-m, if no mining is allowed. These values of available resources have an important role in conjunctive use modelling, as they decide the boundaries of feasible solution space for the optimization model. The developed conjunctive use model tries to find out the optimal combination of model parameters (in this case resource allocations) within this feasible solution space.

7.3 DEMAND ESTIMATION

Water requirement of crops depends on the hydro-meteorological parameters, the type of crop and the growth stage of the crop. Khare (2003) estimated monthly consumptive use for all the crops grown in the Tawa Command Area using monthly climatic normal meteorological data. The net water requirement for the crops has been estimated by subtracting effective rainfall from the consumptive use of the crop. The irrigation water requirement has been calculated from the net water requirement by considering field application efficiency of surface irrigation system as 70% for all crops. The average value for conveyance efficiency of the distribution system has been assumed as 77% (GEC, 1997). Monthly water requirements for all the crops in Tawa Command Area are given in Table 7.3. It should be noted that the water requirements of crops is estimated considering the system efficiencies.

Table 7.3: Monthly crop water requirement (m)

Crop	Paddy	Cotton	Jawar	Groundnut	Maize	Pulses	Soyabean	Wheat	Gram	Peas	Vegetable	Linseed	Perennial
Jan	0	0	0	0	0	0	0	0.1	0.07	0.15	0.2	0.1	0.204
Feb	0	0	0	0	0	0	0	0.187	0	0	0.2	0	0.259
March	0	0	0	0	0	0	0	0.151	0	0	0.1	0	0.168
April	0	0	0	0	0	0	0	0	0	0	0	0	0.217
May	0	0.228	0	0	0	0	0	0	0	0	0	0	0.286
June	0.047	0.01	0	0	0	0.154	0.126	0	0	0	0	0	0.036
July	0.22	0.02	0.02	0.031	0.063	0	0	0	0	0	0	0	0.026
August	0.18	0.019	0.01	0.128	0.018	0	0	0	0	0	0	0	0.018
Sept	0.165	0.111	0.02	0.145	0.097	0.08	0.118	0	0	0	0	0	0.092
Oct	0.102	0.225	0.22	0.142	0.058	0.1	0.222	0.1	0.08	0.1	0.1	0.08	0.226
Nov	0	0.095	0.06	0	0	0.035	0.101	0.1	0.08	0.1	0.2	0.08	0.16
Dec	0	0	0	0	0	0	0	0.1	0.06	0.1	0.2	0.1	0.183

(Source : Khare, 2003)

7.4 COST ANALYSIS FOR GROUNDWATER PUMPING

The inherent objective of conjunctive use planning is to increase the benefits from the irrigated agricultural area in the command. This implies the dependency of conjunctive use models on costs of resources and values of outputs from the system. To quantify the advantages of conjunctive use planning in economic terms, the accurate estimate of cost coefficients for each resource is important. Groundwater cost is complex variable as it is an intrinsic function of total head and rate of discharge. The procedure to derive groundwater cost functions is discussed in the present section.

The total cost of groundwater pumping comprises of two components; fixed costs and recurrent or variable costs. Fixed costs include initial cost of exploration, data collection and analysis, drilling and installing a system, while recurrent costs include those of energy, labour, O/M and interest charges.

The data required for this analysis has been taken from CGWB reports and Ministry of Water Resources (MOWR), Government of India (GOI) project report (Khare, 2003) and from market survey.

7.4.1 Design Aspects of Shallow Tubewells

All the zones in Tawa Command Area constitute a single aquifer system of unconfined nature. The thickness of alluvium ranges between 15 m to 160 m. Basic features of aquifer and groundwater system have already been discussed in detail in Chapter 5. In the study area, the development of groundwater is practiced mostly through shallow tubewells. Number of deep tubewells in the area is small as compared to number of shallow tubewells. Government is also encouraging construction of shallow tubewells as they are owned by farmers and hence they can be managed more efficiently. Further, shallow tubewells require small initial investments. Keeping all these into consideration, it is assumed that future development would take water through shallow tubewells only. Therefore, for the present cost analysis, shallow tubewells are designed as per the methodology given in literature (Sharma and Chawla, 1977; Naggar, 1992; Khare, 1994). Shallow tubewells are designed considering the hydraulic properties of aquifer, like hydraulic conductivity, total aquifer thickness available, total drawdown created in the tubewell during the pumping, depth of water table below the ground level, and seasonal fluctuation in water table.

Shallow tubewells or private tubewells, usually individually owned, are best suited in alluvial formations and their depth seldom exceeds 50 m. A shallow tubewell is generally of a much smaller depth and discharge as compared to a deep tube well which taps deeper aquifers. The capacity of shallow tubewells generally varies from 0.005 m^3/s to 0.020 m^3/s (5 l/s to 20 l/s). The data required for cost analysis of groundwater is taken from project report on Tawa Command Area (Khare, 2003).

7.4.1.1 Pipe system

Shallow tubewells mainly comprises of a borehole, series of pipes and strainers lowered into the borehole. The size of suction pipe is determined for the design discharge and assumed limiting velocity of flow. A value of 1.5 m/s is adopted as the limiting velocity (Sharma and Chawla, 1977). Depending upon the availability of different sizes of pipes in the market, a suitable size is selected. The size of suction and delivery pipes are considered the same for the design and cost analysis of shallow tubewell. Two pipe bends are also proposed at the suction and delivery sides.

An important aspect of the design of the well is determination of diameter of the screen, its length, percentage open area, size and shape of each slot and thickness and material of the screen. A check is usually made to ensure that the maximum entrance velocity through the slots lies within the range of 0.025 to 0.036 m/s. The diameter of the screen is kept equal to the diameter of the well pipe (i.e. the suction pipe). The length of the screen for well is fixed on the basis of U.P. Irrigation Research Institute (UPIRI) recommendations (Sharma and Chawala, 1977) and actual practices prevailing in the areas. Screen length of a tubewell is calculated as follows (Sharma and Chawala, 1977):

$$L = \frac{Q}{\pi \times d \times p \times v} \quad (7.1)$$

where, L is length of the screen pipe in m, Q is discharge in m^3/s, d is diameter of the screen pipe in m, v is screen entrance velocity (slot velocity) in m/s, and p is ratio of effective slot area to total area of the screen.

The slot area is considered as 20% of the total area of screen pipe (IS: 8110, 2000). Effective open area of the slots in the screen is adopted as 50% of total open area. Thus, value of the p would be equal to 0.1 for the computation of length of the screen. Total depth of well is computed as per recommendations of the UPIRI for alluvial formations. Accordingly, screen is provided for about 65% of the depth of aquifer below the location of water table. Therefore, the depth of the shallow tubewell can be obtained as:

Depth of well = Depth of groundwater table + (length of screen/0.65) (7.2)

A foot valve or reflux valve is fitted on to the bottom of the suction pipe to help in priming of the pump.

7.4.1.1.1 Total head (lift)

Based upon the hydro-geological characteristics, discharge and life, tubewells can be commissioned with vertical turbine or submersible pumps. Submersible pumps have advantage over vertical turbine pumps as it reduces the cost of casing and drilling without affecting the mechanical efficiency of the pump. Normally, there is a substantial saving in capital cost when submersible unit is installed, because construction of pump house may not be required along with fewer expenses of drilling and casing pipes. Hence, submersible types of pumps were adopted in the present study conforming to BIS specification (IS: 8034, 2002).

For a given discharge, total head over which water has to be pumped depends on:

i) static head (h_s),

ii) drawdown required to get the estimated discharge (s_t),

iii) velocity head (h_v),

iv) delivery head (h_d) and

v) friction head loss (h_f).

The static head (h_s) adopted for this study has been the average groundwater level in the area for year 2003. However, different depths of water table are considered to develop the cost function.

The most important factor in finding out the lift of pumped water is the drawdown. The drawdown in a pumping well has two components. The first component, termed as aquifer loss, which is a function of both pumping rate and pumping period. The second component is well loss, which depends on the pumping rate alone and does not vary with time. It represents head loss due to the resistance to flow of water as it enters in the well through screen. While calculating drawdown, the aquifer loss is calculated using the method proposed by Theis (Todd, 1980) and the screen loss is computed using recommendations of Chawla and Sharma (1971). Figure 6.2 shows the well loss coefficients which is the ratio of losses through the screen and through aquifer (S_s/S_a) for different values of constants i.e. B and C. These curves were drawn for a value of 'A'=50 (as the authors found that in actual practice the value of 'A' is invariably more than 50 and which would not affect the well loss coefficient). The value of constants (A, B and C) used in their study are given as:

$$A = \frac{32 \times C_c^2 \times C_v^2 \times A_p^2 \times L^2}{D^2} \quad (7.3)$$

$$B = \frac{\pi \times D^4 \times g \times \ln\left(r_e / r_w \right)}{64 \times L \times k \times Q}$$ $A = \frac{32 \times C_c^2 \times C_v^2 \times A_p^2 \times L^2}{D^2}$

(7.4)

$$C = \frac{f \times L}{D}$$ $C = \frac{f \times L}{D}$ (7.5)

Where, C_c is contraction coefficient, C_v is velocity coefficient, A_p is ratio of slot area to the total area of the screen, r_e is radius of influence, r_w is effective radius of well (D/2) and *f* is friction factor for the screen material.

To compute the screen loss, the constants A, B and C have been calculated and well loss coefficient (S_s/S_a) has been, then obtained from Fig. 7.2. From the obtained values of this coefficient the screen loss is computed as below;

$$S_s = S_a \times \text{ well loss coefficient} \quad (7.6)$$

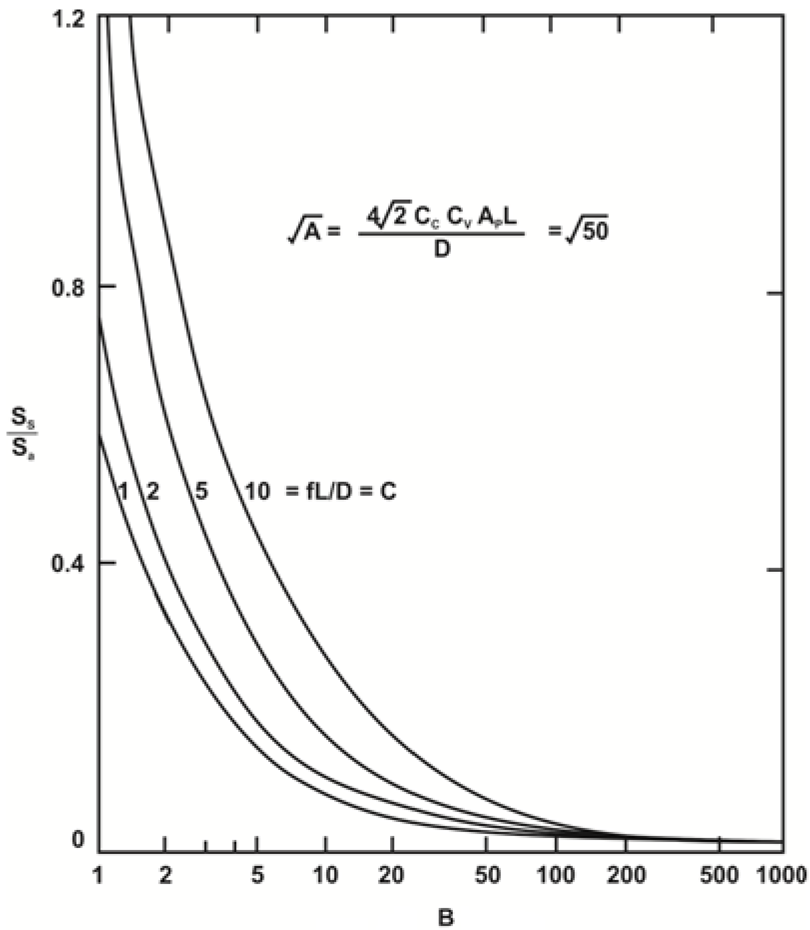


Figure 7.2 Graphical result for well loss coefficient (Chawla and Sharma, 1971)

Average values of hydraulic conductivity, transmissivity and storativity (GEC, 1997) have been adopted from the pumping test data, obtained from CGWB, Bhopal. However, different values of the K (1 to 50.7 m/day) and S (0.007 to 0.32) have been used in the cost analysis. Later on, costs are checked using the calibrated aquifer parameters and no significant difference has been found.

Velocity head has been estimated using the Darcy-Weisbach's velocity head formula and procedure described in the BIS code (IS: 2951, part I and II, 1965). Thus, the total head (i.e. lift of the pump) can be expressed as:

$$H_t = h_s + s_t + h_v + h_f + h_d + h_l \tag{7.7}$$

7.4.1.2 Pump design

For the design of the pump, the following assumptions are considered:

i) Unsteady state condition of drawdown, *ii)* Overall efficiency of the pump has been assumed as 50%, and

iii) Pumps are electric operated.

Knowing the discharge, total head and efficiency of the pump, the power requirement PW has been calculated as:

$$PW = \frac{\rho \times g \times Q \times H_t}{\eta} \qquad (7.8)$$

where, PW is electric power (W), ρ is mass density of water (kg/m^3), g is acceleration due to gravity (9.81 m/s^2), η is overall efficiency of pump and motor, H_t is total head (m), and Q is discharge (m^3/s).

Eq. 6.8 can be written as, after substituting the values of ρ and g as:

$$PW = \frac{9.81 \times Q \times H_t}{\eta} \text{ kW} \qquad (7.9)$$

The required horse power (HPR) for the pump can be calculated as:

$$HPR = \frac{Q \times H_t}{0.076 \times \eta} \qquad (7.10)$$

Overall efficiency of the pump and motor generally varies from 40 to 60%. Therefore, an average value of 50% has been considered for the present investigation. The value of the HP so obtained has been further increased by 20% to account for the peak requirements and fluctuations in the water table (Naggar, 1992; Khare, 1994). Electric operated pump sets are selected as per the BIS specifications.

7.4.1.3 Cost of Different Components of Shallow Tubewell

Cost of the shallow tubewell has been computed considering various items involved in the construction of shallow tubewells and O&M expenses. Further, unit cost of pumped water has been determined. The cost estimates have been carried out for the well capacities ranging from 0.005 m^3/s to 0.02 m^3/s. The cost analysis is made with the following assumption and considerations based on local practices (Khare, 2003; Khare et al., 2007; Jat, 2007):

i) Useful life of the deep tube-well is 15 years,

ii) Useful life of pump and motor is adopted as 15000 running hours

iii) Rate of interest 12%,

iv) The piping system is of mild steel, *v)* Pumps are electrically operated,

vi) Energy charges have been considered as 3.00 Rs./kWh, and

vii) Annual maintenance cost of the pump is assumed as 2% of the total cost.

7.4.1.4 Capital cost

Capital or fixed cost of shallow tubewell comprises cost of pipes, fittings, drilling, electric installations, pumpset and other miscellaneous items. For various well capacities, prices and cost of various components of tubewell have been obtained from different sources, and the same have been used in the computation of the capital cost. Cost of the delivery pipe and casings (CDP), foot valves (CFT) and other fittings (flanges and bends) have directly been adopted from the market (year 2005). Rate of boring for different diameters using Down To Hole Hammer (DTH) machine have been obtained from the market and used for the computation of cost of drilling (CDR) for various sizes of the shallow tubewell. Cost of different electric fittings (CEF) *viz.* main switch, starter, capacitor, earthing etc. have been obtained for pumps of different HP. Cost of pumpset (CPS) for different capacities has been taken corresponding to the required HP. Cost of other Miscellaneous Items (CMI), like nut bolt, transportation, investigation etc., has been taken as lump sum amount.

Annual Capital Cost

Annual capital cost has been calculated by considering the useful life of tubewell and that of pump set in hours. Therefore, the annual cost of all components excluding the cost of pumpset has been determined separately. Annual cost of the pumpset has been computed considering the number of hours of operation and then converted into equivalent number of years. The annual costs have been computed as:

$$ANC1 = (CDP + CFT + CDR + CEF + CMI) \times AF1$$

$$ANC2 = CSP \times AF2$$

$$ANCP = ANC1 + ANC2 \qquad (7.11)$$

where, $AF1$ is annuity factor considering all components except pump set, $AF2$ is annuity factor for the pumpset, corresponding to the useful life in equivalent number of years, $ANC1$ is annual cost of all components of tubewell except pump set, $ANC2$ is annual cost of pumpset, and $ANCP$ is total annual capital cost.

7.4.1.5 Recurring cost (O&M cost)

O&M cost of tubewell includes energy charges and maintenance expenses of the pump and electric accessories. Once for a given capacity total horse power required to pump the water is known, the energy cost can be calculated as:

$$OC = HPP \times 0.746 \times PT \times PRW \qquad (7.12)$$

Where, *OC* is cost of energy (Rs.), *PT* is number of operation hours in a year (hour), *HPP* is horse power provided, and *PRW* is rate of power (Rs./kWh).

Annual maintenance cost (*AMC*) has been computed as 2% of the total capital costs. Therefore, the total annual O&M cost (*AOMC*) has been calculated as:

$$AOMC = OC + AMC \qquad (7.13)$$

Total annual cost (TAC) for a deep tube-well has been calculated as:

$$TAC = ANCP + AOMC \qquad (7.14)$$

7.4.1.6 Unit cost of groundwater pumping

Annual volume of pumped water corresponding to annual pumping hours has been calculated to obtain the unit production cost for different well capacities using the capital, O&M and total costs. The unit costs have been obtained as follows:

Volume of annual pumped water $(V_a) = Q \times PT$

Unit capital cost $(UCV) = ANCP/ V_a$

Unit O&M cost $(UOMC) = AOMC/ V_a$

Unit total cost $(UTC) = TAC/ V_a$ (7.15)

7.4.2 Estimation of Optimum Well Capacity

The Unit Total Cost (UTC) for shallow tubewell has been worked out for different capacities ranging from 0.005 m^3/s to 0.02 m^3/s using a computer program developed based on procedure given by Khare (2003), for this purpose. The flow chart of the program is given in Figs. 7.3 and 7.4. The diameters for various well capacities have been given in the input data depending upon the size available in the market. Rates (price/unit) are given in the input data for various items for different well capacities. To compute the drawdown from the screen (screen losses), equations are obtained from the graphical solution of screen loss function, given by Chawla and Sharma (1971) and the same being used in the program.

To determine the optimum well capacity, program has been run for different well capacities and unit costs have been determined. The unit costs for different well capacities with

250, 500, 750 and 1000 pumping hours per year are shown in Fig. 7.5. The unit costs have been computed with the following constant parameters; (static head 4 m, hydraulic conductivity 0.00075 m/s, entrance velocity 0.025 m/s and specific yield as 0.01). Figure 7.5 indicates that the unit production cost decreases with increasing pumping hours as the amount of water pumped annually increases. The unit cost decreases as the well capacity increases. However, there is no appreciable change in unit cost with an increase in the well capacity exceeding 0.015 m^3/s. Unit cost of well capacity of 0.015 m^3/s has been found to be minimum and therefore considered as economical well capacity. In the study area, capacity of most of the shallow tubewells has been found to be between 0.005 m^3/s and 0.020 m^3/s.

7.4.3 Pumping Cost Function

The one of the important factors which affects the pumping cost is the static head (depth to water table). To develop the cost function for total unit cost of pumping, the computer program mentioned in earlier section has been run for optimal well capacity (0.015m^3/s) with static head ranging from 2 to 30 m, keeping other parameters constant. The annual pumping hours have been changed from 250 to 1000. Tables 7.3 to 7.7 show the effect of depth to water table on total unit cost for all the cases. As expected, the unit cost increases significantly with the increase in static head throughout. Cost functions have been developed for the unit pumping cost (capital, O&M and total) using the regression analysis. Depth to water table (static head) has been considered as independent variable and unit pumping cost adopted as dependent variable. As evident from Figs. 7.6 to 7.9, pumping cost is proportional to the depth to water table; hence linear regression technique has been used for the development of cost function.

For the optimum well capacity (0.015m^3/s), cost functions have been developed for unit capital, O&M and total cost, using linear regression technique. Detailed results of regression analysis for optimum well capacity are given in Table 7.8.

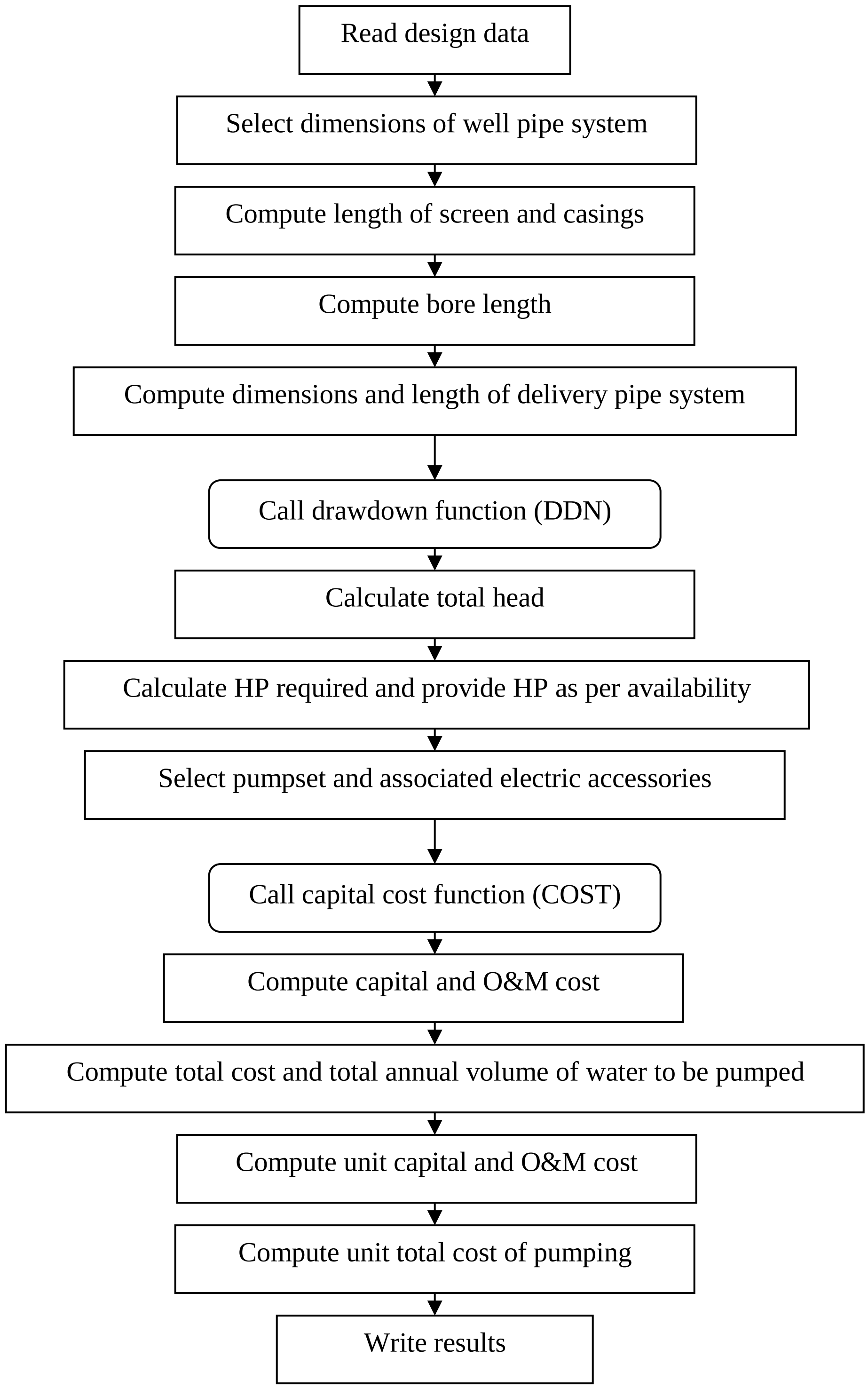


Figure 7.3 Flowchart of the computer program for unit cost of groundwater pumping in TCA

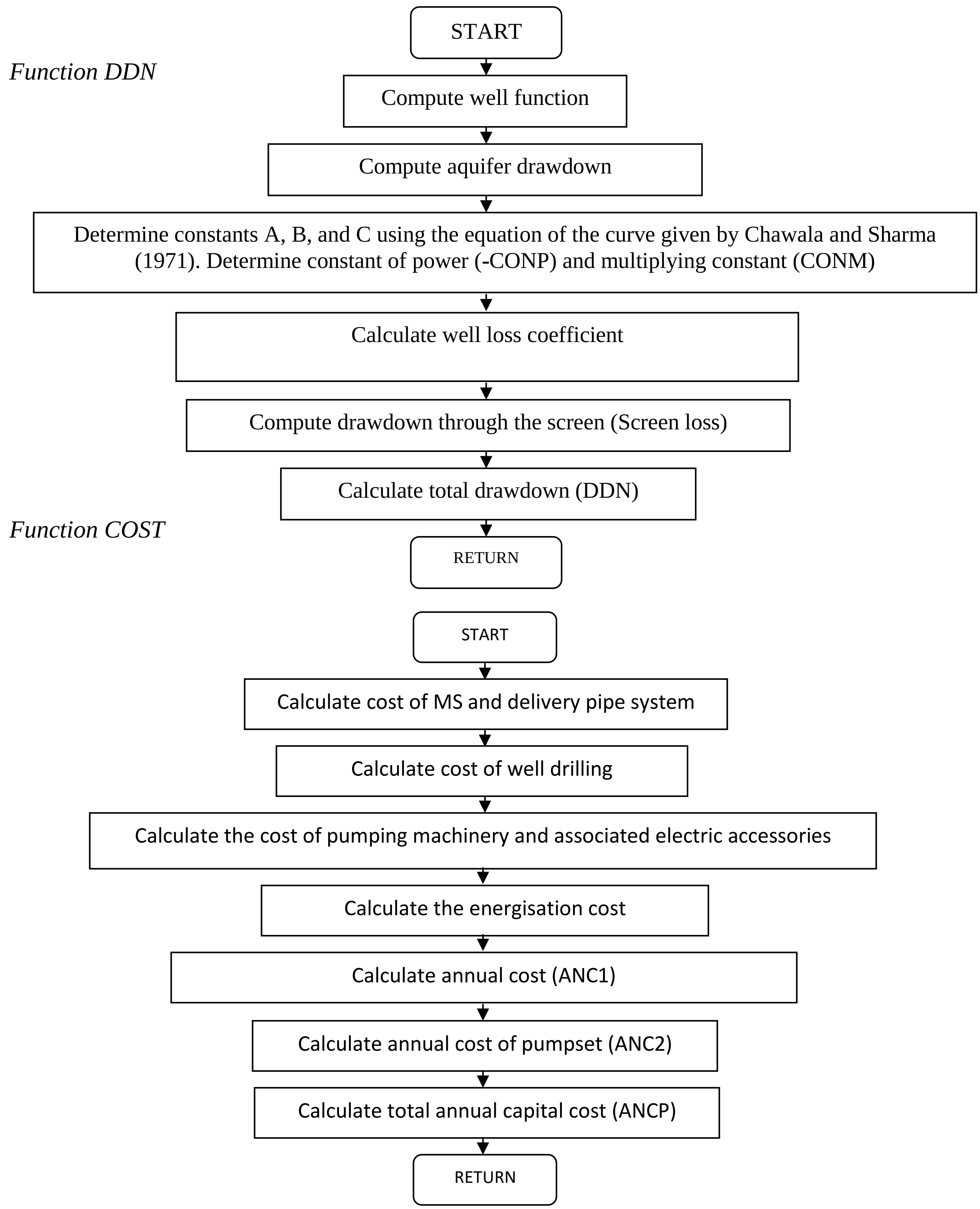


Figure 7.4: Function DDN and COST used to calculate drawdown and capital cost

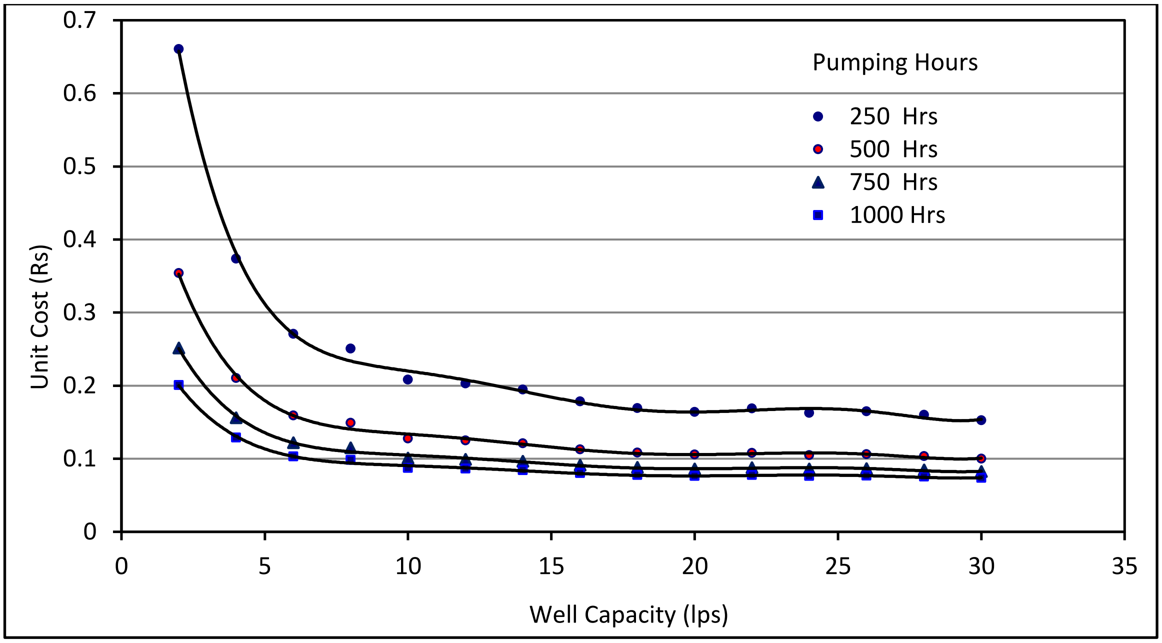


Figure 7.5 Unit cost vs. well capacities for different annual pumping hours

Table 7.4 Variation of unit cost with depth of water table for annual pumping of 250 hrs

Head (m)	Recurring Cost (Rs)	Annual Capital Cost (Rs)	Maintenance Cost (Rs)	Total Cost (Rs)
2	85.26	8536.46	1103.32	9725.03
4	170.51	9086.89	1174.46	10431.86
6	255.77	9342.59	1207.51	10805.87
8	341.03	11322.86	1463.45	13127.34
10	426.29	11183.43	1445.43	13055.15
12	511.54	12995.77	1679.67	15186.99
14	596.80	14359.08	1855.88	16811.76
16	682.06	14610.78	1887.41	17181.24
18	767.31	15292.00	1976.45	18035.77
20	852.57	16236.29	2097.50	19187.36
22	937.83	18593.88	2403.21	21934.92
24	1023.09	19275.10	2491.26	22789.45
26	1107.34	21272.25	2749.39	25129.98
28	1193.60	21953.47	2837.43	25984.50
30	1277.86	21953.47	2837.43	26069.76

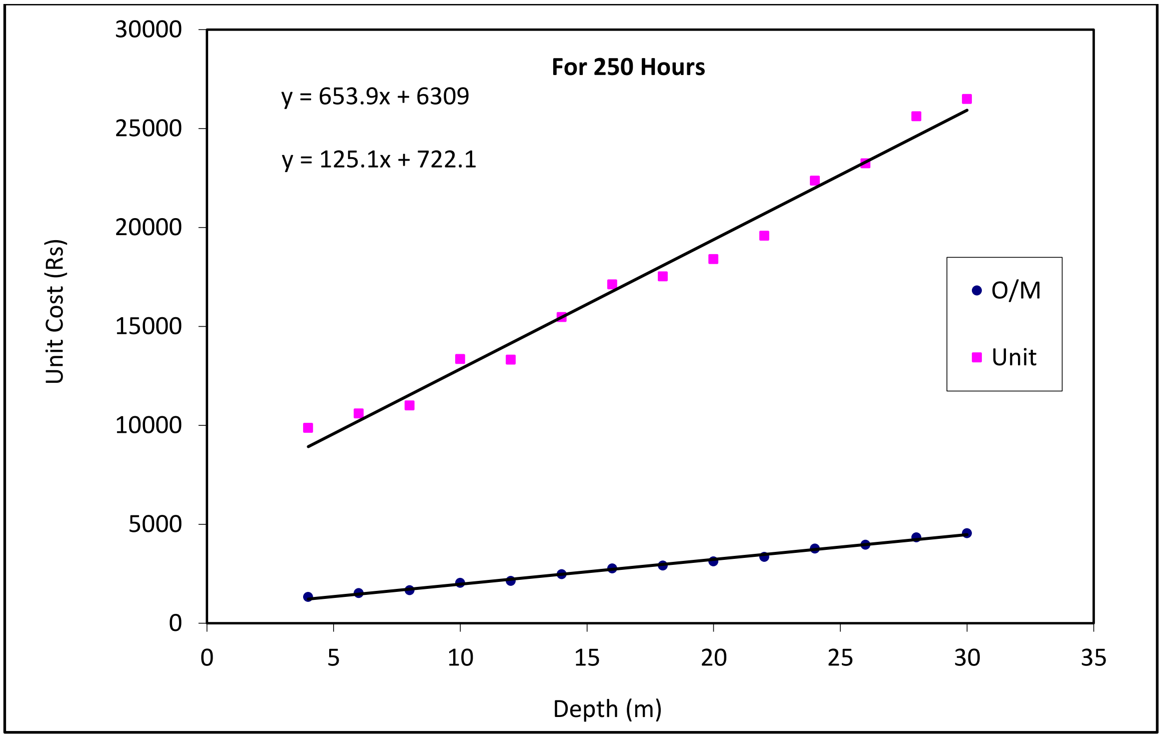


Figure 7.6 Unit cost vs. depth for annual pumping of 250 hours 6.6a

Table 7.5 Variation of unit cost with depth of water table for annual pumping of 500 hrs

Head (m)	Recurring Cost (Rs)	Annual Capital Cost (Rs)	Maintenance Cost (Rs)	Total Cost (Rs)
2	170.51	8536.46	1103.32	9810.29
4	341.03	9086.89	1174.46	10602.37
6	511.54	9342.59	1207.51	11061.64
8	682.06	11322.86	1463.45	13467.37
10	852.57	11183.43	1445.43	13481.44
12	1023.09	12995.77	1679.67	15697.53
14	1193.60	14359.08	1855.88	17407.56
16	1364.11	14610.78	1887.41	17863.30
18	1534.63	15292.00	1976.45	18803.08
20	1705.14	16236.29	2097.50	20039.93
22	1875.66	18593.88	2403.21	22872.75
24	2046.17	19275.10	2491.26	23812.53
26	2216.69	21272.25	2749.39	26237.32
28	2387.20	21953.47	2837.43	27177.10
30	2557.71	21953.47	2837.43	27347.62

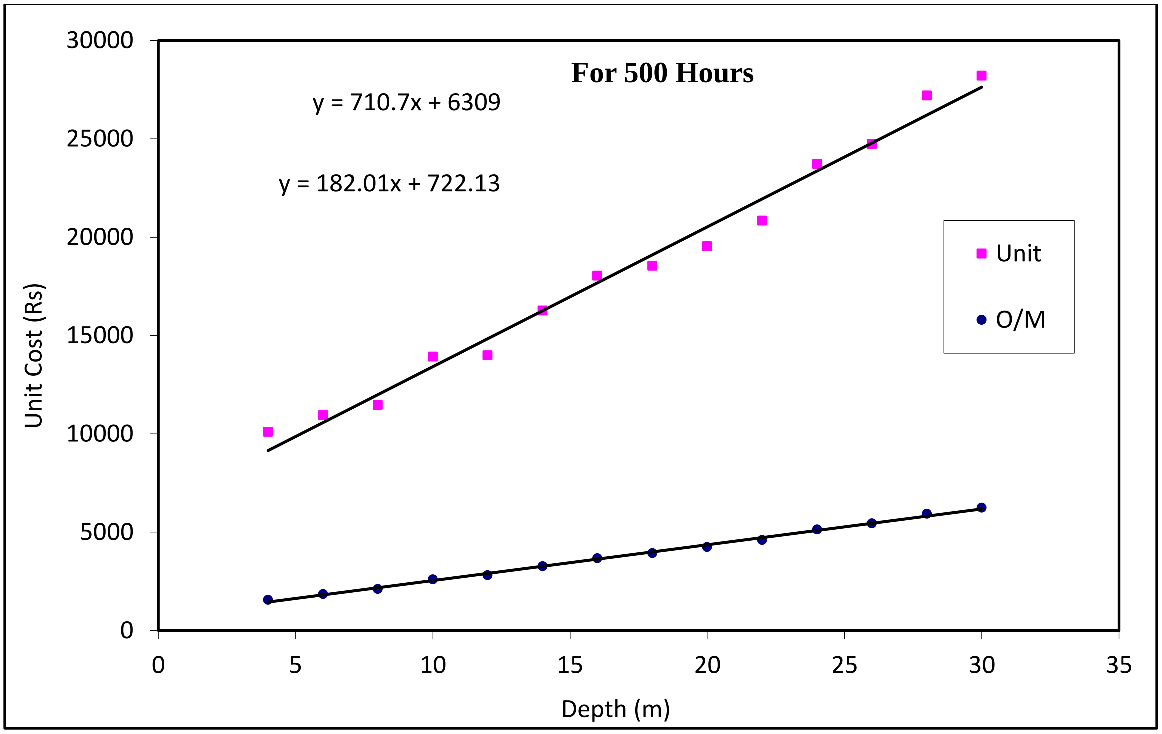


Figure 7.7 Unit cost vs. depth for annual pumping of 500 hours 6.6b

Table 7.6 Variation of unit cost with depth of water table for annual pumping of 750 hrs

Head (m)	Recurring Cost (Rs)	Annual Capital Cost (Rs)	Maintenance Cost (Rs)	Total Cost (Rs)
2	255.77	8536.46	1103.32	9895.55
4	511.54	9086.89	1174.46	10772.89
6	767.31	9342.59	1207.51	11317.41
8	1023.09	11322.86	1463.45	13809.40
10	1277.86	11183.43	1445.43	13907.72
12	1534.63	12995.77	1679.67	16210.07
14	1790.40	14359.08	1855.88	18005.36
16	2046.17	14610.78	1887.41	18545.36
18	2301.94	15292.00	1976.45	19570.40
20	2557.71	16236.29	2097.50	20892.50
22	2813.49	18593.88	2403.21	23810.58
24	3069.26	19275.10	2491.26	24835.62
26	3325.03	21272.25	2749.39	27346.66
28	3580.80	21953.47	2837.43	28371.70
30	3836.57	21953.47	2837.43	28627.47

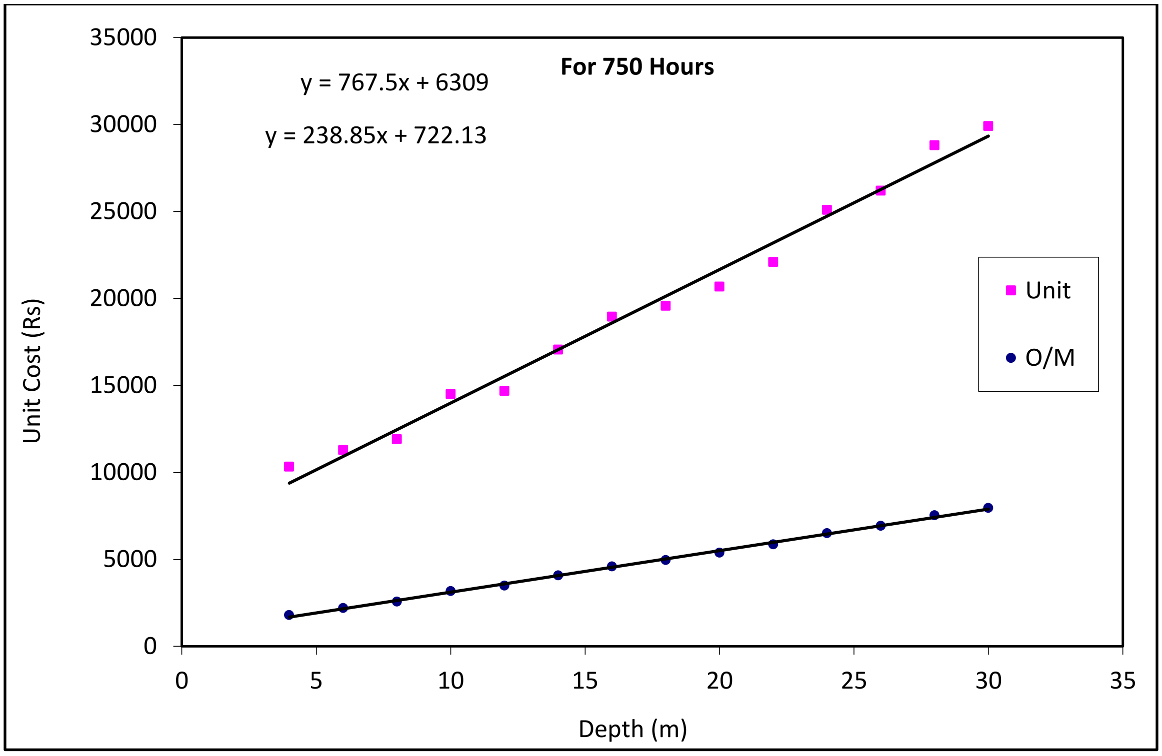


Figure 7.8 Unit cost vs. depth for annual pumping of 750 hours 6.6c

Table 7.7 Variation of unit cost with depth of water table for annual pumping of 1000 hrs

Head (m)	Recurring Cost (Rs)	Annual Capital Cost (Rs)	Maintenance Cost (Rs)	Total Cost (Rs)
2	341.03	8536.46	1103.32	9980.81
4	682.06	9086.89	1174.46	10943.40
6	1023.09	9342.59	1207.51	11573.18
8	1364.11	11322.86	1463.45	14150.43
10	1705.14	11183.43	1445.43	14334.01
12	2046.17	12995.77	1679.67	16721.61
14	2387.20	14359.08	1855.88	18602.16
16	2727.23	14610.78	1887.41	19227.41
18	3069.26	15292.00	1976.45	20337.71
20	3410.29	16236.29	2097.50	21745.07
22	3751.31	18593.88	2403.21	24747.41
24	4092.34	19275.10	2491.26	25857.70
26	4433.37	21272.25	2749.39	28455.01
28	4774.40	21953.47	2837.43	29565.30
30	5115.43	37257.81	4815.48	47187.72

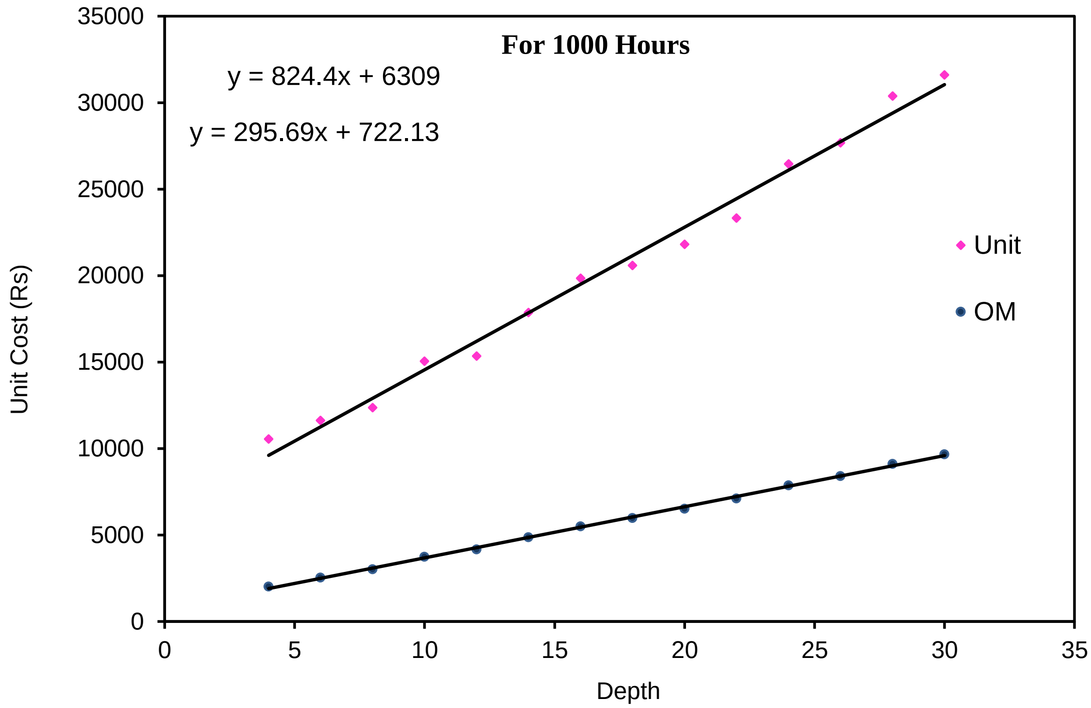


Figure 7.9 Unit cost vs. depth for annual pumping of 1000 hours 6.6d

Table 7.8 Cost function of groundwater pumping for optimum well capacity

Annual pumping Hours	Cost parameter	Cost function	R^2
250	O&M cost	Ucost= 125.1×H + 722.1	0.994
	Unit Cost	Ucost= 653.9×H + 6309	0.983
500	O&M cost	Ucost =182.0×H + 722.1	0.997
	Unit Cost	Ucost = 710.7×H + 6309	0.986
750	O&M cost	Ucost = 238.8×H + 722.1	0.998
	Unit Cost	Ucost = 767.5×H + 6309	0.988
1000	O&M cost	Ucost = 295.6×H + 722.1	0.999
	Unit Cost	Ucost = 824.4×H + 6309	0.989

These cost functions have been used to determine the cost of groundwater pumping for a given depth of water table. Subsequently, O&M cost has been used as the cost coefficient in the conjunctive use model.

7.5 COST OF SURFACE WATER

The surface water supply for irrigation in the command area is in place since last three and half decades. Project authorities estimate the surface water cost on regular basis, the same has been taken for present study. Table 7.9 shows the cost of surface water in each zone of TCA.

Table 7.9 Cost of surface water in different zones of TCA

Canal System	Zone No.	Conveyance Efficiency (%)	Total Capital Cost (Rs/ha)	O & M Cost (Rs/ha)	Total Unit Cost (Rs/ha)
LBC	1	77	1822.22	363.62	2185.84
	2	77	1873.57	373.87	2247.44
	3	77	1956.45	390.41	2346.86
RBC	4	77	1858.55	370.87	2229.42
	5	77	1959.21	390.96	2350.17

(Source : Khare, 2003, GEC 1997)

7.6 BENEFITS FROM DIFFERENT CROPS

For determining net benefits from all the crops in the study area, gross receipts and cost of cultivation have been considered. The yields of various crops have been considered as fixed quantities obtained by averaging the corresponding yields over a period of five years. These yield values have been obtained from office of Director of Agriculture, Madhya Pradesh. The cost of fertilisers, seeds, tractor ploughing, harvesting, threshing, nursery preparation (wherever applicable) and plant protections have been considered for estimation of expenditures and have been obtained from the office of Chief Engineer, Tawa Irrigation Project, Bhopal. The total receipt from a crop has been obtained from the yield of the main crop, and the by-products and their respective market prices (as per Reserve Bank of India rates). Benefits have been then, computed from yield in metric tons (mt) to gross receipts in Rupees per hectare and actual cost of cultivation per hectare and their details are given in Table 7.10.

Table 7.10 Net benefit from all the crops

S.No.	Crop	Total Expense (Rs/ha)	Total Benefits (Rs/ha)	Benefits (Rs/ha)
1	Paddy	7814	32450	24636
2	Cotton	13240	21540	8299
3	Jawar	7099	23200	16101
4	Groundnut	13485	60000	46516

5	Maize	12181	19960	7778
6	Pulses	8369	12375	4005
7	Soyabean	8449	25000	16551
8	Wheat	32558	103500	35050
9	Gram	13546	47925	21807
10	Peas	10818	32625	13263
11	Vegetables	7136	20400	79978
12	Linseed	21272	101250	4005
13	Perennial	8369	12375	70942

(Source: Khare, 2003; *www.rbi.gov.in*)

7.7 CROP PRODUCTION RESPONSE FUNCTION (CPRF)

The relationship between crop, climate, water and soil are complex as many biological, physiological, physical and chemical processes are involved. All components of this relationship affect the crop growth and yield. Amongst all, water is the most important component which can be quantified with ease and accuracy (Hexem and Heady, 1978). A great deal of research information on effect of water on crop yield is available (Stewart and Hagan., 1977; Hexem and Heady, 1978; Rao et al., 1988; Rao et al., 1988; Willis et al, 1989; Parihar et al., 1997; Wesseling and Feddes, 2006) however, for practical application, this information must be reduced to a manageable number of major components to allow a meaningful analysis of crop response to water at the field level (Doorenbos et al., 1979). Some of the methods suggested in the past have considered crop yield as a linear function of water supplied, while an important research have shown that the crop yield is nonlinear function of water supply (Willis et al., 1989). The nonlinear equations available in literature for estimating crop yield with respect to water supplied are data extensive and site specific, so their use in practical cases is limited.

In projects dealing with planning, design and operation of irrigation systems, the approach used to analyse the effect of water supply on crop yields must be simple but accurate. Stewart et al., (1977) emphasized that the relationship between crop yield and water supply can be determined when crop water requirements and crop water deficits, on the one hand, and maximum and actual crop yield on the other can be quantified.

In order to quantify the effect of water stress, it is necessary to derive the relationship between relative yield decrease and relative evapotranspiration deficit. Generalized field data on crop yield under different water supply conditions is available in FAO Irrigation Drainage Paper - 33. This data indicates the effect of water deficit in different growth stages on the yield of crop, for all the major crops. The effect of water stress on winter Wheat in three different stages is shown in Figs.7.6 to 7.9 The relation between water stress in different stages of crop and yield is nonlinear in nature as can been seen in Figs. 7.10 to 7.12, however Doorenbos et al., (1979) suggested simple yet a robust technique to deal with nonlinear relation by defining different linear equations for each stage with an empirically derived yield response factor (K_y). In this approach the actual yield can be estimated as:

$$Y_a = Y_m \left[1 - \sum_{i=1}^{n} K_{y,i} \left(1 - \frac{ET_{a,i}}{ET_{m,i}} \right) \right] \tag{7.16}$$

where, Y_a is actual yield of crop, Y_m is maximum yield of the crop, $K_{y,i}$ is yield response factor of crop for i^{th} stage, $ET_{a,i}$ is actual evapotranspiration in i^{th} stage and $ET_{m,i}$ is maximum evapotranspiration expected from healthy crop in i^{th} stage.

The maximum yield of a crop (Y_m) is defined as the harvested yield of crop, adapted to the given growing environment, including the time available to reach maturity, under conditions where water, nutrients and pests and diseases do not limit yield.

The additive approach depicted in Eq. 7.16 is being used by many researchers in planning irrigation systems with major crops (Barret and Skogerboe, 1980; Azaiez and Hariga, 2001; Vedula et al., 2005). In present study the values of yield response factor (K_y) for different crops have been estimated by statistical analysis of data given in FAO Irrigation and Drainage Paper - 33 (Doorenbos et al., 1979). The values of K_y factor estimated for all 13 crops grown in Tawa Command are shown in Table 7.11 The values of maximum yield of each crop have been obtained as described in Section 6.6.

Table 7.11 Yield response factors (K_y) of different crops

Crops	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Paddy	-	-	-	-	-	0.8	0.8	1.2	1.2	0.3	-	-
Cotton	-	-	-	-	0.2	0.2	0.5	0.5	0.5	0.25	0.25	-
Jawar	-	-	-	-	-	-	0.2	0.2	0.4	0.3	0.1	-
Groundnut	-	-	-	-	-	-	0.2	0.8	0.6	0.2	-	-
Maize	-	-	-	-	-	-	0.4	1.5	0.5	0.2	-	-
Pulses	-	-	-	-	-	0.2	0.2	1.1	0.75	0.2	0.2	-
Soyabean	-	-	-	-	-	0.2	0.2	0.55	0.45	0.2	-	-
Wheat	0.6	0.5	0.2	-	-	-	-	-	-	0.2	0.2	0.6
Gram	0.2	-	-	-	-	-	-	-	-	0.2	0.6	0.5

Peas	0.2	-	-	-	-	-	-	-	-	0.2	0.9	0.7
Vegetables	0.8	0.3	0.3	-	-	-	-	-	-	0.57	0.8	0.8
Linseed	0.1	-	-	-	-	-	-	-	-	0.2	0.6	0.3
Perennial	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5

The CPRF generated in this section will be incorporated in the objective function of the conjunctive use model to estimate actual yield of different crop considering the inputs allocated by conjunctive use model.

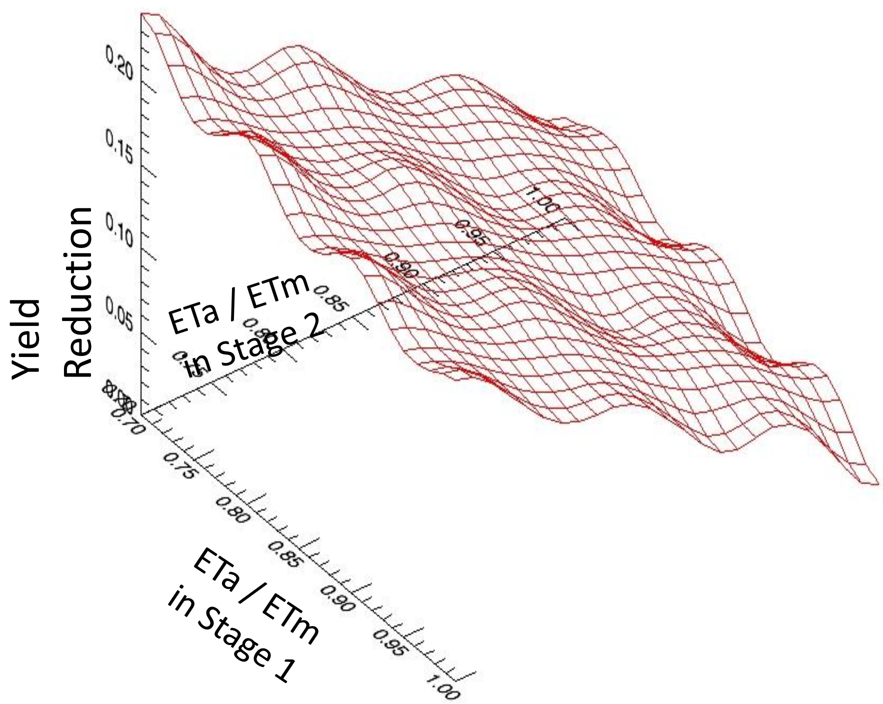


Figure 7.10: Relative yield reduction in Wheat crop with different water stress conditions in first and second stage

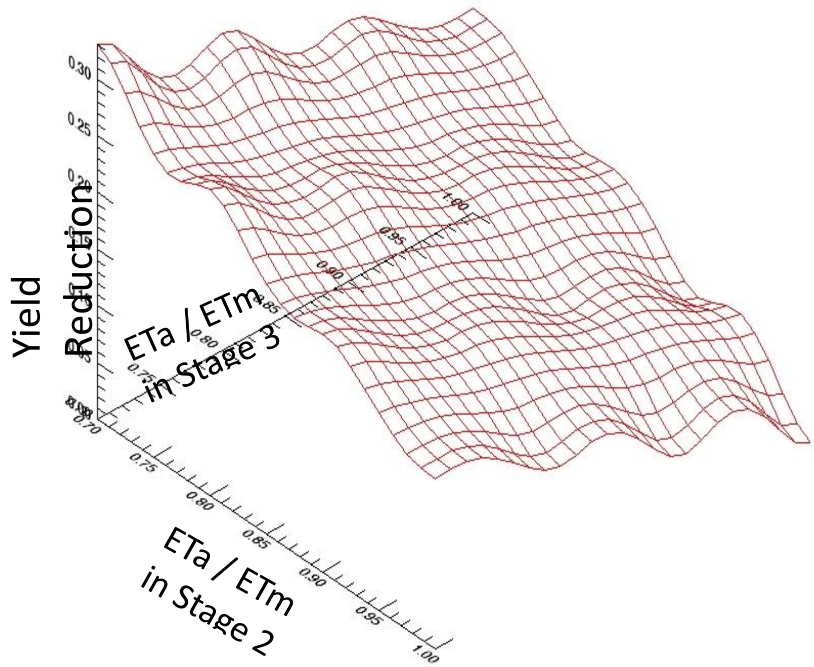


Figure 7.11: Relative yield reduction in Wheat crop with different water stress conditions in second and third stage

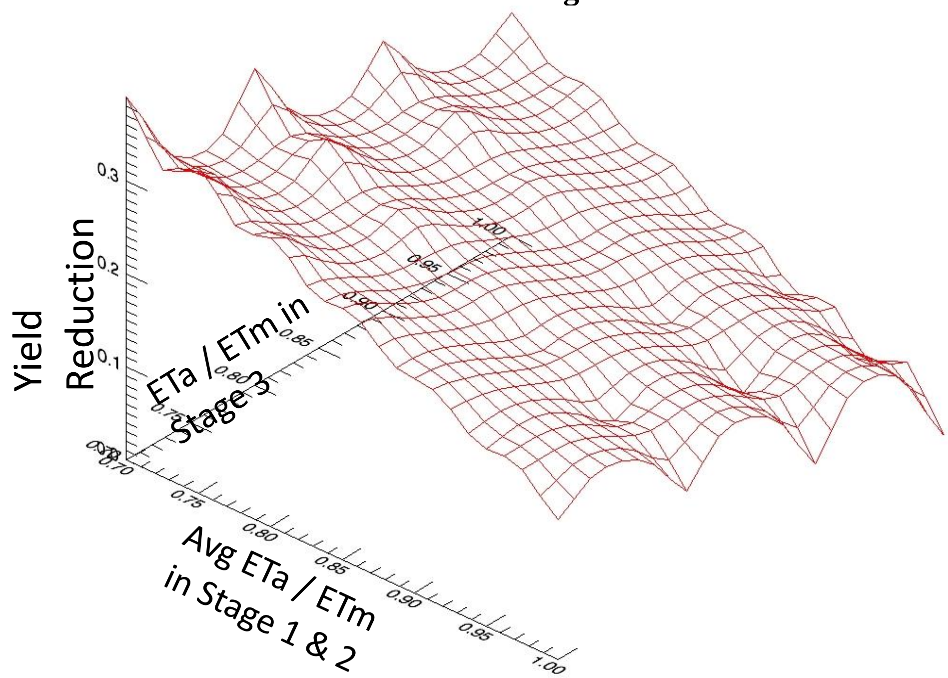


Figure 7.12: Relative yield reduction in Wheat crop with different water stress conditions in first two stages and third stage

7.8 MODEL FORMULATION

An optimization model is required for conjunctive use planning to obtain optimal allocations of resources. The mathematical formulation of a model includes definition of objective function, physical constraints of different components and operational constraints. The distributed conjunctive use model has been formulated by integrating and coupling various cost coefficients. The model has been used to arrive at the optimal allocations of surface water and groundwater with optimal cropping pattern, satisfying a series of constraints. The formulation of conjunctive use is discussed in this section.

7.8.1 Development of an Objective Function

The objective function has been formulated for maximizing the net benefits generated from the cropping activity in the study area. The objective function has the following components:

i) Benefits from cropping activity

ii) Crop yield

iii) Cost of surface water

iv) Cost of groundwater

The description and mathematical formulation of each of these components is given in following sections.

7.8.1.1 Benefits from cropping activity

The benefits from different crops are presented in Table 7.10 These benefits exclude the cost of supplied water. The gross benefits will depend upon the yields, market prices and the costs of cultivation of different crops in the study area. Therefore, the benefits can be written as:

$$\sum_{i=1}^{nz}\sum_{j=1}^{nc} A_{i,j} \times \left(Y_j \times P_j - CCL_j\right)$$

or

$$\sum_{i=1}^{nz}\sum_{j=1}^{nc} A_{i,j} \times NB_j \tag{7.17}$$

where, *nz* is number of zones (5 for present study), *nc* is number of crops (13 for present case), $A_{i,j}$ is area of j^{th} crop for the i^{th} zone (ha), Y_j is yield of j^{th} crop (mt/ha), P_j is price of j^{th}

crop (Rs/mt), CCL_j is total cost of cultivation for j^{th} crop excluding the cost of water, NB_j is net benefits for j^{th} crop excluding the cost of water.

7.8.1.2 Crop yield

As described in Section 7.7, yield of crop is a function of water supplied. Water is an important and easily quantifiable input for crop production, so the crop yield in objective function has been defined as function of water supplied from both the sources to the crop in each growth stage. The developed CPRF have been used to define this relationship in quantitative terms as given below;

$$Y_{a,i,j} = Y_{m,i,j}\left[1 - \sum_{K=1}^{n} K_{y,j,k}\left(1 - \frac{(SW+GW)_{i,j,k}}{WR_{i,j,k}}\right)\right] \qquad (7.18)$$

where, $Y_{a,i,j}$ is actual yield of j^{th} crop in i^{th} zone (mt), $Y_{m,i,j}$ is maximum potential yield expected from j^{th} crop in i^{th} zone (mt), $K_{y,j,k}$ is yield response factor of j^{th} crop in k^{th} month, n is number of months, $(SW+GW)_{i,j,k}$ is total water allocated to the j^{th} crop in i^{th} zone in k^{th} month (mm), $WR_{i,j,k}$ is irrigation water requirement of the j^{th} crop in i^{th} zone in k^{th} month.

7.8.1.3 Cost of surface water

The cost of providing surface water at the outlet of each zone of the study area is given in Table 7.6. The unit cost of surface water has been considered same for all the months from October to March, during which the surface water is available for irrigation. Therefore, the cost of providing surface water can be expressed as:

$$\sum_{k=1}^{n} CST_i \times SW_{i,j,k} \qquad \forall i \text{ and } j \qquad (7.19)$$

Where, CST_i *is total unit cost of surface water for* i^{th} *zone (Rs/ha-m),* $SW_{i,k}$ *is surface water allocation to* j^{th} *crop in* i^{th} *zone in* k^{th} *month (ha-m).*

7.8.1.4 Cost of groundwater

Cost analysis of groundwater is described in Section 6.4. A well capacity of 0.015 m^3/s has been found economical and the cost functions developed for this well capacity have been used in the present study. Separate cost functions have been obtained for total cost, capital cost and O&M cost. These cost functions have been used in the conjunctive use model depending upon the type of investigation. In present study only O&M cost has been used to estimate the groundwater pumping cost as per the recommendations of Khare (1994). The following cost functions (Rs/ha-m) have been obtained for groundwater pumped from tubewells:

$$CFC = 824.43 \times dw + 6309.3 \tag{7.20}$$
$$CFO = 295.69 \times dw + 722.13 \tag{7.21}$$
$$CFT = 1120.12 \times dw + 7031.43 \tag{7.22}$$

Where, *dw* is depth to water table (m), *CFC* is cost function for capital cost (Rs/ha-m), *CFO* is cost function for O/M costs (Rs/ha-m), *CFT* is cost function for total cost (Rs/ha-m)

For a known value of *dw* the cost function would be converted to a numerical value and thus the unit costs for ground water pumped from tubewell can be written as

$$CGC_{i,k} = \mathrm{CFC}$$

$$CGO_{i,k} = \mathrm{CFO}$$

$$CGT_{i,k} = CGC_{i,k} + CGO_{i,k} = \mathrm{CFT}$$

Where, $CGC_{i,k}$ is unit capital cost of groundwater for i^{th} zone during k^{th} month (Rs/ha-m), $CGO_{i,k}$ is unit O&M cost of groundwater for i^{th} zone during k^{th} month (Rs/ha-m), $CGT_{i,k}$ is unit total cost of groundwater for i^{th} zone during k^{th} month (Rs/ha-m). Thus, the cost of providing groundwater can be written as:

$$\sum_{k=1}^{n} CGO_{i,k} \times GW_{i,j,k} \qquad \forall i \text{ and } j \tag{7.23}$$

where, $GW_{i,k}$ is groundwater allocations to j^{th} crop in i^{th} zone during k^{th} month (ha-m).

The objective function for maximizing the net benefits from the command has been build using Eqs. 6.17, 6.18, 6.19 and 6.23. The final form of the objective function can be expressed as

$$Maximize\, Z = \sum_{j=1}^{nc} \left(\sum_{i=1}^{nz} A_{i,j} \times NB_j - \sum_{i=1}^{nz} \sum_{k=1}^{n} CST_i \times SW_{i,j,k} - \sum_{i=1}^{nz} \sum_{k=1}^{n} CGT \times GW_{i,j,k} \right) \tag{7.24}$$

The above objective function would be subjected to multiple of constraints discussed in the following section.

7.8.2 Model Constraints

Constraints on the model are physical, geometric and operational limitations imposed on the model to represent the actual operational characteristics of a water resources system. These include capacity constraints for sources, resources utilization constraints, equity in distribution, demand constraint and non-negativity constraint.

7.8.2.1 Water requirement constraints

Surface water and groundwater allocations in respective months must meet the total monthly water requirement of the crops in each zone. The water requirement and water allocation has been considered at the outlet in the present investigation. Therefore, constraints for water requirement of crops can be written as

$$\frac{(WR_{i,j,k} \times A_{i,j})}{(SW_{i,j,k} + GW_{i,j,k})} \geq 1 \qquad \forall\, i,\, j \ and\ k \tag{7.25}$$

where, $WR_{i,j,k}$ is water requirement of j^{th} crop in i^{th} zone for k^{th} month (m)

In planning phase, the right hand side of the Eq. 6.25 is kept equal to one to provide irrigation water equal to actual irrigation water requirement of the crops. In case of water deficit scenario the right hand side can be brought down as per the water availability, so in case of water deficit scenario the water requirement constraints can be formulated as;

$$\frac{(WR_{i,j,k} \times A_{i,j})}{(SW_{i,j,k} + GW_{i,j,k})} \leq 1 \qquad \forall\, i,\, j and\, k \tag{7.26}$$

7.8.2.2 Area availability constraints

For each zone, the Cultivable Commanded Area (CCA) has been worked out and presented in Table 6.1. The total area for all crops cannot exceed the CCA of that particular zone for all the months. Since only two cropping seasons have been considered in the present study viz. Kharif and Rabi, only two constraints, one for Kharif and another for Rabi season would be effective (or active). Remaining constraints for the other months will be redundant.

Therefore, the area for all the crops of either Kharif or Rabi season should not exceed the CCA of the relevant zone. This constraint can be expressed as

$$\sum_{j=1}^{nc} \lambda_{j,kk} \times A_{i,j} \leq CCA_i \qquad \forall\, kk \ \ and \ \ i \tag{7.27}$$

$$\sum_{j=1}^{nc} \lambda_{j,kr} \times A_{i,j} \leq CCA_i \qquad \forall\ kr \ and \ \ i \tag{7.28}$$

Where, $\lambda_{j,kk}$ is land use coefficient for j^{th} crop in kk^{th} season, $\lambda_{j,kr}$ is land use coefficient for j^{th} crop in kr^{th} season, *kk* is months of Kharif season, *kr* is months of Rabi season, CCA_i is cultivable commanded area for i^{th} zone (ha).

For every zone, only two constraints have been provided for each season i.e. Kharif and Rabi. Therefore, the land use coefficient would be equal to seasonal irrigation intensity or cropping intensity for the present investigation.

7.8.2.3 Surface water availability constraints

The Tawa LBC and RBC runs about 150 days in the year. The month wise availability of surface water is given in Table 6.2. Surface water in any month for all the zones cannot exceed the available water at the head of canal for that month. Therefore, surface water availability constraint can be written as

$$\frac{\sum_{j=1}^{nc} SW_{i,j,k}}{\left(ES_{dm,i} \times ES_{c,i}\right)} \le ASW_{i,k} \qquad \forall i \quad and \quad k \tag{7.29}$$

where, $ASW_{i,k}$ is available surface water at the head of i^{th} zone in k^{th} month (ha-m), $ES_{dm,i}$ is efficiency of surface water system for distributaries and minors of i^{th} zone, $Es_{c,i}$ is conveyance efficiency of canal for i^{th} zone.

The zone-wise efficiencies have been computed and it has been found that 23% losses would occur from distributaries and minors based on the existing practices in the nearby regions of the study area. Therefore, conveyance efficiency for distributaries and minors has been taken as 77% (GEC, 1997).

7.8.2.4 Groundwater availability constraints

The total water pumped annually from the groundwater system of the study area should not exceed the annual recharge without allowing mining. The annual groundwater availability has been reported as 140809 ha-m (Khare, 2003). Thus, the constraints on groundwater availability for all the zones of the study area can be written as

$$\sum_{i=1}^{nz}\sum_{k=1}^{n}\sum_{j=1}^{nc} GW_{i,j,k} \le m \times AGW \quad (7.30)$$

Where, AGW is total available groundwater (ha-m), m is mining allowance (1 when no mining is allowed)

7.8.2.5 Crop area constraints

These constraints have been imposed on each crop to limit the area under each crop considering the technical and social requirements of the area

$$A_{i,j} \le p_{i,j} \times CCA_i \qquad \forall i \text{ and } j \quad (7.31)$$

where, p_{ij} is the ratio of area of j^{th} crop in i^{th} zone and CCA of i^{th} zone.

7.8.2.6 Non-negativity constraints

All the decision variables (quantity of water supplied from both the sources during each time period and area allocated to each crop in each time period) should be equal to or greater than zero.

$$\left.\begin{array}{l} SW_{i,j} \ge 0 \quad \forall\, i,\ j \text{ and } k \\ GW_{i,j} \ge 0 \quad \forall\, i,\ j \text{ and } k \\ A_{i,j} \ge 0 \quad \forall\, i,\ j \text{ and } k \end{array}\right\} \quad (7.32)$$

$SW_{ij} \ge 0 \forall i, j, k$ $GW_{ij} \ge 0 \forall i, j, k$

$A_{ij} \ge 0 \forall i, j, k$korKr

7.9 INTEGRATION OF COST FUNCTIONS IN CONJUNCTIVE USE MODEL

The cost coefficients (except groundwater pumping cost functions) and CPRF have been integrated into optimization models. The groundwater model and pumping cost function have been coupled externally to optimization model to incorporate the dynamic behaviour of groundwater system for optimum allocation of water resources. In the optimization model, monthly allocations of water from both the sources have been obtained over one year planning horizon. Groundwater model has been coupled externally with the optimization model through input/output file transfer. Groundwater model has been run for a year planning horizon at seasonal time step. Initially unit cost of groundwater withdrawal has been estimated using the seasonal average value of groundwater table depth. The cost of groundwater withdrawal per unit volume is then used in the optimization model to determine the optimal integration of both the sources for irrigation. Optimum allocation of water from both sources has been determined from the optimization model. These groundwater allocations have been supplied to the groundwater model as an input, which determines the position of water table at the end of each season.

From the water table positions at the beginning and end of each season, the average depth of water table in non-monsoon and monsoon seasons have been determined. Unit costs of groundwater withdrawal are revised as per the new values of average groundwater depth. These revised unit costs are again used in optimization model in the next trial. In a similar manner, process is repeated till the convergence criterion is satisfied for the average zonal depth to water table in all zones of the study area. For illustrating the procedure of external coupling, cost function for O&M cost of groundwater withdrawal has been considered (Khare, 1994) (Eq. 6.21), the resulting functional relationship of groundwater pumping cost can be written as (considering depth to water table as a time variant quantity).

$$GW_{i,k} \times [(295.69 \times dw) + 722.13] \quad (7.33)$$

This function makes the model nonlinear, as the depth of groundwater table is an implicit function of groundwater withdrawal ($GW_{i\ k}$), which is a decision variable in the objective function of the model. Since, global solution is not guaranteed from the solution of a nonlinear model, therefore, it is better to formulate the optimization model as a linear formulation and any other alternative can be adopted to account the nonlinearties of groundwater pumping cost. In the present study, nonlinearity of groundwater cost has been accounted by successive linearization approach.

For this, initial mean seasonal water table depth (the average depth to water table at the beginning and at the end of season) has been determined for each zone in GIS by calculating the zonal statistics using conjunctive use zone polygon layer and initial seasonal water table surfaces (DEM of water table in non-monsoon and monsoon). With these initial zone-wise water table depths, the unit cost of groundwater withdrawal is computed for each zone using Eq. 6.33. These costs are then used in optimization model and monthly allocations of water from both the sources are obtained. Further monthly groundwater withdrawal is converted into groundwater pumping rates, and again used into groundwater model.

Groundwater model is again re-run for groundwater withdrawal obtained from optimization model and new groundwater table elevations are obtained at the end of monsoon (end of November) and non-monsoon period (end of May). For each zone, with these revised water table elevations, mean seasonal water table depths are determined in GIS. These revised average seasonal water table elevations are then compared with the initial average seasonal depth. If the difference between these two values is within acceptable limits i.e., difference is less than an acceptable value (convergence criteria, ccr = 0.5 m), the process stops. Otherwise, the new average seasonal water table depths are used for computing the unit cost of groundwater pumping using cost functions, and the whole cycle of computation, as stated above is repeated. The flow chart of this process is shown in Fig. 7.13.

7.10 SOLUTION OF MODEL

In the present study, LINGO (version 10), a comprehensive tool designed for building and solving linear, nonlinear and integer optimization models, has been used for solving the formulated conjunctive use model (optimization model). This software is developed by the LINDO Systems Inc. (Chicago, USA). The LINGO provides a completely integrated package that includes a powerful language for expressing optimization models, a full featured environment for building and editing problems and a set of fast built-in solvers. It is capable of providing solution of linear, nonlinear (convex & non-convex), quadratic, quadratically constrained, and integer optimization problems. Extended version of the LINGO is capable of handling of unlimited constraints, variables, integers, non-linear and global variables.

The LINGO uses the modified simplex and interior point methods for the solution of linear programming problems. For non-linear programming models, the primary technique used by the LINGO is based on the Generalized Reduced Gradient (GRG) algorithm. Successive Linear Programming (SLP) algorithm is also available in LINGO for the solution of non-linear programming problems. The LINGO (version 10) also has Global and Multi-start solvers, which are capable of achieving global solution of non-convex and non-linear problem. The Global solver converts the original non-convex and nonlinear problem into several convex and linear sub-problems. It then uses the branch-and-bound technique to exhaustively search over these sub-problems for the global solution.

7.11 APPLICATION OF MODEL

The developed conjunctive use model has been used to derive optimal scenario of resources allocation in Tawa Command. The input parameters for distributed conjunctive use model have been obtained from geodatabase discussed in Chapter 4, results of groundwater model discussed in Chapter-5 and results of resources assessment discussed in Section 6.2. The groundwater cost functions for optimum well capacity of $0.015 m^3/s$ and 1000 annual pumping hours per year has been taken from Table 7.5. The cost of surface water and benefits from all the crops have been used as per the estimates given in Section 7.5 and 7.6. The monthly water demand in terms of depth for each crop (Table 7.3) has been used to estimate total water requirement in each month. In model run the groundwater pumping cost for each zone has been estimated using zonal average groundwater level value and zone average ground surface elevation values in 'Spatial Analysis' environment of Arc GIS. Initially the designed cropping pattern and irrigation intensity scenario suggested by project authorities has been evaluated to know the level of resource allocations and total benefits accrued, while satisfying the system constraints.

Cropping pattern in the Tawa Command has changed drastically in recent past (Khare, 2003); this is also observed in comparison of land use for year 1995 and 2005 in Chapter 4. Intensity of Wheat crop in the command has increased in Rabi season. The reports also indicate the shift from Paddy to Soyabean in Kharif season (Khare, 2003). So the conjunctive use model has been applied over this changed scenario, which will be termed as existing cropping scenario from now onwards. In existing cropping pattern scenario the irrigation intensity has been kept 67% in both the seasons in all zones, area under Paddy has been reduced and area under Soyabean has been increased as per reported values. Within the framework of existing condition, the surface water supply to Zone-3 has been reduced from 20% to 100% and the excess water has been diverted to Zone-1, to counter problems of rising groundwater levels in Zone-3 and groundwater depletion in Zone-1. The effect of water utilization on groundwater system in existing cropping pattern scenario has been estimated by running the groundwater model for the years 2004 to 2010.

Keeping in view the amount of surface water unutilized during Rabi season in existing cropping pattern scenario, the irrigation intensity in Rabi season has been increased to 80%. The water allocation plans have been developed with increased cropping intensity in all zones, diverting surface water supply form Zone-3 (from 20% to 100%) to Zone-1. The spatio-temporal conjunctive water use approach has also been tested through this model. In the end to demonstrate the capability of developed model in optimally managing water deficit scenario, the total ground water availability has been reduced by 43% and the water allocation plan for existing cropping pattern has been obtained through the conjunctive use model.

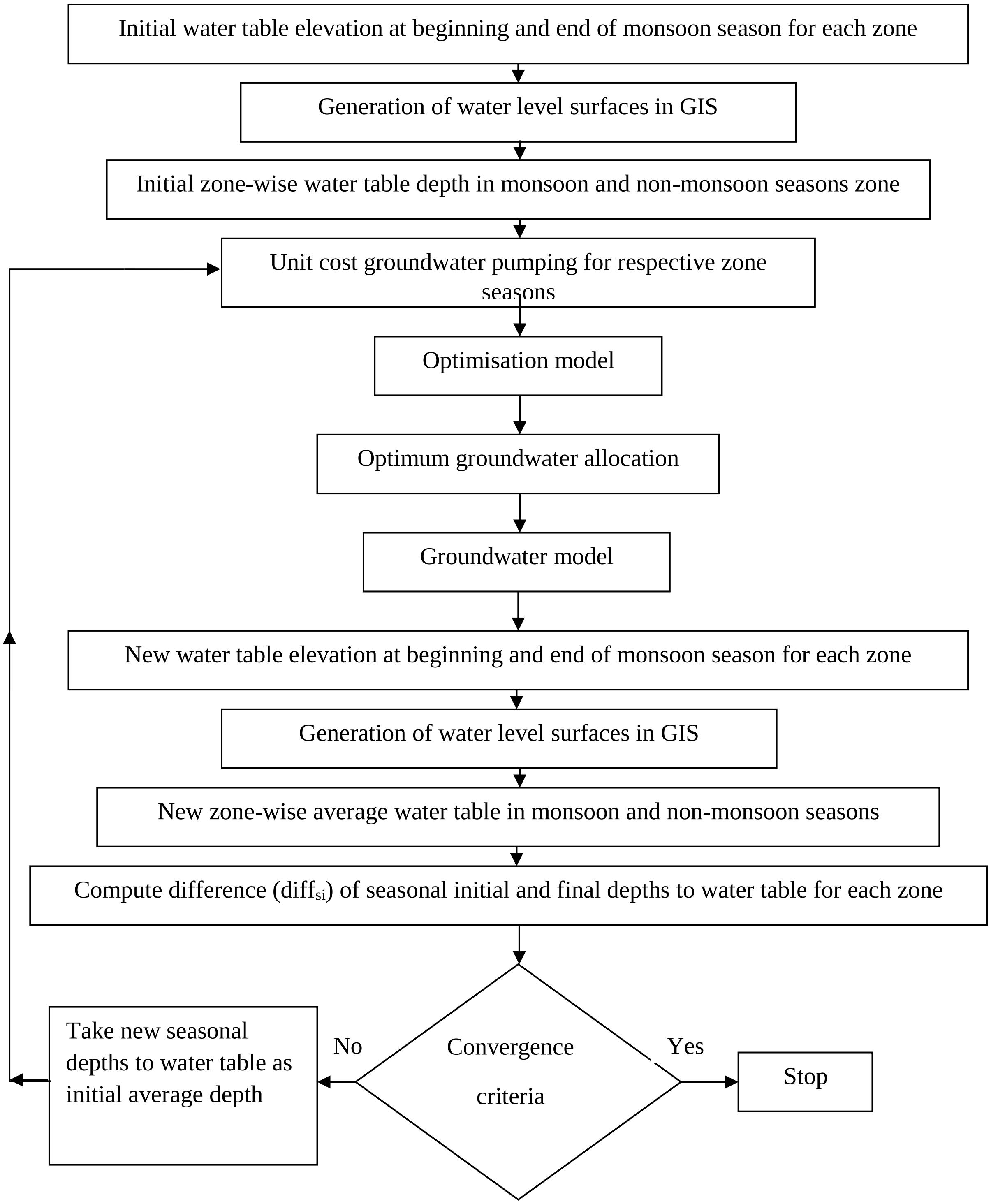


Figure 7.13: Flowchart for the linearization of groundwater pumping cost.

7.12 CONCLUDING REMARKS

This Chapter presents a generalized modelling framework of conjunctive use model *i.e.*, optimum water resources allocation in a irrigation command. Initially, the resources on which the model has to run are quantified for Tawa Command. The generation of Crop Production Response Functions for thirteen crops grown in Tawa Command is presented along with cost functions of surface water and groundwater. The mathematical formulation of conjunctive use model (objective function, constraints) and integration of water cost functions and CPRF in objective function of conjunctive use model is described in details. Integration of groundwater model and optimization model is discussed subsequently.

The cost functions for surface water, groundwater and CPRF, optimization model and groundwater model have been coupled for optimum planning of water resources in command area. The season-wise cost of pumping has been considered in the model corresponding to the average seasonal depths to water table in each zone of the study area. Originally presented model is a nonlinear programming model because of nonlinearities of groundwater pumping cost, as cost of groundwater is an implicit function of groundwater withdrawal and the lift. The problem, however, has been converted into linear, by successive linearization approach. LINGO optimization package has been used for the solution of the model.

The proposed model is a generalized formulation and can be used for any other command area, by incorporating required input data. Models explicitly consider various physical and operational characteristics of a realistic water supply system. Model application results for different scenarios are investigated and presented in Chapter 8.

CHAPTER 8
OPTICAL ALLOCATION POLICIES – EVALUATION - FORMULATION AND MODEL RESULTS

8.1 GENERAL

The developed conjunctive use model has been applied over Tawa Command Area to investigate the different scenarios of resources allocation, and suggest the optimal scenario. The results of resources allocation obtained in each scenario are discussed in details in present chapter. Initially, different management scenarios considered in the present study are listed along with their associated assumptions. The scenario to counter environmental degradation problems along with elevated economic returns are discussed in this chapter. The optimal scenario is suggested through comparative analysis of all the results. Subsequently, the potential of developed conjunctive use model in optimal management of water deficit situations has also been demonstrated.

8.2 MANAGEMENT SCENARIOS INVESTIGATED

In the present study, following six scenarios were investigated for resources allocations in the Tawa Command:

Scenario 1: Designed cropping pattern and irrigation intensity (Strategy 1)

Scenario 2: Existing cropping pattern and 67% irrigation intensity/cropping intensity in Rabi and Kharif seasons (Strategy 2)

Scenario 3: Existing cropping pattern with 67% irrigation intensity in both the seasons and changed surface water supply levels in Zone-3 and Zone-1 (Strategy 3 to 12)

Scenario 4: Increased irrigation intensity in Rabi season (80%) and 67% cropping intensity in Kharif season (Strategy 13)

Scenario 5: Increased irrigation intensity in Rabi season (80%) and 67% cropping intensity in Kharif season with changed surface water supply levels in Zone-3 and Zone-1 (Strategy 14 to 18)

Scenario 6: Spatio-temporal conjunctive use approach (Strategy 19)

The required data, as described in previous chapters, were used while solving the model for resources allocations in different scenarios.

8.3 MODEL ASSUMPTIONS

Various assumptions made in the present study are listed below:

i) In all the scenarios except in water deficit scenario, irrigation level for all crops in all the zones has been assumed to be 100%.

ii) Since the purpose of this study is to investigate the effect of distributed conjunctive use modelling on profitability and sustainability of the command system, the cost coefficients for all the crops, irrigation water demand, cost of water (surface and groundwater) have been considered to be time independent.

iii) The surface irrigation efficiencies, canal distribution efficiencies have been assumed to be uniform in entire command.

iv) The cropping intensities have been assumed to be similar in all zones of the command.

v) In those scenarios where surface water supply to Zone-3 is reduced, it has been assumed that infrastructure is available to pump additional groundwater to meet irrigation requirements.

vi) In those scenarios where the additional surface water supply has been proposed in Zone-1, it has been assumed that the conveyance and distribution system has a capability to convey the additional water.

8.4 MODEL RESULTS

In this section, solutions for resources allocation under various scenarios considered in the present study for Tawa Command are presented. Solutions for these scenarios are based on the formulated model and database prepared in previous chapters. For each scenario, model solution has been obtained using the optimization model LINGO 10.0.

8.4.1 Designed Cropping Pattern (Scenario-1)

Surface irrigation projects are designed for a particular cropping pattern termed as designed cropping pattern. Present scenario (Strategy-1) has been considered to analyse the resources allocations to the designed cropping pattern of Tawa project. The designed seasonal irrigation intensity and cropping pattern has been obtained from the Detailed Project Report (DPR) of the Tawa Irrigation Project. Tawa canal system is designed to supply water in Rabi season during the period from October to March. The major crops grown in both Rabi (October to March) and Kharif (June to October) seasons in LBC and RBC are listed in Table 8.1. The designed irrigation intensity during Rabi season in all the zones (Zone 1, 2 and 3) of Left Bank Canal (LBC) system is 67%, the cropping intensity in Kharif season is also 67% but groundwater as the only source of irrigation. In case of Zone-4 and Zone-5 of

Right Bank Canal (RBC) system, the irrigation intensity in Rabi season is designed similar to LBC (i.e. 67%), with the only change in the Kharif cropping intensity which is 58%.

Table 8.1 Designed cropping pattern of Tawa project

Season	Crops	LBC		RBC	
		Percent of Crop	Area (ha)	Percent of Crop	Area (ha)
Kharif (June to October)	Paddy	30	59450.6	30	18905.0
	Cotton	05	9908.4	04	2520.7
	Jawar	07	13871.8	05	3150.8
	Groundnut	05	9908.4	02	1260.3
	Maize	08	15853.5	06	3781.0
	Pulses	05	9908.4	05	3150.8
	Soyabean	07	13871.8	30	3781.0
Total		**67**	132772.9	**58**	36549.7
Rabi (October to March)	Wheat	55	108992.7	55	34659.2
	Gram	07	13871.8	07	4411.2
	Peas	02	3963.4	02	1260.3
	Vegetables	01	1981.7	01	630.2
	Linseed	02	3963.4	02	1260.3
Total		**67**	132772.9	**67**	42221.2

In this scenario, the water availability estimates mentioned in previous chapters have been used for solving resources allocations problem. It has been assumed that each zone will adopt the designed cropping pattern and hence the area constraint under each crop has been made a tight constraint. The cost coefficients given in Chapter 6 have been integrated in the objective function and the model has been solved using the approach described in Section 6.9 and 6.10 (Chapter 6). The results obtained (Table 8.2) indicate that, in designed cropping pattern and irrigation intensity scenario, total benefits from the command are around 9223.555 Million Rupees. Total benefits are then converted in terms of benefit per unit of cultivated area (Rs/ha) and benefits per unit of water utilized (Rs/ha-m). Accordingly, the benefits per unit of cultivated area are found to be 25999 Rs/ha and benefits per unit of water utilized are around 40488 Rs/ha-m. The irrigated area and the water utilization in Kharif and Rabi seasons are shown in Figs.8.1 and 8.2 respectively.

In Strategy-1 (designed cropping pattern and irrigation intensity scenario), around 84.37% (110473.7 ha-m) of total available surface water (130952.9 ha-m) in the canal system is utilized for irrigation. Similarly, the groundwater utilization level is around 83.33% (117333.2 ha-m) of total available groundwater (140809 ha-m). The utilization level of surface water for all the months by each zone is shown in Figs. 8.3 to 8.7. The monthly surface water and groundwater allocation in the entire command system is shown in Fig. 8.8.

Table 8.2 Allocations of different resources and benefits for the designed cropping pattern (Strategy-1)

						TOTAL BENEFITS (Million Rs)= 9223.555
AREA UNDER DIFFERENT CROPS (ha)						
	ZONE-1	ZONE-2	ZONE-3	ZONE-4	ZONE-5	TOTAL
PADDY	28570	21400.9	9479.7	14231.9	4673.2	78355.7
COTTON	4761.7	3566.8	1579.9	1897.6	623.1	12429.1
JAWAR	6666.3	4993.5	2211.9	2372	778.9	17022.6
GROUNDNUT	4761.7	3566.8	1579.9	948.8	311.5	11168.7
MAIZE	7618.7	5706.9	2527.9	2846.4	934.6	19634.5
PULSES	4761.7	3566.8	1579.9	2372	778.9	13059.3
SOYABEAN	6666.3	4993.5	2211.9	2846.4	934.6	17652.7
PERENNIAL	3809.3	2853.5	1264	1897.6	623.1	10447.5
WHEAT	52378.2	39235	17379.4	26091.8	8567.5	143651.9
GRAM	6666.3	4993.5	2211.9	3320.8	1090.4	18282.9
PEAS	1904.7	1426.7	632.0	948.8	311.5	5223.7
VEGETABLE	952.3	713.4	316.0	474.4	155.8	2611.9
LINSEED	1904.7	1426.7	632.0	948.8	311.5	5223.7
KHARIF CROPS	63806.4	47795.2	21171.1	27515.1	9034.8	169322.6
RABI CROPS	63806.2	47795.3	21171.3	31784.6	10436.7	174994.1
OPTIMAL ALLOCATION OF SURFACE WATER (ha-m)						
JANUARY	7148.2	5354.5	2371.8	3371.8	1169.2	19415.6
FEBRUARY	8239.3	8218.7	3135.6	3371.8	1794.7	24760.0
MARCH	3570.3	4213.8	1358.7	1461.1	821.4	11425.3
OCTOBER	4394.3	5186.2	1672.3	1798.3	1010.9	14062.0
NOVEMBER	8239.3	6241.9	2764.9	3371.8	1320.2	21938.1
DECEMBER	6906.3	5173.3	2291.6	3371.8	1129.7	18872.7
TOTAL	38497.7	34388.4	13594.9	16746.7	7246.0	**110473.7**
OPTIMAL ALLOCATION OF GROUNDWATER (ha-m)						
JANUARY	0.0	0.0	0.0	189.0	0.0	189.0
FEBRUARY	2732.5	0.0	504.9	2093.7	0.0	5331.1
MARCH	5074.0	2261.4	1509.5	2845.0	592.5	12282.5
APRIL	826.6	619.2	274.3	411.8	135.2	2267.1
MAY	2175.1	1629.3	721.7	975.4	320.3	5821.8
JUNE	2434.2	1823.4	807.7	1195.5	392.6	6653.2
JULY	7240.6	5423.7	2402.5	3474.5	1140.9	19682.1
AUG	6114.9	4580.5	2029.0	2828.4	928.7	16481.5
SEPTEMBER	8203.4	6144.9	2721.9	3669.0	1204.7	21944.0
OCTOBER	10468.8	5947.2	3259.3	4979.9	1214.8	25870.0
NOVEMBER	93.6	0.0	0.0	648.7	0.0	742.3
DECEMBER	0.0	0.0	0.0	68.5	0.0	68.5
TOTAL	45363.7	28429.7	14230.8	23379.3	5929.7	**117333.2**

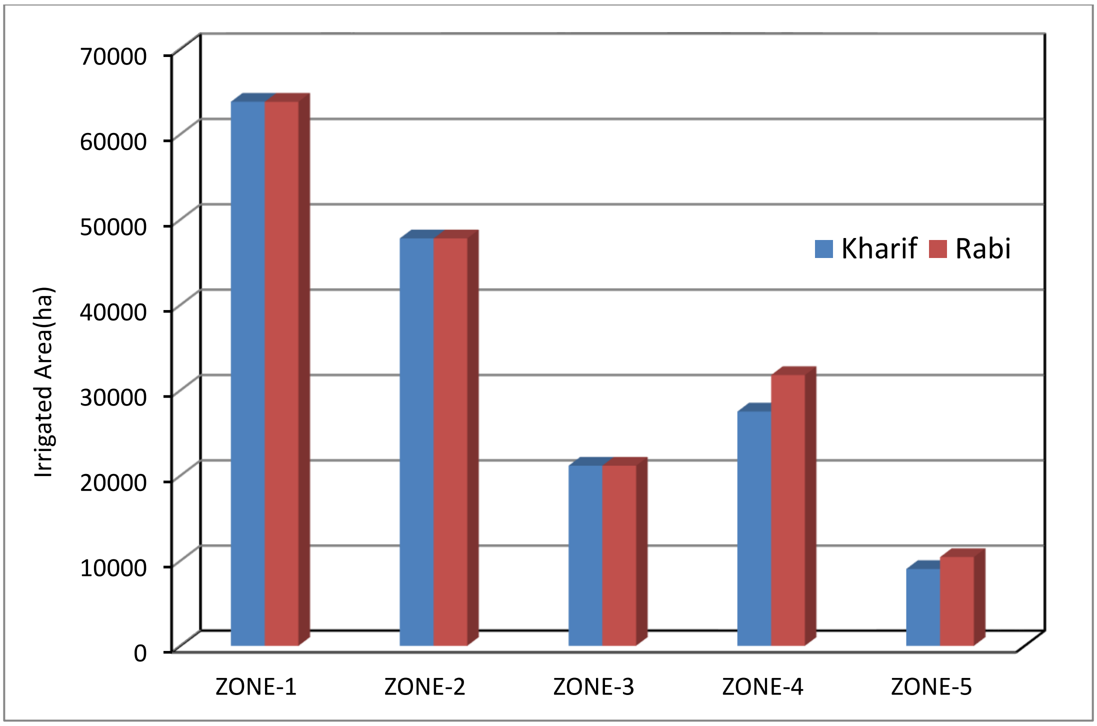


Figure 8.1: Irrigated area in all the zones for Strategy-1

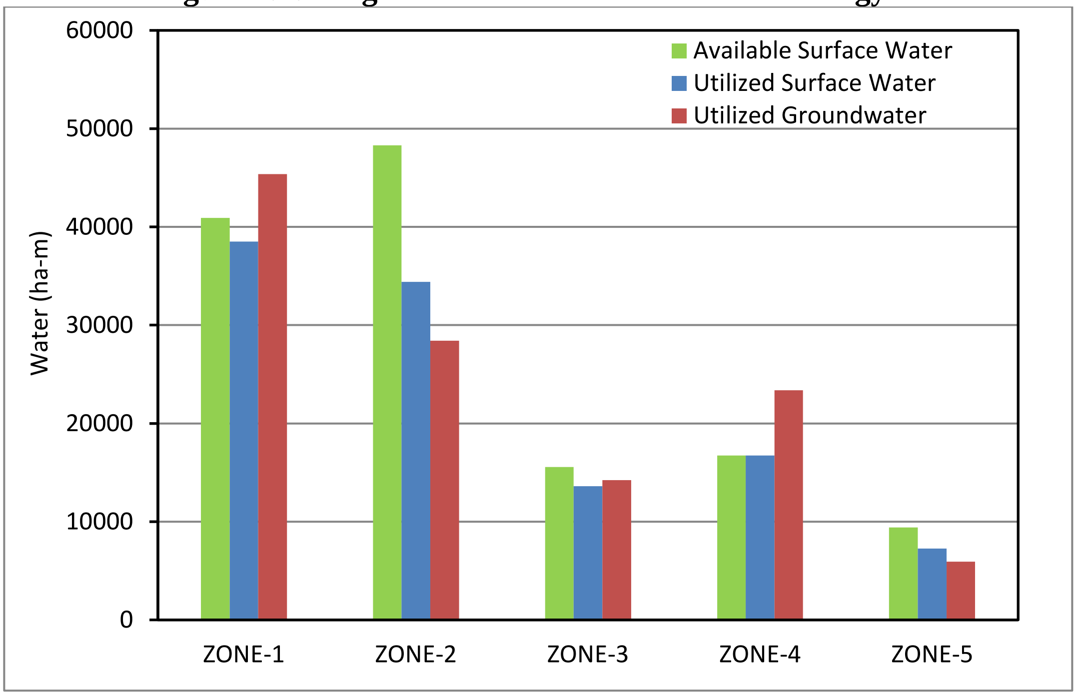


Figure 8.2: Surface water and groundwater utilization in all the zones for Strategy-1

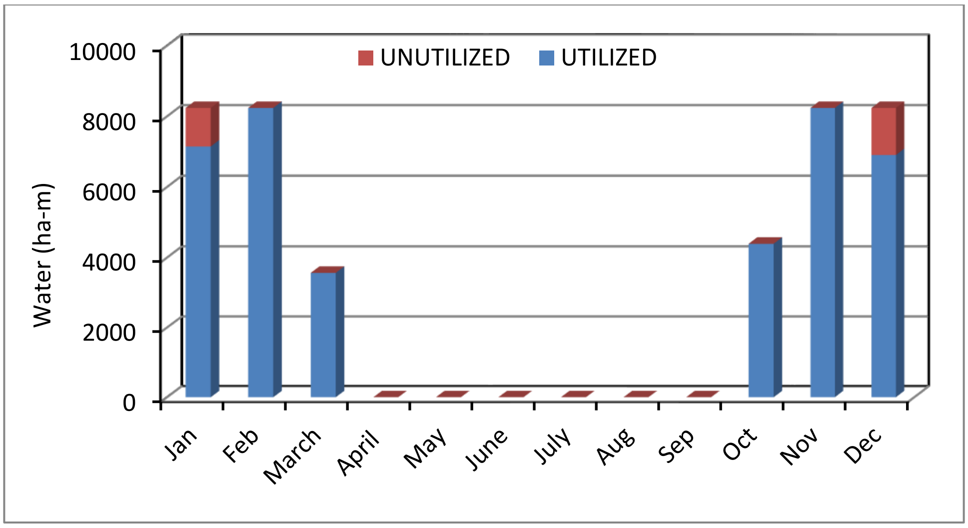


Figure 8.3: Utilization level of surface water in Zone-1 for Strategy-1

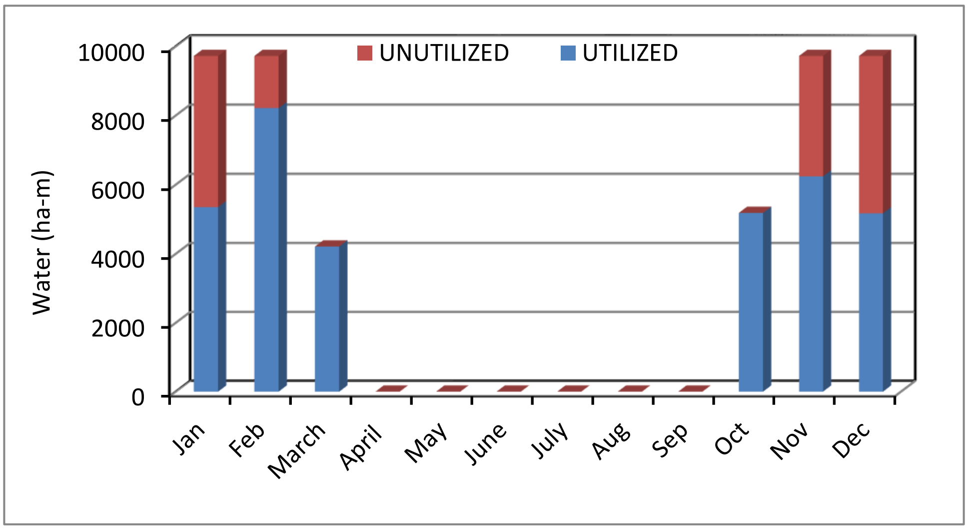


Figure 8.4: Utilization level of surface water in Zone-2 for Strategy-1

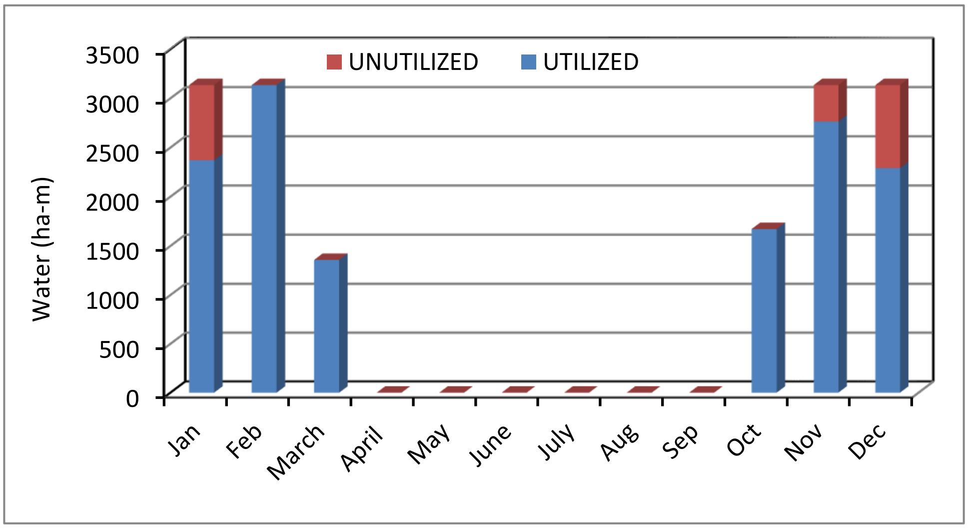


Figure 8.5: Utilization level of surface water in Zone-3 for Strategy-1

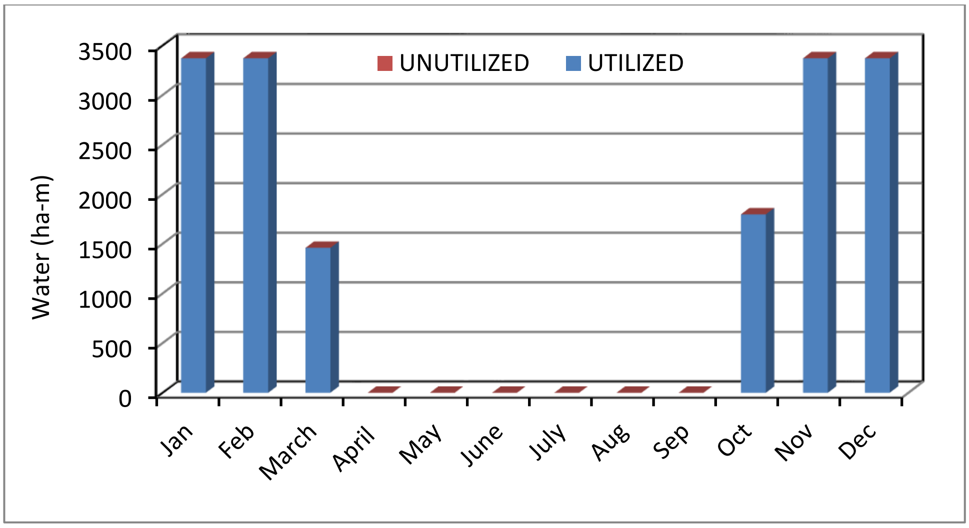


Figure 8.6: Utilization level of surface water in Zone-4 for Strategy-1

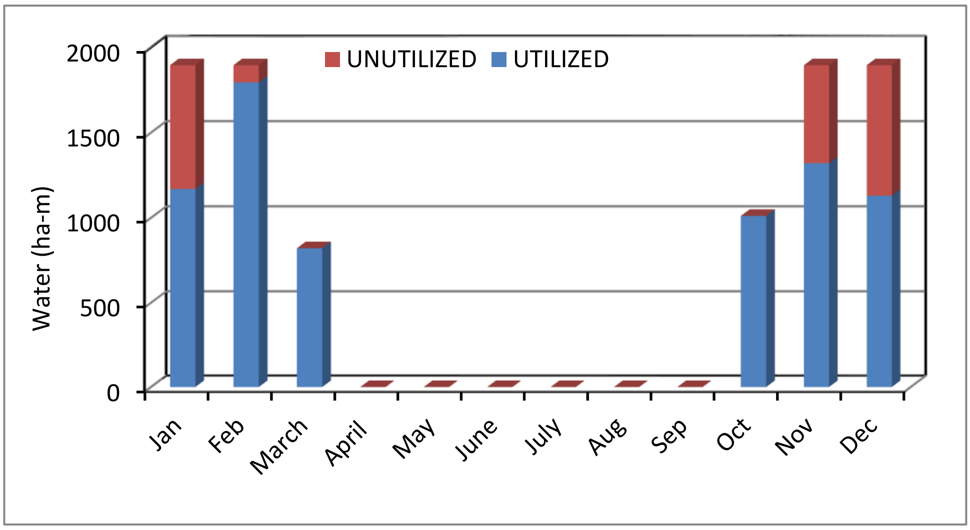


Figure 8.7: Utilization level of surface water in Zone-5 for Strategy-1

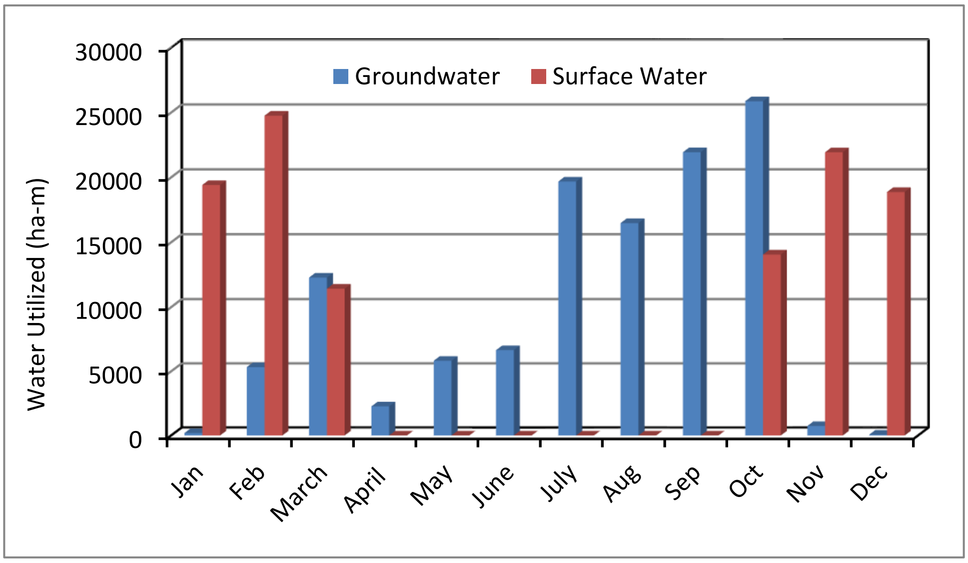


Figure 8.8: Monthly surface water and groundwater allocations for Strategy-1

It may be noted from these figures that the surface water is under utilized in all the zones except Zone-4. The groundwater utilization/pumping is higher in July, August, September and October months to satisfy irrigation demand of Kharif crops. Groundwater utilization is highest (25870.0 ha-m) in month of October. This could be due to transition from Kharif to Rabi season and the canal water supply is not sufficient to satisfy the irrigation water demand of the crops. Amongst all zones, the groundwater utilization is highest in Zone-1 (45363.7 ha-m). Presently, in Zone-3 the groundwater utilization is approximately 14230.8 ha-m. These estimates of resources allocations and benefits from Strategy-1 will be used to compare the profitability and performance of each proposed scenario.

8.4.2 Existing Cropping Pattern (Scenario-2)

The strategy discussed in previous section is based on designed cropping pattern and irrigation intensities. Reports indicate that farmers in Tawa Command Area have shifted from Paddy to Soyabean crop in Kharif season and the cropping intensity of RBC has increased (Khare, 2003). These change has been incorporated in Scenario 2 (Strategy-2). The definition of Scenario 2 (Strategy-2) is given below:

In Scenario 2 (Strategy-2), irrigation intensity has been assumed to be 67% during both Rabi and Kharif seasons in all the zones. Surface water supply for irrigation will be available for Rabi season only. In Kharif season, irrigation water requirement will be met by groundwater pumping, however groundwater will augment surface water during high demand periods of Rabi season. Cropping pattern for Rabi season will remain same. For Kharif season, area under Paddy has been reduced to 5% and around 32% of CCA has been brought under Soyabean as per the reported values (Khare, 2003). Surface water and groundwater availability have been assumed to be the same as in case of Strategy-1.

The model has been solved using cost coefficients listed in Chapter 6. The results obtained for resources allocation and benefits from this scenario (Strategy-2) are given in Table 8.3. Total benefits incurred in this scenario are around 8899.792 Million Rupees, 3.5% less than the benefits achieved in Strategy-1. The economic loss in this strategy is in the range of 323.763 Million Rupees. The benefits per unit of cultivated area in Strategy-2 are around 24692 Rs/ha with reduction of around 1307 Rs/ha as compared to Strategy-1. Benefits per unit of water utilized are around 43877 Rs/ha-m with an increase of 3389 Rs/ha-m. The improvement in returns per unit of water utilized is achieved because of the reduction in groundwater draft from 117333.2 ha-m in Strategy-1 to 90643.2 ha-m in present strategy.

The improvement in benefits per unit water utilized is also because of shift from Paddy to Soyabean in Kharif season. This change in cropping pattern reduced the irrigation water requirement of Kharif season, which is fulfilled by groundwater pumping, a costly source of irrigation water.

Table 8.3 Allocations of different resources and benefits for the existing cropping pattern (Strategy-2)

						TOTAL BENEFITS (Million Rs)= 8899.792
AREA UNDER DIFFERENT CROPS (ha)						
	ZONE-1	ZONE-2	ZONE-3	ZONE-4	ZONE-5	TOTAL
PADDY	4761.7	3566.8	1579.9	2372	778.9	13059.3
COTTON	4761.7	3566.8	1579.9	2372	778.9	13059.3
JAWAR	6666.3	4993.5	2211.9	3320.8	1090.4	18282.9
GROUNDNUT	4761.7	3566.8	1579.9	2372	778.9	13059.3
MAIZE	7618.7	5706.9	2527.9	3795.2	1246.2	20894.9
PULSES	4761.7	3566.8	1579.9	2372	778.9	13059.3
SOYABEAN	30474.6	22827.6	10111.7	15180.7	4984.7	83579.3
PERENNIAL	3809.3	2853.5	1264	1897.6	623.1	10447.5
WHEAT	52378.2	39235	17379.4	26091.8	8567.5	143651.9
GRAM	6666.3	4993.5	2211.9	3320.8	1090.4	18282.9
PEAS	1904.7	1426.7	632.0	948.8	311.5	5223.7
VEGETABLE	952.3	713.4	316.0	474.4	155.8	2611.9
LINSEED	1904.7	1426.7	632.0	948.8	311.5	5223.7
KHARIF CROPS	63806.4	47795.2	21171.1	31784.7	10436.9	174994.3
RABI CROPS	63806.2	47795.3	21171.3	31784.6	10436.7	174994.1
OPTIMAL ALLOCATION OF SURFACE WATER (ha-m)						
JANUARY	7148.2	5354.5	2371.8	3371.8	1169.2	19415.6
FEBRUARY	8239.3	8218.7	3135.6	3371.8	1794.7	24760.1
MARCH	3570.3	4213.8	1358.7	1461.1	821.4	11425.3
OCTOBER	4394.3	5186.2	1672.3	1798.3	1010.9	14062.0
NOVEMBER	8239.3	7311.9	3135.6	3371.8	1596.7	23655.4
DECEMBER	6906.3	5173.3	2291.6	3371.8	1129.7	18872.7
TOTAL	38497.6	35458.5	13965.6	16746.7	7522.5	**112191.0**
OPTIMAL ALLOCATION OF GROUNDWATER (ha-m)						
JANUARY	0.0	0.0	0.00	189.0	0.0	189.0
FEBRUARY	2732.5	0.0	504.9	2093.7	0.0	5331.1
MARCH	5074.0	2261.4	1509.5	2845.0	592.5	12282.5
APRIL	826.6	619.2	274.3	411.8	135.2	2267.2
MAY	2175.1	1629.3	721.7	1083.5	355.8	5965.5
JUNE	1934.2	1448.8	641.8	963.5	316.3	5304.7
JULY	2002.8	1500.2	664.5	997.7	327.6	5492.7
AUGUST	1829.4	1370.4	607.0	911.3	299.2	5017.4
SEPTEMBER	6655.9	4985.7	2208.4	3315.6	1088.7	18254.3

OCTOBER	10706.8	6125.6	3338.3	5724.2	1459.2	27354.2
NOVEMBER	1522.1	0.0	103.3	1490.7	0.0	3116.2
DECEMBER	0.00	0.0	0.00	68.5	0.0	68.5
TOTAL	35459.5	19940.6	10573.8	20094.5	4574.7	**90643.2**

The land and water resources allocated in this Strategy are shown in Figs. 8.9 and 8.10. In Strategy-2, surface water utilization is 112190.98 ha-m, which is 85.67% of total available surface water in the canal system. The level of surface water utilization is slightly better as compared to Strategy-1. Since the cropping pattern in Strategy-2 is changed in Kharif season, the utilization of groundwater has reduced by 18.9% of total available groundwater. The groundwater utilized in this strategy is 90643.2 ha-m, of which 69655.87 ha-m (76.84%) is pumped during the months of April to October.

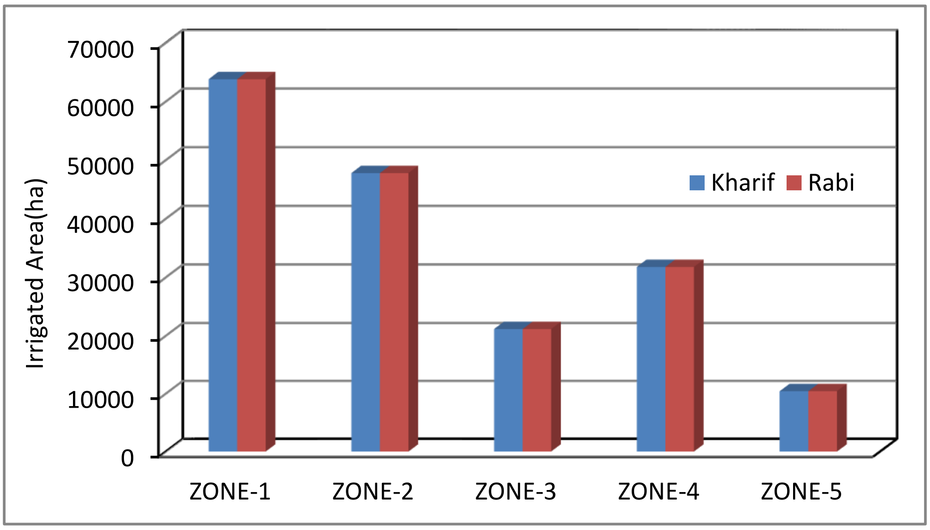


Figure 8.9: Irrigated area in all the zones for Strategy-2

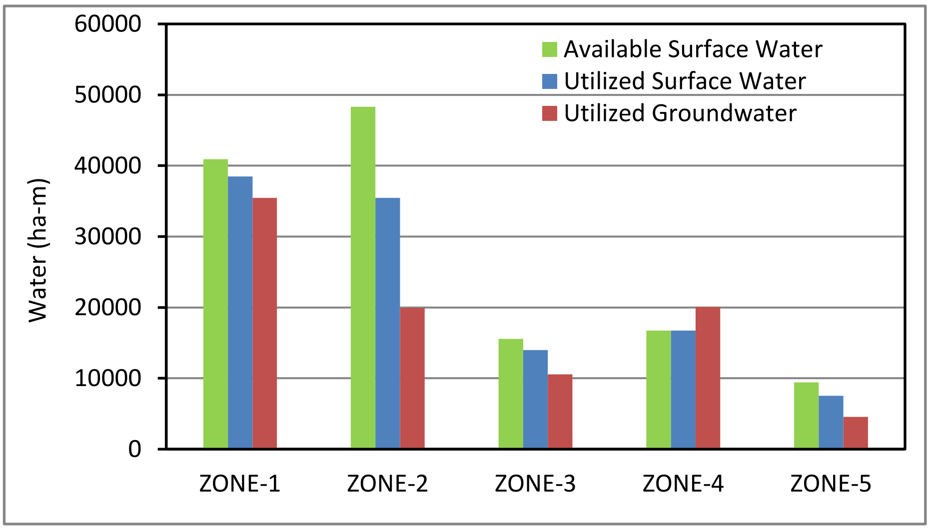


Figure 8.10: Surface water and groundwater utilization in all the zones for Strategy-2

It is clear from Table 8.3 that all resources (cultivable land, surface water and groundwater) are under utilized in this strategy. The monthly surface water and groundwater allocations in Strategy-2 is shown in Fig. 8.11 The figure indicates that groundwater allocation is highest in the month of October, similar to Strategy-1. The total groundwater extraction in Kharif season (April to September) is around 42301.69 ha-m as compared to 72849.7 ha-m in Strategy-1. This reduction is due to the decrease in irrigation water demand for changed cropping pattern (i.e. shift from Paddy to Soyabean).

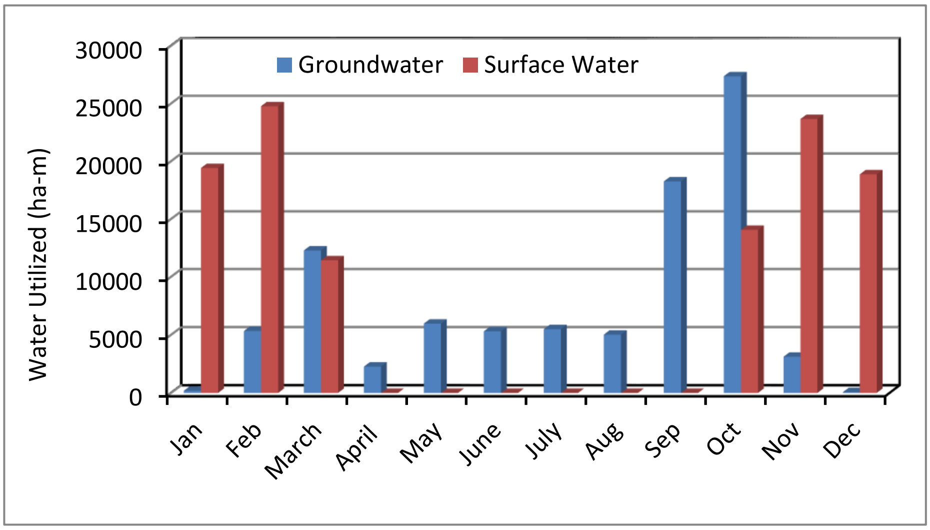


Figure 8.11: Monthly surface water and groundwater allocations in Strategy-2

The comparison between surface water and groundwater allocations in Strategy-1 and Strategy-2 (Fig. 8.12) indicates that surface water utilization in all the zones is almost same in both the strategies. Groundwater utilization is reduced in Strategy-2 in all the zones and highest reduction can be observed in Zone-1 due to shift from Paddy to Soyabean in Kharif season.

In Strategy-2, the highest groundwater allocation/pumping is done in Zone-1 i.e. 35459.5 ha-m which is 21.83% less as compared to groundwater pumping in same zone in Strategy-1. In Zone-3 the groundwater allocation/pumping is around 10573.8 ha-m whereas there is only marginal reduction in surface water utilization in Zone-3. If under utilization of groundwater in Zone-3 continues the problem of rising groundwater levels and waterlogging may further aggravate which are already witnessed in the region.

To see the effect of Strategy-2 on sustainability of command area, the results of resources allocation model are used as input to calibrated groundwater model as described in Chapter 5. The groundwater behaviour for the years 2004 to 2010 with same allocation strategy has been estimated with the assumption that same level of resources allocation will continue for the prediction period (2004-2010) for all the zones and are represented in Figs. 8.13 to 8.17. It can be seen from these figures that if same resources allocation strategy continues the groundwater table in Zone-1 will steadily deplete and on the other hand the groundwater levels in Zone-3 will rise continuously. The rise in groundwater level in Zone-3 may create problem of waterlogging in the area, where as the depleting groundwater in all zones will make this strategy even more uneconomic (less benefits than Strategy-1).

Though, there is an increase in benefits per unit water utilized in this strategy and the groundwater draft is also reducepd but the strategy is economically inferior in case of total benefits from command area and also environmentally unsustainable.

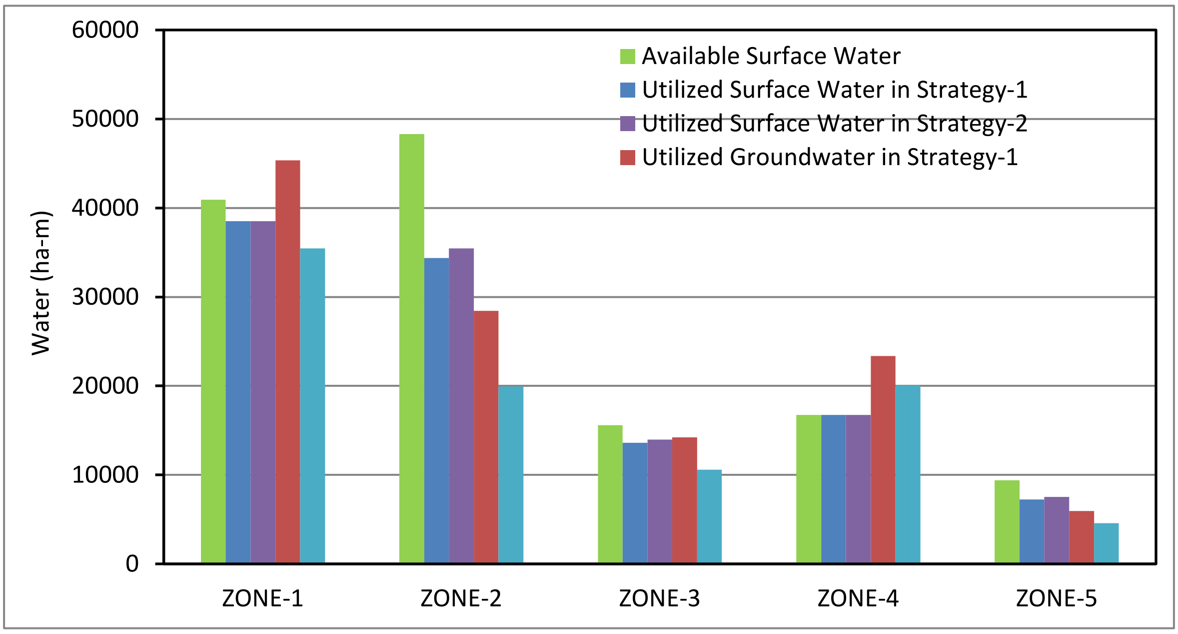


Figure 8.12: Surface water and groundwater allocations in Strategies 1 & 2

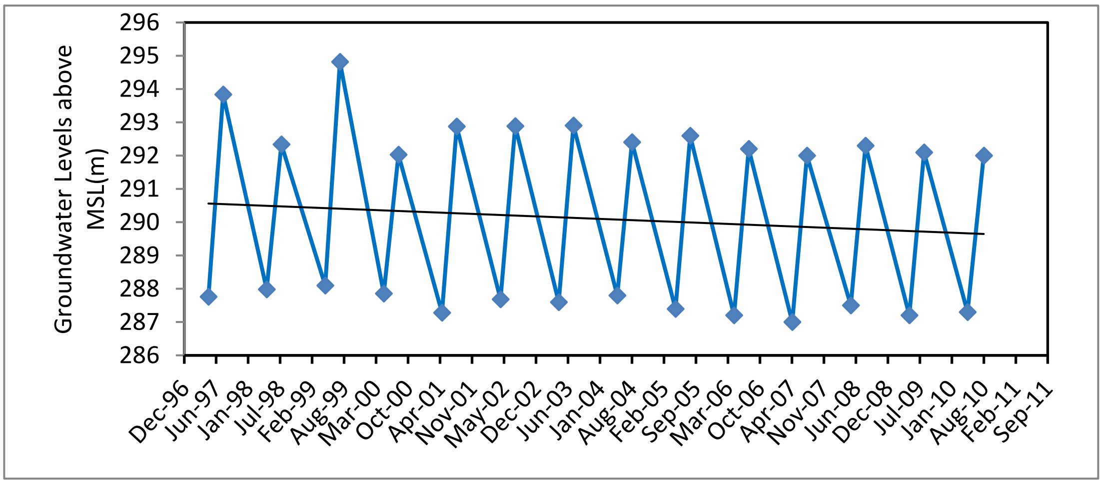


Figure 8.13: Groundwater behaviour in Zone-1 with resources allocation for Strategy-2

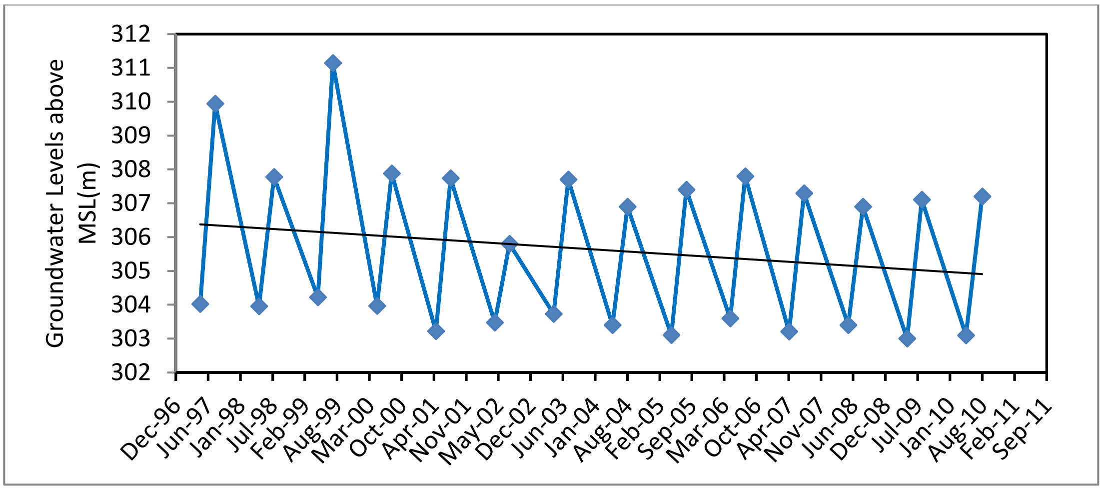


Figure 8.14: Groundwater behaviour in Zone-2 with resources allocation for Strategy-2

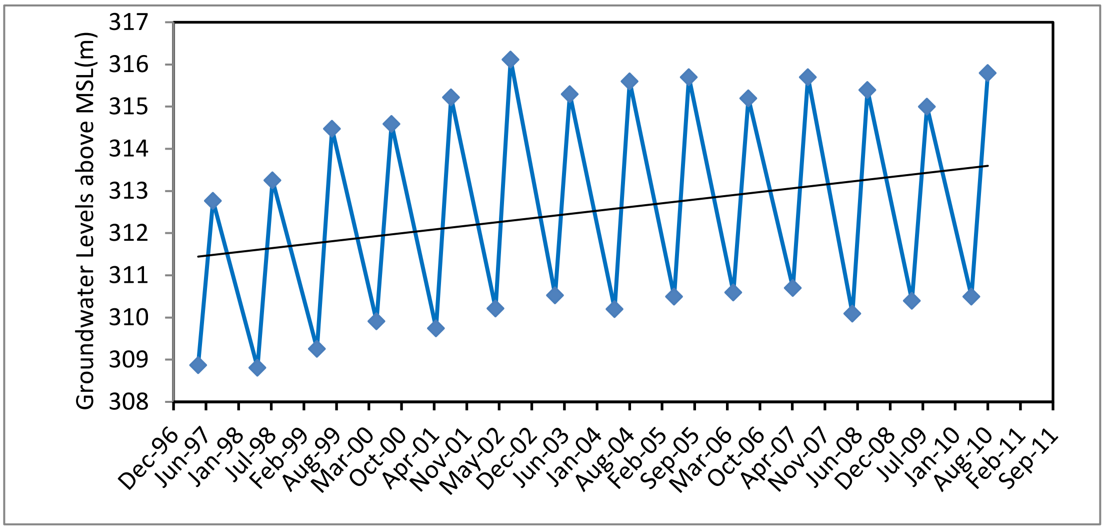


Figure 8.15: Groundwater behaviour in Zone-3 with resources allocation for Strategy-2

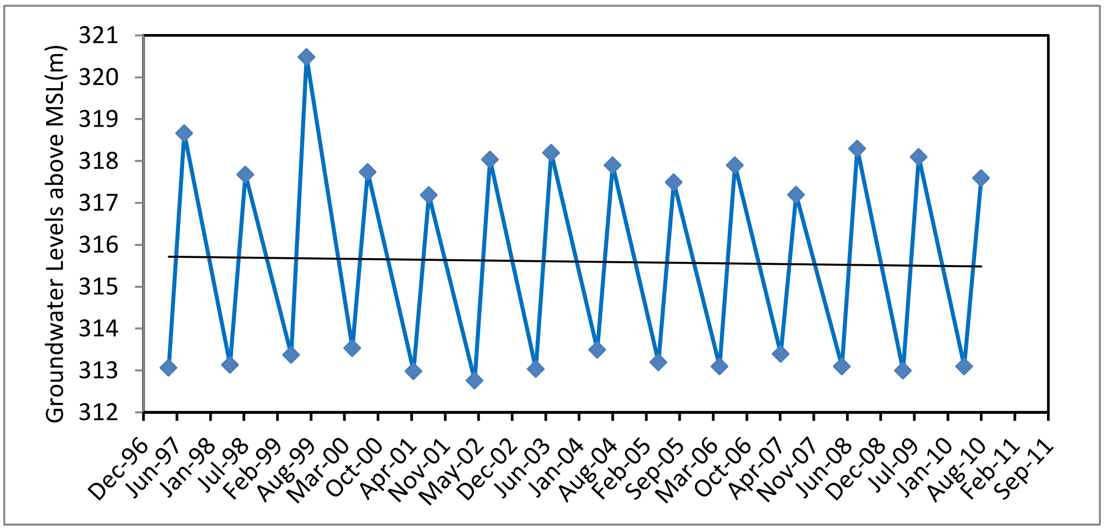


Figure 8.16: Groundwater behaviour in Zone-4 with resources allocation for Strategy-2

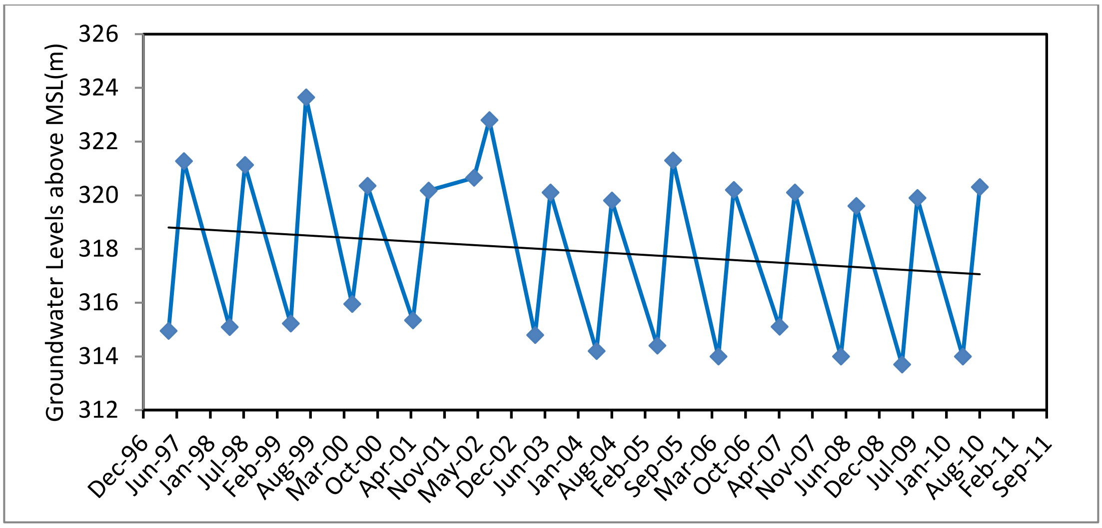


Figure 8.17: Groundwater behaviour in Zone-5 with resources allocation for Strategy-2

8.4.3 Existing Cropping Pattern with Changed Surface Water Supply in Zone-3 and Zone-1 (Scenario-3)

The strategy discussed in Section 8.4.2 describes the resources allocation for existing cropping pattern in the command area. The results from Strategy-2 indicate that if same practice continues, the problem of rising groundwater levels in Zone-3 and depletion in groundwater levels in Zone-1 will continue to exist. To counter these problems and to improve the total returns from the command, 10 different strategies have been evaluated in this scenario. The resource availability in this scenario is assumed to be same as mentioned in Chapter 6. Availability of surface water in Zone-3 (area having rising water levels problems) is decreased by 20%, 40%, 60% 80% and 100% in different strategies. The details of these strategies are given in Table 8.4.

In strategies S3, S5, S7, S9 and S11, it has been assumed that due to capacity limitations of conveyance system feeding to Zone-1 the excess water available due to reduced supply in Zone-3 can not be diverted to Zone-1. These strategies will be called "**water reduction strategies**" from now onwards. On the other hand, in strategies S4, S6, S8, S10 and S12 it has been assumed that the excess water available due to reduced supply in Zone-3 will be diverted to Zone-1. These strategies will be termed as "**water diversion strategies**" in further description. In this scenario, the water supply to Zone 3 and 1 have been changed to counter the problems of rising groundwater levels in Zone-3 and water table depletion in Zone-1. The detailed results of each of these 10 strategies are given in Appendix-I. Total benefits, benefits per unit cultivated area, benefits per unit water utilized, surface water and groundwater utilization status in each strategy (S3 to S12) are consolidated in Table 8.5 and the same are presented in Figs. 8.18 to 8.20. Surface water and groundwater allocation in each zone in respective strategy is presented in Table 8.6.

Table 8.4 Different strategies in Scenario-3

Strategy Number		Description of Strategy
3	S3	20% reduction in surface water supply in Zone-3, surface water supply to all other zones is kept same as described in Table 6.2. Cropping pattern and irrigation intensity same as per Strategy-2
4	S4	20% reduction in surface water supply in Zone-3, the reduced water from Zone-3 is diverted to Zone-1 in addition to existing supply, surface water supply to all other zones is kept same as described in Table 6.2. Cropping pattern and irrigation intensity same as per Strategy-2
5	S5	40% reduction in surface water supply in Zone-3, surface water supply to all other zones is kept same as described in Table 6.2. Cropping pattern and irrigation intensity same as per Strategy-2
6	S6	40% reduction in surface water supply in Zone-3, the reduced water from Zone-3 is diverted to Zone-1 in addition to existing supply, surface water supply to all other zones is kept same as described in Table 6.2. Cropping pattern and irrigation intensity same as per Strategy-2
7	S7	60% reduction in surface water supply in Zone-3, surface water supply to all other zones is kept same as described in Table 6.2. Cropping pattern and irrigation intensity same as per Strategy-2
8	S8	60% reduction in surface water supply in Zone-3, the reduced water from Zone-3 is diverted to Zone-1 in addition to existing supply, surface water supply to all other zones is kept same as described in Table 6.2. Cropping pattern and irrigation intensity same as per Strategy-2
9	S9	80% reduction in surface water supply in Zone-3, surface water supply to all other zones is kept same as described in Table 6.2. Cropping pattern and irrigation intensity same as per Strategy-2
10	S10	80% reduction in surface water supply in Zone-3, the reduced water from Zone-3 is diverted to Zone-1 in addition to existing supply, surface water supply to all other zones is kept same as described in Table 6.2. Cropping pattern and irrigation intensity same as per Strategy-2
11	S11	100% reduction in surface water supply in Zone-3, surface water supply to all other zones is kept same as described in Table 6.2. Cropping pattern and irrigation intensity same as per Strategy-2
12	S12	100% reduction in surface water supply in Zone-3, the reduced water from Zone-3 is diverted to Zone-1 in addition to existing supply, surface water supply to all other zones is kept same as described in Table 6.2. Cropping pattern and irrigation intensity same as per Strategy-2

Highest total benefits from water reduction strategies are achieved from Strategy-3, but the total benefits are marginally less than the total benefits for existing cropping pattern scenario (Strategy-2). The benefits per unit of water utilized varies from 43863 Rs./ha-m to 43877 Rs./ha-m with the highest value in Strategies 3, 5 and 7 (i.e. 20%, 40% and 60% reduction in surface water supply in Zone-3). The variation in benefit per unit of cultivated area is very small i.e. from 24684 Rs/ha to 24692 Rs/ha. In all the surface water reduction strategies, total benefits are less than total benefits achieved in Strategy-2. On the contrary, total benefits achieved in water diversion strategies are marginally higher than that of Strategy-2 with the highest in Strategy-10 (i.e. 80% of surface water from Zone-3 is diverted to Zone-1). The highest benefits per unit of water utilized (43893 Rs/ha-m) and benefits per unit of cultivated area (24701 Rs/ha) are also achieved in Strategy-10. However, variation in values of benefits per unit cultivated area and per unit of water utilized is very small.

Table 8.5 Consolidated results from strategies (S3 to S12) in Scenario-3

S. No.	Benefits			Irrigated Area (ha)	Water Utilized (ha-m)		Water Utilization Level (%)	
	Total (Rs)	Rs/ha	Rs/ha-m		SW	GW	SW	GW
Reduction in Surface Water Supply to Zone-3								
S3	8899790000	24692	43877	360435.9	110330.5	92503.6	84.25	65.69
S5	8899785000	24692	43877	360435.9	107569.4	95264.7	82.14	67.66
S7	8899780000	24692	43877	360435.9	104454.7	98379.4	79.77	69.87
S9	8899056000	24690	43874	360435.9	101285.5	101548.7	77.34	72.12
S11	8896842000	24684	43863	360435.9	98225.4	104608.8	75.01	74.29
Surface Water Diverted from Zone-3 to Zone-1								
S4	8900917000	24695	43883	360435.9	112191.0	90643.2	85.67	64.37
S6	8902041000	24698	43888	360435.9	111290.2	91543.9	84.98	65.01
S8	8902946000	24700	43893	360435.9	109676.8	93157.3	83.75	66.16
S10	8902969000	24701	43893	360435.9	107795.4	95038.7	82.32	67.49
S12	8901258000	24696	43884	360435.9	105511.0	97323.1	80.57	69.12

SW – Surface water, GW – Groundwater

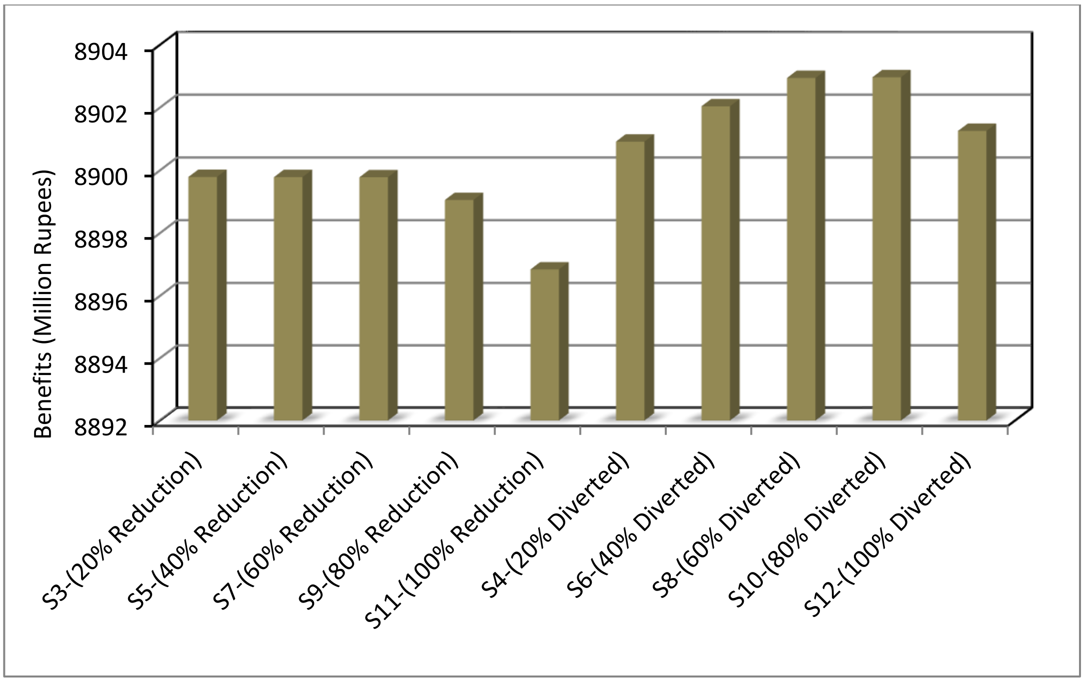


Figure 8.18: Total Benefits from different strategies in Scenario-3

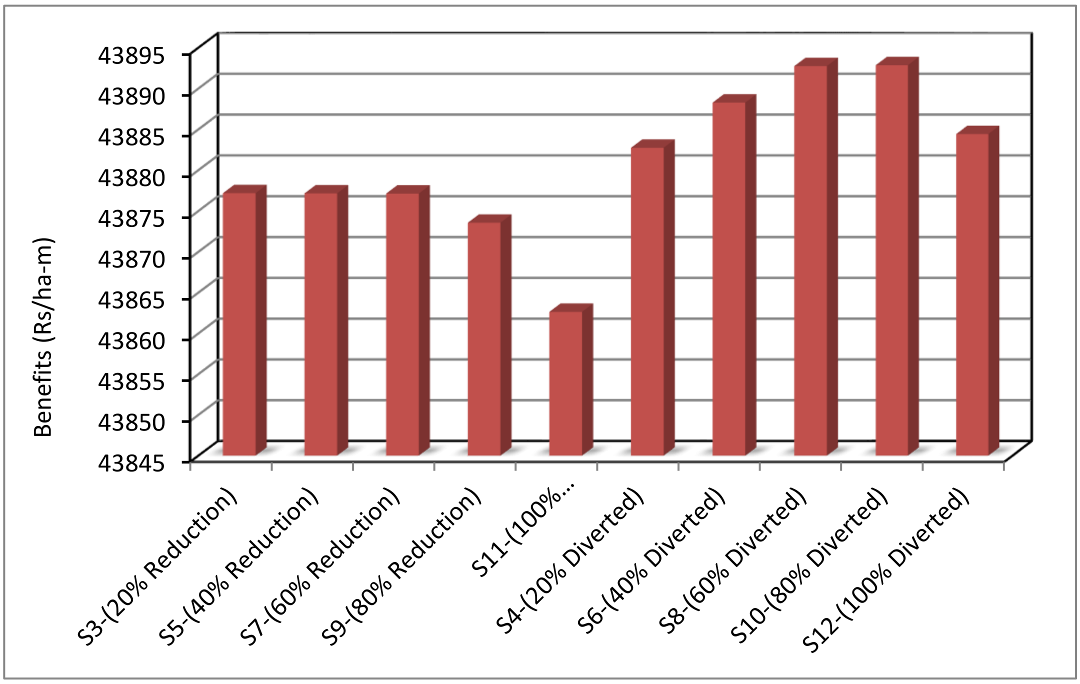


Figure 8.19: Benefits per unit water utilized in different strategies of Scenario-3

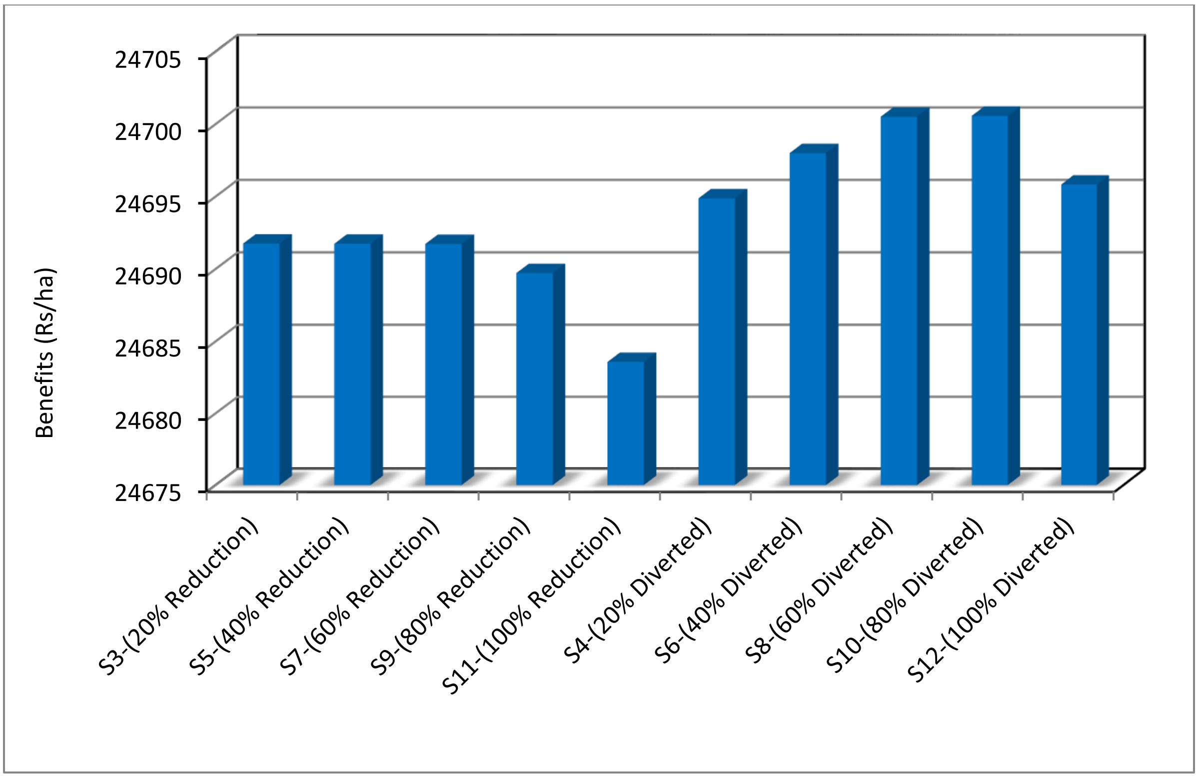


Figure 8.20: Benefits per unit cultivated area in different strategies of Scenario-3

Table 8.6 Surface water and groundwater allocations in Strategies S3 to S12

Surface Water Utilized (ha-m)						
S. No.	Zone-1	Zone-2	Zone-3	Zone-4	Zone-5	Total
S3	38497.7	35458.5	12105.2	16746.7	7522.5	110330.5
S5	38497.7	35458.5	9344.1	16746.7	7522.5	107569.4
S7	38497.7	35458.5	6229.4	16746.7	7522.5	104454.7
S9	38497.7	35458.5	3060.1	16746.7	7522.5	101285.5
S11	38497.7	35458.5	0.0	16746.7	7522.5	98225.4
S4	40358.1	35458.5	12105.2	16746.7	7522.5	112191.0
S6	42218.4	35458.5	9344.1	16746.7	7522.5	111290.2
S8	43719.7	35458.5	6229.4	16746.7	7522.5	109676.8
S10	44953.0	35458.5	3114.7	16746.7	7522.5	107795.4
S12	45783.3	35458.5	0.0	16746.7	7522.5	105511.0
Groundwater Utilized (ha-m)						
S. No.	Zone-1	Zone-2	Zone-3	Zone-4	Zone-5	Total
S3	35459.5	19940.6	12434.2	20094.6	4574.7	92503.6
S5	35459.5	19940.6	15195.4	20094.6	4574.7	95264.7
S7	35459.5	19940.6	18310.0	20094.6	4574.7	98379.4
S9	35459.5	19940.6	21479.3	20094.6	4574.7	101548.7
S11	35459.5	19940.6	24539.4	20094.6	4574.7	104608.8
S4	33599.1	19940.6	12434.2	20094.6	4574.7	90643.2
S6	31738.7	19940.6	15195.4	20094.6	4574.7	91543.9
S8	30237.4	19940.6	18310.0	20094.6	4574.7	93157.3
S10	29004.1	19940.6	21424.7	20094.6	4574.7	95038.7
S12	28173.9	19940.6	24539.4	20094.6	4574.7	97323.1

It is clear from Table 8.5 and Figs 8.18 to 8.20 that the benefits will increase in case of utilizing the reduced surface water supply in Zone-3 in water deficit zone (Zone-1). The highest surface water utilization is achieved in Strategy-4 (112191.0 ha-m), which is around 85% of total surface water available. In water diversion strategies, the utilization level of surface water is gradually decreasing with increased surface water diversion to Zone-1.

In Strategies 10 and 12, amount of excess water diverted to Zone-1 is around 12105.2 ha-m and 15165.3 ha-m respectively. On the other hand, groundwater pumping is reduced only by 6455.4 ha-m and 7285.6 ha-m respectively with reference to groundwater pumping in Strategy-2 (existing cropping pattern scenario). This under utilization of surface water indicates the temporal disparity between water demand and water supply. The groundwater pumping in Zone-3 is showing inverse linear trend with percentage reduction of surface water supply to Zone-3.

Water utilization level in case of surface water varies from 75% to 84% and groundwater utilization varies from 65% to 74% in surface water reduction strategies. In surface water diversion strategies there is improvement in surface water utilization level and it varies from 80% to 85% in different strategies and the groundwater utilization levels are lowered to 64% to 69%. Resources are underutilized, as can be seen from utilization level values and the total benefits are less in comparison to Strategy-1 (design cropping pattern). The diversion of surface water may solve the problem of rising groundwater level in Zone-3 and water table depletion in Zone-1, but the Strategy will be economically inferior. Hence, there is scope for improvement in resources utilization levels in the command area.

8.4.4 Increased Irrigation Intensity in Rabi Season (Scenario-4)

Modernization work of Tawa canal system has already been initiated by project authorities, with an objective to increase the irrigation intensity during Rabi season. Major part of this work has been completed. With this information and the experience gained in earlier strategies in background, it has been assumed that irrigation intensity in Rabi season will increase up to 80% while it will remain 67% in Kharif season. The constraints for area under each crop have been modified accordingly. The area availability constraint for each zone for Rabi season has also been modified. It has been assumed that same amount of irrigation water is available for irrigating Rabi crops. All cost coefficients used in previous strategies have been used to solve the scenario of increased irrigation intensity in Rabi season (Strategy-13).

The resources allocation results obtained from this strategy are given in Table 8.7. Allocations of cultivable area, surface water and groundwater are shown in Figs. 8.21 and 8.22. Total benefits achieved in this strategy are around 9678.892 Million Rupees, around 5% (455.337 Million Rupees) higher than the Strategy-1. The total benefits are around 779 Million Rupees (8.75%) higher compared to the existing cropping patterns and allocation scenario, i.e. Strategy-2. Along with increase in benefits, the resources utilization levels are also elevated in present strategy. Surface water utilization level is around 90% (118122.1 ha-m) of the total available surface water and around 102059.9 ha-m (72.5%) of groundwater is utilized in this strategy. Monthly allocations of surface water and groundwater are given in Fig. 8.23.

In the present strategy (S13), area under cultivation in Rabi season is increased up to 80% of CCA. Due to addition in cultivated area, water resources utilization level is improved and total benefits from the command have surpassed the benefits of design cropping pattern scenario (Strategy-1).

Table 8.7 Allocations of different resources and benefits for the increased irrigation intensity scenario (Strategy-13)

						TOTAL BENEFITS (Million Rs)= 9678.892
AREA UNDER DIFFERENT CROPS (ha)						
	ZONE-1	ZONE-2	ZONE-3	ZONE-4	ZONE-5	TOTAL
PADDY	4761.7	3566.8	1579.9	2372.0	778.9	13059.3
COTTON	4761.7	3566.8	1579.9	2372.0	778.9	13059.3
JAWAR	6666.3	4993.5	2211.9	3320.8	1090.4	18282.9
GROUNDNUT	4761.7	3566.8	1579.9	2372.0	778.9	13059.3
MAIZE	7618.7	5706.9	2527.9	3795.2	1246.2	20894.9
PULSES	4761.7	3566.8	1579.9	2372.0	778.9	13059.3
SOYABEAN	30474.6	22827.6	10111.7	15180.7	4984.7	83579.3
PERENNIAL	3809.3	2853.5	1264.0	1897.6	623.1	10447.5
WHEAT	60949.2	45655.3	20223.3	30361.3	9969.5	167158.5
GRAM	6666.3	4993.5	2211.9	3320.8	1090.4	18282.9
PEAS	1904.7	1426.7	632.0	948.8	311.5	5223.7
VEGETABLE	952.3	713.4	316.0	474.4	155.8	2611.9
LINSEED	1904.7	1426.7	632.0	948.8	311.5	5223.7
KHARIF CROPS	63806.4	47795.2	21171.1	31784.7	10436.9	174994.3
RABI CROPS	72377.2	54215.6	24015.2	36054.1	11838.7	198500.7
OPTIMAL ALLOCATION OF SURFACE WATER (ha-m)						
JANUARY	8005.3	5996.5	2656.2	3371.8	1309.4	21339.3
FEBRUARY	8239.3	9419.3	3135.6	3371.8	1895.6	26061.5
MARCH	3570.3	4213.8	1358.7	1461.1	821.4	11425.3
OCTOBER	4394.3	5186.2	1672.3	1798.3	1010.9	14062.0
NOVEMBER	8239.3	7954.0	3135.6	3371.8	1736.9	24437.6
DECEMBER	7763.4	5815.3	2576.0	3371.8	1269.9	20796.4
TOTAL	40211.9	38585.2	14534.4	16746.7	8044.0	**118122.1**
OPTIMAL ALLOCATION OF GROUNDWATER (ha-m)						
JANUARY	0.0	0.0	0.0	616.0	0.0	616.0
FEBRUARY	4335.3	0.0	1036.7	2892.1	161.3	8425.4
MARCH	6368.2	3230.9	1939.0	3489.7	804.2	15832.0
APRIL	826.6	619.2	274.3	411.8	135.2	2267.1
MAY	2175.1	1629.3	721.7	1083.5	355.8	5965.5
JUNE	1934.2	1448.8	641.8	963.5	316.4	5304.7
JULY	2002.8	1500.2	664.5	997.7	327.6	5492.7
AUGUST	1829.4	1370.4	607.0	911.3	299.3	5017.4
SEPTEMBER	6655.9	4985.7	2208.4	3315.6	1088.7	18254.3
OCTOBER	11563.9	6767.6	3622.7	6151.2	1599.4	29704.8
NOVEMBER	2379.2	0.0	387.7	1917.7	0.0	4684.6
DECEMBER	0.0	0.0	0.0	495.4	0.0	495.4
TOTAL	40070.7	21552.1	12103.8	23245.4	5087.9	**102059.9**

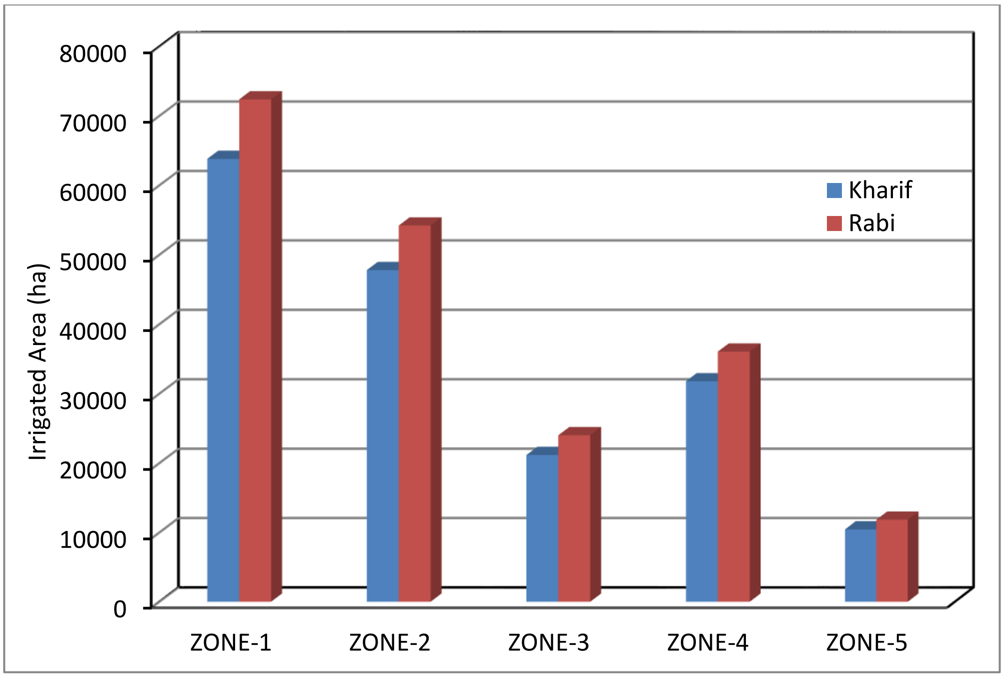


Figure 8.21: Irrigated area in all the zones for Strategy-13

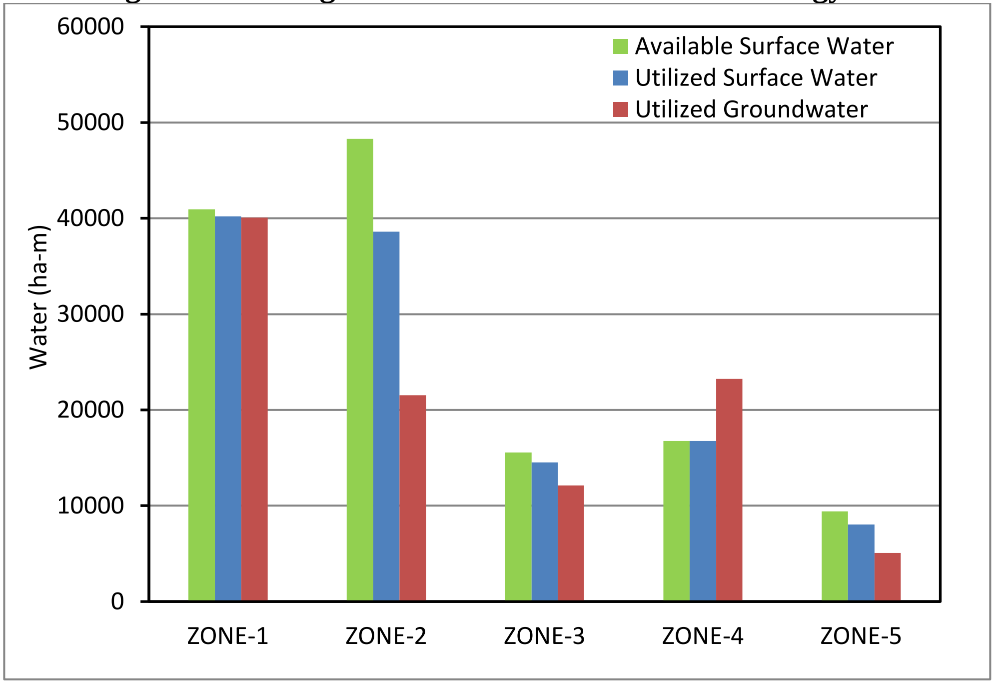


Figure 8.22 Surface water and groundwater utilization in all the zones for Strategy-13

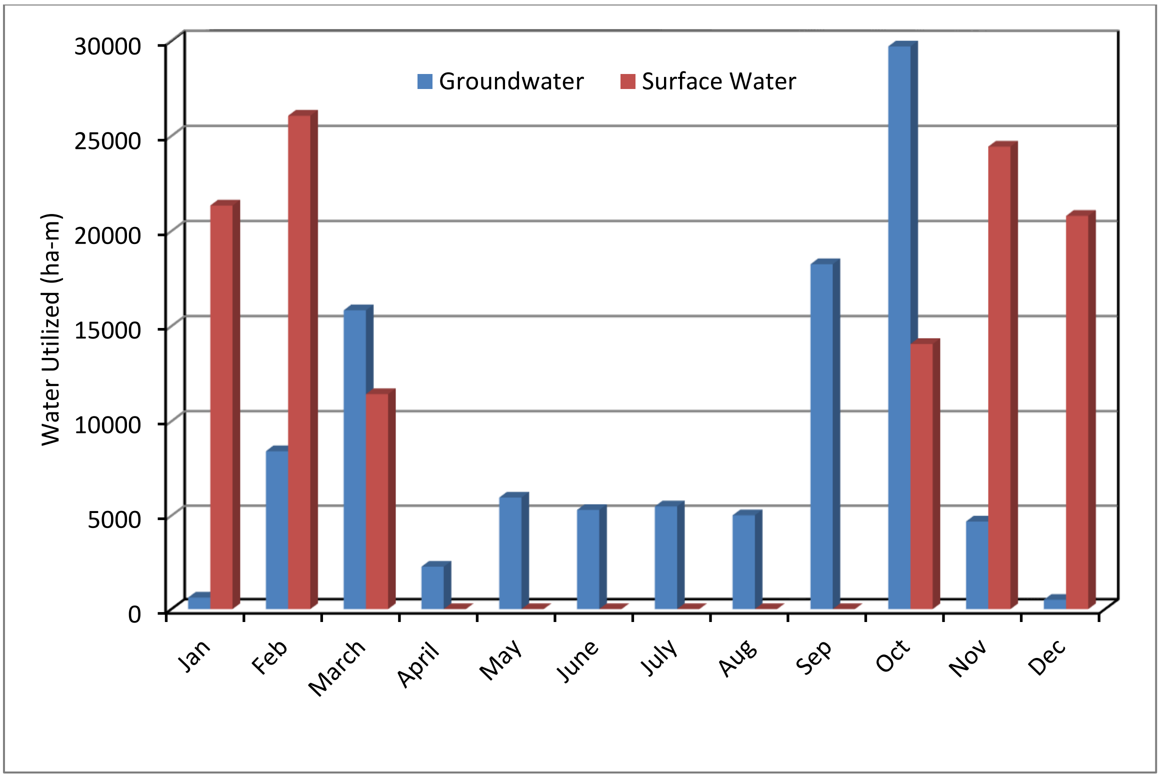


Figure 8.23: Monthly surface water and groundwater allocations in Strategy-13

In the present strategy, benefits per unit cultivated area are around 25209 Rs/ha. These benefits are around 790 Rs/ha (3.04%) less than the values achieved in Strategy-1, but are 2% (159 Rs/ha) higher than the benefits achieved in Strategy-2 (existing condition). The reduction in benefits per unit cultivated area may be due to change in cropping pattern, i.e. shift from Paddy crop to Soybean. The benefits per unit of water utilized in present strategy are 43959 Rs/ha-m, which are 8.6% (3470 Rs/ha-m) higher than the Strategy-1. The area under cultivation is increased in present strategy, even then the increase in benefits per unit of water utilized over Strategy-1, indicates better water management in present strategy.

Groundwater utilization/pumping is more in the months of March, September, October. Groundwater pumping/utilization in Kharif season (April to October) is around 72006 ha-m (72% of total utilization) out of which around 28704 ha-m in the month of October alone. High groundwater pumping in October indicates high irrigation water demand in the month and insufficient surface water supply.

The water resources utilization and surface water availability in Strategy-2 and Strategy-13 are depicted in Fig. 8.24. The figure indicates approximately 8% increase in groundwater utilization is achieved as compared to Strategy-2. The groundwater pumping is increased in all zones and highest increase of 4611 ha-m is observed in Zone-1 over the amount of pumping from same zone in Strategy-2. In Zone-3, marginal increase of groundwater pumping of 1530 ha-m is observed. The figure also indicates the same trend of increased utilization of surface water and rise in groundwater pumping in all the zones.

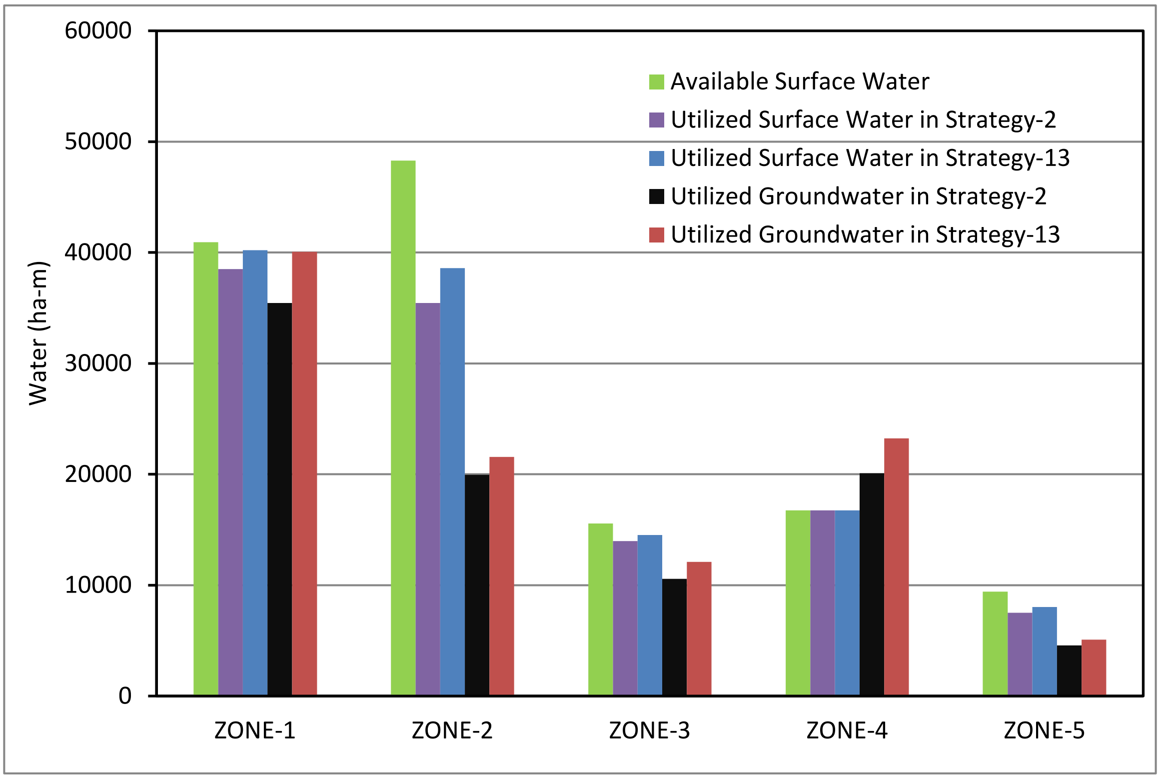


Figure 8.24: Surface water and groundwater allocations in Strategies 2 & 13

The economically inferior existing practice (Strategy-2) can be improved with increase in cropping intensity in Rabi season as discussed in present Strategy (S13). Though this Strategy is economically superior, but there is no provision for improvement in degrading groundwater scenarios in Zone-1 and Zone-3. The groundwater utilization/pumping will increase by 13% over existing rate (as per Strategy-2), where as surface water availability will remain same, this will further aggravate the problem of depletion in groundwater levels in Zone-1. So there is need for changing the surface water supply in problematic zones (i.e. Zone-1 and Zone-3).

8.4.5 Increased Irrigation Intensity and Changed Surface Water Supply in Zone-3 and Zone-1 (Scenario-5)

The increase in irrigation intensity in Rabi season, as discussed in Strategy-13 will have positive impact on benefits and resources utilization, but will put additional pressure on the depleting groundwater table in Zone-1. To counter the problem of rising groundwater levels in Zone-3 and depletion in water table in Zone-1, five different strategies of water diversion from Zone-3 to Zone-1 have been evaluated through developed conjunctive use model. The description of different strategies is given in Table 8.8. All other resources availability is assumed as per Strategy-13.

Table 8.8 Different strategies in Scenario-5

Strategy Number		Description of Strategy
14	S14	20% reduction in surface water supply in Zone-3, the reduced water from Zone-3 is diverted to Zone-1 in addition to existing supply, surface water supply to all other zones is kept same as described in Table 8.2. Cropping pattern and irrigation intensity same as per Strategy-13
15	S15	40% reduction in surface water supply in Zone-3, the reduced water from Zone-3 is diverted to Zone-1 in addition to existing supply, surface water supply to all other zones is kept same as described in Table 8.2. Cropping pattern and irrigation intensity same as per Strategy-13
16	S16	60% reduction in surface water supply in Zone-3, the reduced water from Zone-3 is diverted to Zone-1 in addition to existing supply, surface water supply to all other zones is kept same as described in Table 8.2. Cropping pattern and irrigation intensity same as per Strategy-13
17	S17	80% reduction in surface water supply in Zone-3, the reduced water from Zone-3 is diverted to Zone-1 in addition to existing supply, surface water supply to all other zones is kept same as described in Table 8.2. Cropping pattern and irrigation intensity same as per Strategy-13
18	S18	100% reduction in surface water supply in Zone-3, the reduced water from Zone-3 is diverted to Zone-1 in addition to existing supply, surface water supply to all other zones is kept same as described in Table 8.2. Cropping pattern and irrigation intensity same as per Strategy-13

In this scenario, it has been assumed that the conveyance system feeding Zone-1 has capability to carry the additional water diverted to Zone-1, and in Zone-3 the infrastructure is in place and has capability to pump extra groundwater to meet additional demand raised due to reduction of surface water supply in Zone-3. Each of these strategies has been evaluated and the detailed results are given in Appendix-I. Total benefits, benefits per unit cultivated area, benefits per unit water utilized, surface water and groundwater utilization status in each strategy (S14 to S18) are consolidated in Table 8.9 and the same are present in Figs. 8.25 to 8.27. Surface water and groundwater allocation in each zone in respective strategy is presented in Table 8.10.

Highest total benefits in Scenario-5 are achieved from Strategy-17 (i.e. 80% diversion of surface water supply form Zone-3 to Zone-1). The total benefits in this strategy are 521.184 Million Rupees (6%) higher than the total benefits of Strategy-1, the increase in total benefits over existing condition of command (Strategy-2) is in the range of 844.947 Million Rupees (9%). Table 8.9 indicates that the benefits per unit area cultivated are also highest (25381 Rs/ha) in Strategy-17. The benefits per unit water utilized are highest in Strategy-18 (44218 Rs/ha-m), followed by Strategy-17 (44184 Rs/ha-m).

Table 8.9 Consolidated results from strategies (S14 to S18) in Scenario-5

S. No.	Benefits			Irrigated Area (ha)	Water Utilizes (ha-m)		Water Utilization Level (%)	
	Total (Rs)	Rs/ha	Rs/ha-m		SW	GW	SW	GW
S14	9742168000	25374	44172	383943	118327	102222	90.36	72.60
S15	9743291000	25377	44177	383943	117073	103476	89.40	73.49
S16	9744414000	25380	44182	383943	115819	104730	88.44	74.38
S17	9744739000	25381	44184	383943	114435	106114	87.39	75.36
S18	9743272000	25377	44218	383943	112554	107794	85.95	76.55

SW – Surface water, GW – Groundwater

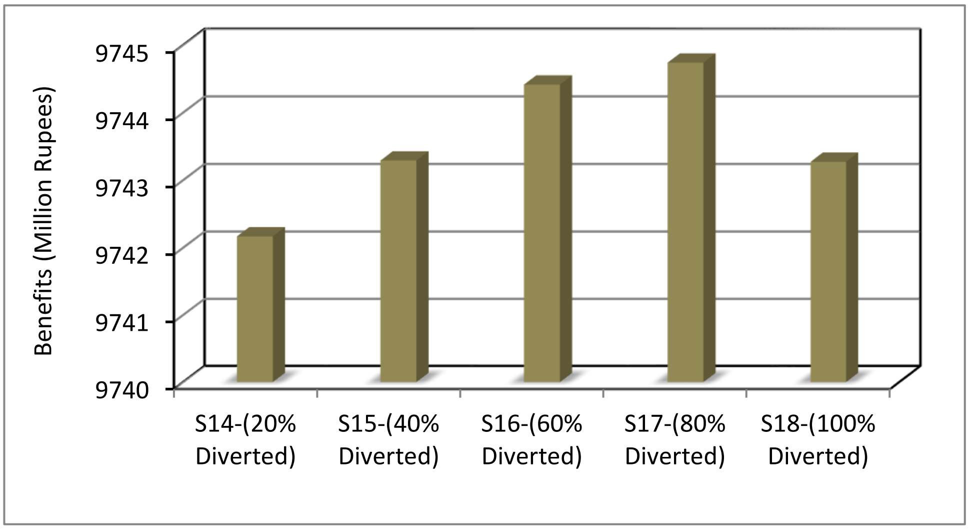


Figure 8.25: Total benefits from different strategies in Scenario-5

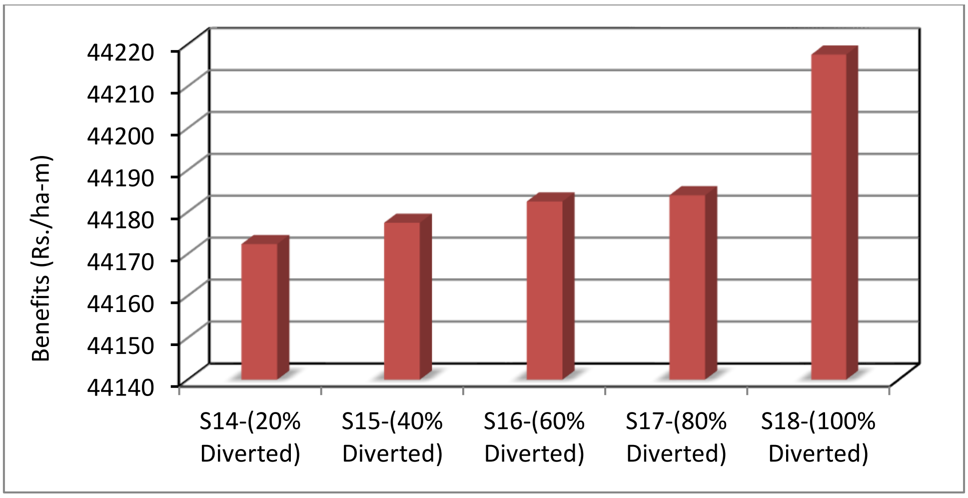


Figure 8.26: Benefits per unit water utilized in different strategies of Scenario-5

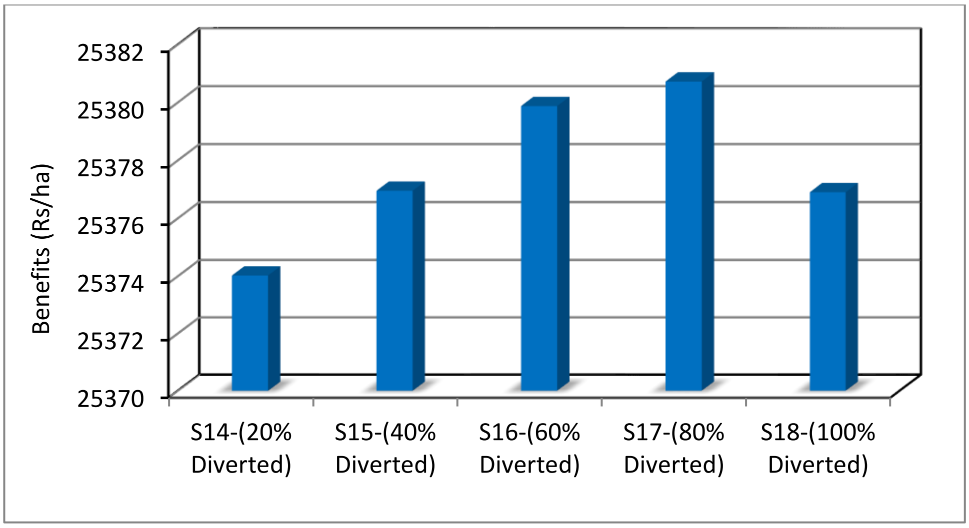


Figure 8.27: Benefits per unit of cultivated area in different strategies of Scenario-5

Table 8.10 Surface water and groundwater allocations in strategies S14 to S18

Surface Water Utilized (ha-m)						
S. No.	Zone-1	Zone-2	Zone-3	Zone-4	Zone-5	Total
S14	42072.3	38585.2	12458.7	16746.7	8464.6	118327.5
S15	43932.7	38585.2	9344.0	16746.7	8464.6	117073.2
S16	45793.1	38585.2	6229.4	16746.7	8464.6	115818.9
S17	47524.3	38585.2	3114.7	16746.7	8464.6	114435.5
S18	48757.7	38585.2	0.0	16746.7	8464.6	112554.1
Groundwater Utilized (ha-m)						
S. No.	Zone-1	Zone-2	Zone-3	Zone-4	Zone-5	Total
S14	38210.3	21552.1	14179.5	23245.4	5034.6	102221.9
S15	36349.8	21552.1	17294.1	23245.4	5034.6	103476.1
S16	34489.4	21552.1	20408.8	23245.4	5034.6	104730.4
S17	32758.2	21552.1	23523.5	23245.4	5034.6	106113.8
S18	31524.9	21552.1	26557.9	23124.9	5034.6	107794.4

There is an inverse trend between water diversion and surface water utilization level, more the water diverted from Zone-3 to Zone-1, less the level of surface water utilization in that strategy. However, there is a direct relationship between water diversion and groundwater utilization levels due to increased groundwater pumping in Zone-3. Highest surface water utilization is achieved in Strategy-14 (i.e. 20% diversion of surface water from Zone-3 to Zone-1), the estimates of surface water utilization (90.36%) is almost similar as achieved in Strategy-13, indicating complete utilization of diverted water by Zone-1. The reduction in surface water utilization level in subsequent strategies indicates the temporal disparity in demand and supply system. The highest groundwater pumping/utilization (107794 ha-m) is observed in Strategy-18, which is about 76.6% of total available groundwater. This is 12% more than the pumping in Strategy-2 and of 6% less than that in Strategy-1.

The surface water utilization levels in all the strategies in present scenario are higher than those achieved in Strategy-1 to Strategy-13, indicating better water management in present scenario.

In case of Zone-3, the reduction in surface water supply is from 3114.7 ha-m to 15573.4 ha-m (20% to 100% of total surface water supply to Zone-3). The increase in groundwater pumping is in the range of 2075 ha-m to 14454 ha-m in comparison to Strategy-13, clearly indicating higher surface water supply in normal conditions than the water demand. In Zone-1, the additional supply of 3114.7 ha-m to 15573.4 ha-m, reduces groundwater pumping/utilization by 1860 ha-m to 8545 ha-m, resulting in decrease in surface water utilization level. The main reason for the low surface water utilization level may be attributed to the temporal disparity between water supply and water demand.

Though the highest total benefits are achieved in Strategy-17 (i.e. 80% diversion of surface water from Zone-3 to Zone-1), but practically this strategy will be inefficient and difficult to maintain as the flow to be supplied to Zone-3 are in the order of 200 to 600 ha-m in a month which is very low for a large canal systems. On the other hand, benefits per unit of water utilized are highest in Strategy-18. Based on the analysis of results obtained for all the strategies in present scenario (Scenario-5), it is clear that there is temporal disparity between water demand and supply in Zone-1. To solve this problem and to maximize the resources utilization along with total benefits, a spatio-temporal conjunctive use scenario is required.

8.4.6 Spatio-Temporal Conjunctive Use (Scenario-6)

In the present study, distributed conjunctive use model has been developed for optimizing the resources utilization and total benefits from the command area. The results of strategies S14 to S18 indicate that with increase in cropping intensity (irrigation intensity) in Rabi season, total benefits from command can be increased by 9% over the existing condition in the command. To counter problems like rising groundwater levels in Zone-3 and depletions in groundwater in Zone-1, strategies of surface water supply diversion from Zone-3 to Zone-1 have been evaluated based on total benefits, benefits per unit water utilized, benefits per unit cultivated area. The trend in surface water reduction and increase in groundwater pumping in Zone-3 indicates the opportunity for improvements in groundwater system (i.e. decrease in rate of groundwater rise or may be reversal of the trend in groundwater). The additional surface water in Zone-1 reduces the annual groundwater pumping requirements by 30% compared to groundwater utilization/pumping in designed cropping pattern scenario (Strategy-1). However, the diverted surface water to Zone-1 is partially utilized, which is reflected in decreased surface water utilization levels. This under utilization is a result of temporal disparity between irrigation water demand and supply. Hence, to improve the utilization level of water resources along with benefits, a spatio-temporal conjunctive use scenario has been discussed in the present section.

In spatio-temporal conjunctive use scenario (Strategy-19) the diverted water from Zone-3 will be supplied to Zone-1 but the supply schedule will be changed based on peak demand. Monthly surface water and groundwater utilization in all the strategies indicate that groundwater extraction is highest in three months viz. September, October and March out of which supply from canal is done in October and March. The surface water in Zone-1 is underutilized in Jnuary, November and December. So, in present strategy it has been proposed that, the amount of diverted surface water during January and March will be supplied to Zone-1 in the month of March. Similarly, diverted surface water from October to December will be supplied to Zone-1 in the month of October. It has been assumed that the conveyance system capacity will not limit this scenario, as in both the months, very low flow (almost 40% of annual highest supply levels) is supplied to Zone-1 in normal scenario. Though total benefits are higher in case of Strategy-17 (80% surface water diversion), yet this strategy is not considered here due to the practical complications in operation. Benefits per unit of water utilized are higher in case of 100% diversion of surface water from Zone-3 to Zone-1 hence, only 100% surface water diversion scenario has been considered in present strategy. The water availability constraints for Zone-3 and Zone-1 are changed. The water availability for all other zones has been kept similar to Strategy-13. The cropping intensity and cost coefficients used to solve strategies in Scenario-5 have been used to solve the resources allocations problem in present strategy. The results obtained are given in Table 8.11.

Total benefits achieved in spatio-temporal conjunctive use scenario are around 9747.532 Million Rupees, which is 10% (847.74 Million Rupees) higher than the total benefits of existing cropping pattern scenario (Strategy-2) and 6% (523.977 Million Rupees) higher than designed cropping pattern scenario (Strategy-1). Benefits per unit of water utilized are around 44237 Rs/ha-m, highest among all the strategies. Benefits per unit cultivated area are 25388 Rs/ha.

Table 8.11 Allocations of different resources and benefits for the spatio-temporal conjunctive use scenario (Strategy-19)

						BENEFITS (Million Rs)= 9747.532
AREA UNDER DIFFERENT CROPS (ha)						
	ZONE-1	ZONE-2	ZONE-3	ZONE-4	ZONE-5	TOTAL
PADDY	4761.7	3566.8	1579.9	2372.0	778.9	13059.3
COTTON	4761.7	3566.8	1579.9	2372.0	778.9	13059.3
JAWAR	6666.3	4993.5	2211.9	3320.8	1090.4	18282.9
GROUNDNUT	4761.7	3566.8	1579.9	2372.0	778.9	13059.3
MAIZE	7618.7	5706.9	2527.9	3795.2	1246.2	20894.9
PULSES	4761.7	3566.8	1579.9	2372.0	778.9	13059.3
SOYABEAN	30474.6	22827.6	10111.7	15180.7	4984.7	83579.3
PERENNIAL	3809.3	2853.5	1264.0	1897.6	623.1	10447.5
WHEAT	60949.2	45655.3	20223.3	30361.3	8567.5	165756.5
GRAM	6666.3	4993.5	2211.9	3320.8	1090.4	18282.9
PEAS	1904.7	1426.7	632.0	948.8	311.5	5223.7
VEGETABLE	952.3	713.4	316.0	474.4	1557.8	4013.9
LINSEED	1904.7	1426.7	632.0	948.8	311.5	5223.7
KHARIF CROPS	63806.4	47795.2	21171.1	31784.7	10436.9	
RABI CROPS	72377.2	54215.6	24015.2	36054.1	11838.7	
OPTIMAL ALLOCATION OF SURFACE WATER (ha-m)						
JANUARY	8005.3	5996.5	0.0	3371.8	1449.6	18823.3
FEBRUARY	11374.9	9419.3	0.0	3371.8	1895.6	26061.5
MARCH	8064.6	4213.8	0.0	1461.1	821.4	14560.9
OCTOBER	12337.8	5186.2	0.0	1798.3	1010.9	20333.2
NOVEMBER	8239.2	7954.0	0.0	3371.8	1877.1	21442.1
DECEMBER	7763.4	5815.3	0.0	3371.8	1410.1	18360.6
TOTAL	55785.2	38585.2	0.0	16746.7	8464.6	**119581.7**
OPTIMAL ALLOCATION OF GROUNDWATER (ha-m)						
JANUARY	1199.7	0.0	4172.3	2892.1	179.5	8443.6
FEBRUARY	1873.9	3230.9	3297.7	3489.7	732.7	12624.9
MARCH	826.6	619.2	274.3	411.8	135.2	2267.1
APRIL	2175.1	1629.3	721.7	1083.5	355.8	5965.5
MAY	1934.2	1448.8	641.8	963.5	316.4	5304.7
JUNE	2002.8	1500.2	664.5	997.7	327.6	5492.7
JULY	1829.4	1370.4	607.0	911.3	299.3	5017.4
AUGUST	6655.9	4985.7	2208.4	3315.6	1088.7	18254.3
SEPTEMBER	3620.4	6767.6	5295.0	6151.2	1599.4	23433.6
OCTOBER	2379.3	0.0	3523.3	1917.7	0.0	7820.3
NOVEMBER	0.0	0.0	2576.0	495.4	0.0	3071.4
DECEMBER	0.0	0.0	2576.0	495.4	0.0	3071.4
TOTAL	24497.4	21552.1	26557.9	23124.9	5034.6	**100766.9**

The land and water allocation in this strategy for all the zones during both the seasons is shown in Figs. 8.28 and 8.29, respectively. In spatio-temporal conjunctive use scenario (Strategy-19), surface water utilization level is raised to 91.32% (119581.7 ha-m) of the total available surface water (130952.9 ha-m) in the canal system and the groundwater utilization level is kept 71.56% (100767 ha-m) of total available groundwater (140809 ha-m).

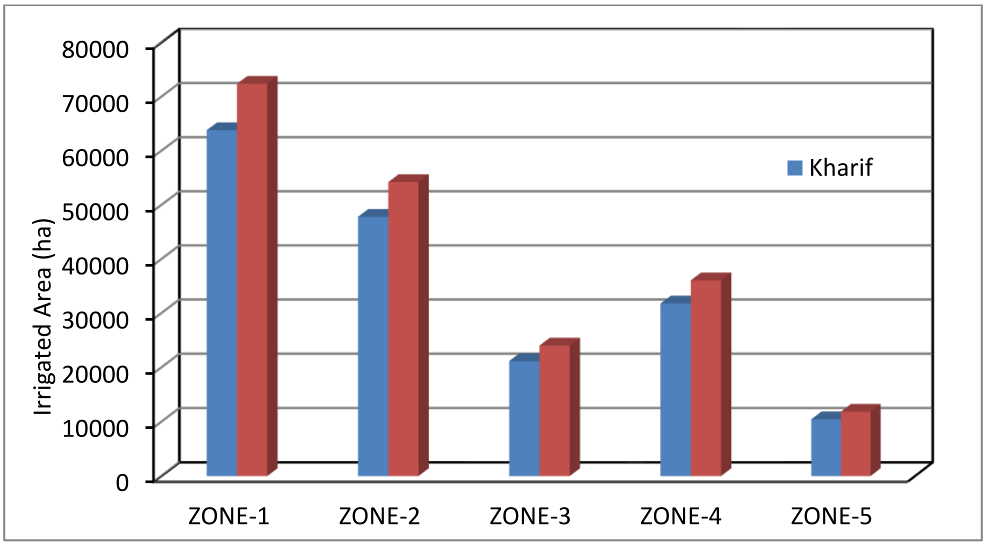


Figure 8.28: Irrigated area in all the zones for Strategy-19

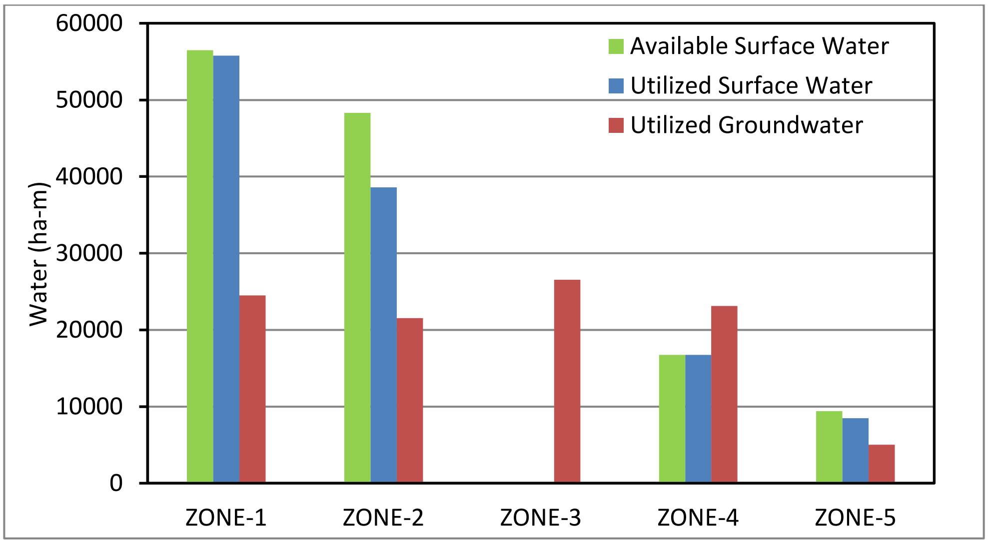


Figure 8.29 Surface water and groundwater utilization in all the zones for Strategy-19

The utilization level of surface water in all the months by each zone except Zone-3 is shown in Figs. 8.30 to 8.33 The monthly surface water and groundwater allocation in the entire command system is shown in Fig. 8.34.

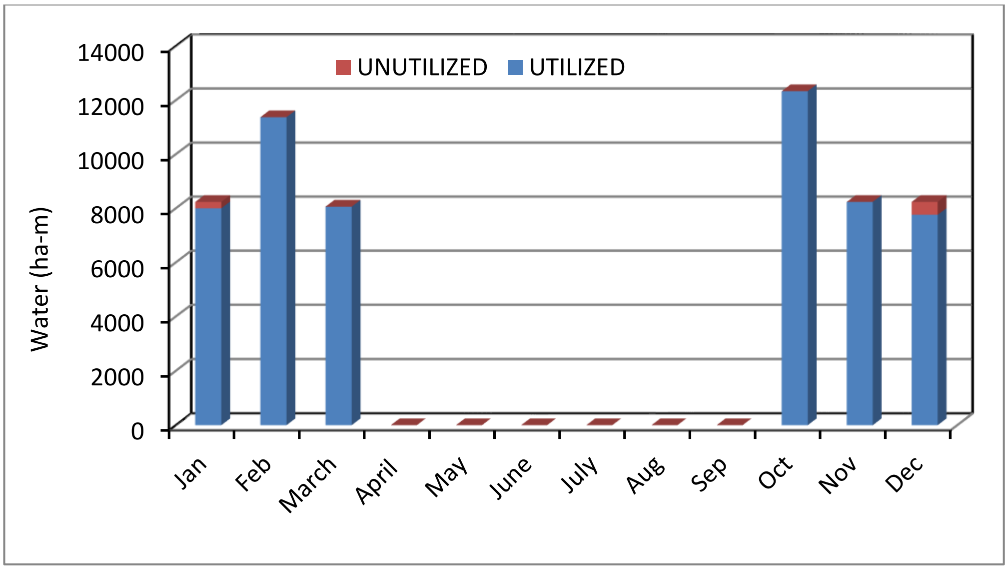


Figure 8.30 Utilization level of surface water in Zone-1 for Strategy-19

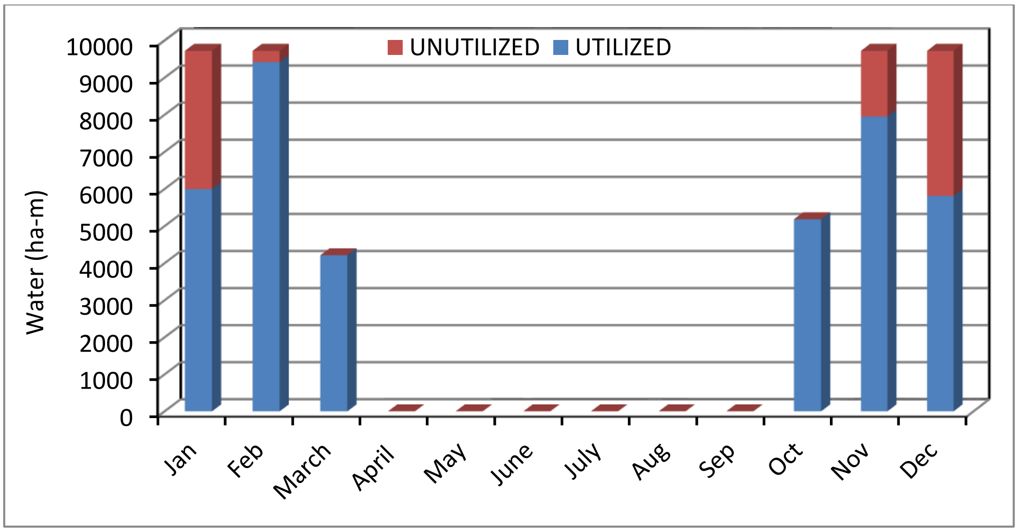


Figure 8.31 Utilization level of surface water in Zone-2 for Strategy-19

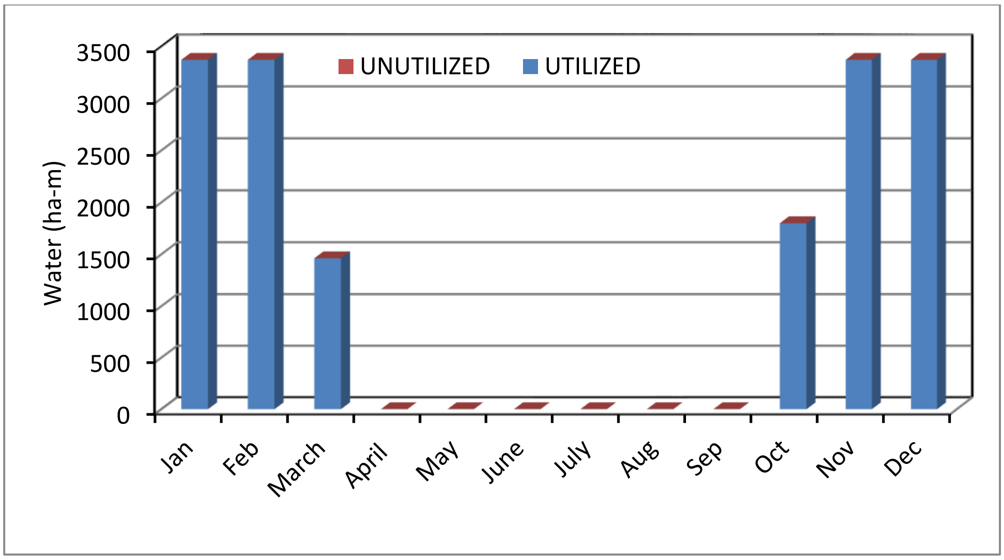


Figure 8.32 Utilization level of surface water in Zone-4 for Strategy-19

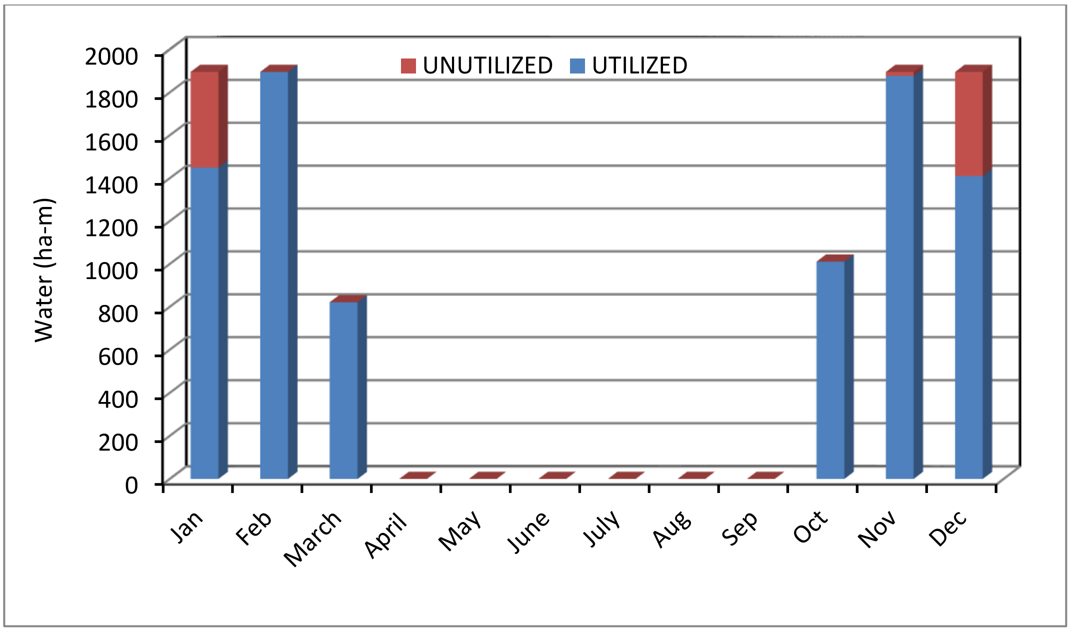


Figure 8.33 Utilization level of surface water in Zone-5 for Strategy-19

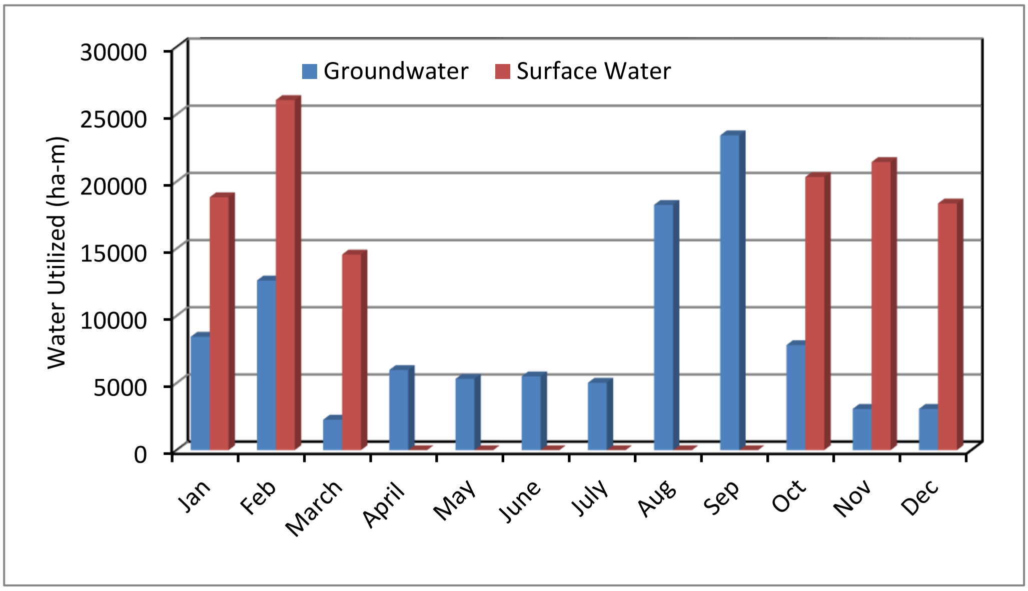


Figure 8.34 Monthly surface water and groundwater allocations in Strategy-19

Figure 8.30 clearly suggests an improved scenario in the surface water utilization in Zone-1. The excess water diverted into Zone-1 using spatio-temporal conjunctive use approach is completely utilized in respective months. Due to temporal change in the supply of diverted surface water in Zone-1, the groundwater pumping in March and October has gone down to 826.6 ha-m and 2379.3 ha-m as compared to 5074 ha-m and 10468.8 ha-m respectively in designed cropping pattern scenario (Strategy-1). The reduction in groundwater pumping is to the tune of 77% in October and 83% in March compared to existing cropping pattern scenario (Strategy-2). With excess surface water supply of 15573 ha-m in Zone-1, the total reduction of groundwater draft up to same amount is achieved in present Strategy, which indicates that the diverted surface water is fully utilized in Zone-1.

In the present case, highest groundwater pumping/utilization is observed in Zone-3 (26557.9 ha-m), almost 90% higher than the groundwater pumping in Strategy-1 and one and half times higher than the groundwater pumping in Strategy-2. With reduction of around 15573 ha-m of surface water supply, the groundwater pumping is increased by 14454.1 ha-m, which is 1.2 times higher than the groundwater pumping for similar cropping pattern in Strategy-13. The comparison between surface water and groundwater allocations in Strategy-19 and 2 (Fig.8.20) indicates that, surface water utilization for Strategy-19 is improved in all the zones except Zone-3 (no surface water supply). Groundwater utilization is increased in all the zones except Zone-1, due to supply of diverted surface water from Zone-3. The increase in groundwater utilization in all the zones except Zone-3 is mainly due to increased cropping intensity in Rabi season. In Zone-3, the increase in groundwater utilization is more than double due to 100% reduction in surface water supply in the zone.

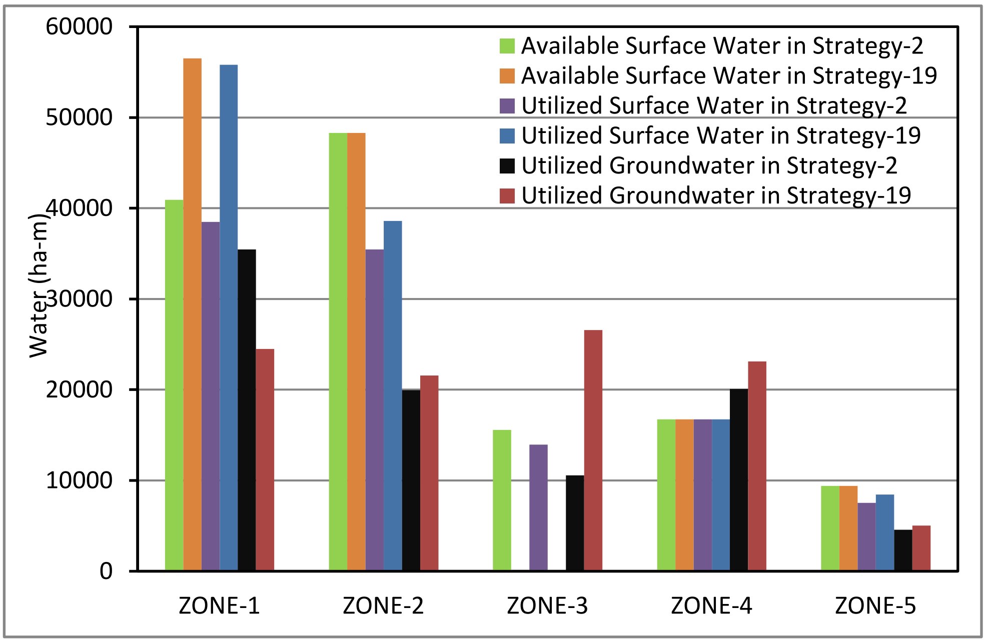


Figure 8.35: Surface water and groundwater allocations in Strategies 2 & 19

To see the effect of present strategy on sustainability of command area, the results of allocation model have been used as input to calibrated groundwater model. The groundwater behaviour for the years 2004 to 2010 with same allocation strategy has been estimated with the assumption that same level of resources allocation will continue for the prediction period (2004-2010) for all the zones. This is represented in Figs. 8.36 to 8.40

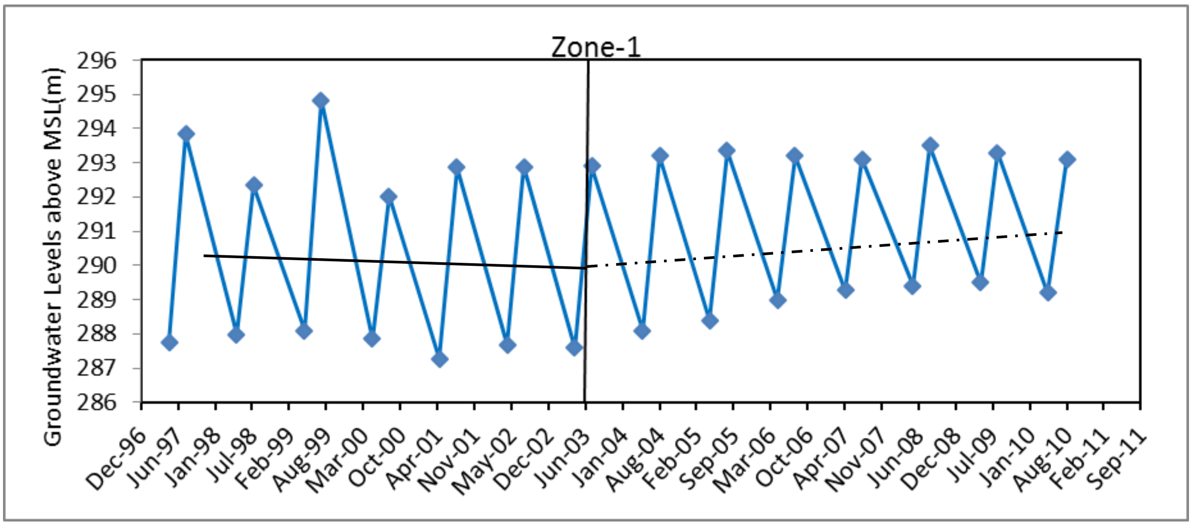


Figure 8.36 Groundwater behaviour in Zone-1 with resources allocation for Strategy-19

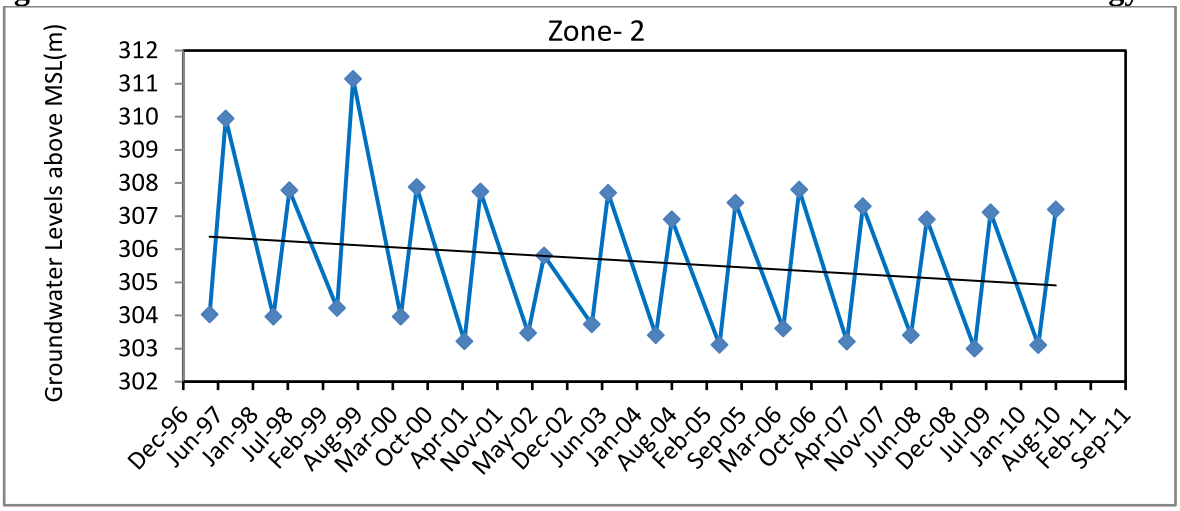


Figure 8.37 Groundwater behaviour in Zone-2 with resources allocation for Strategy-19

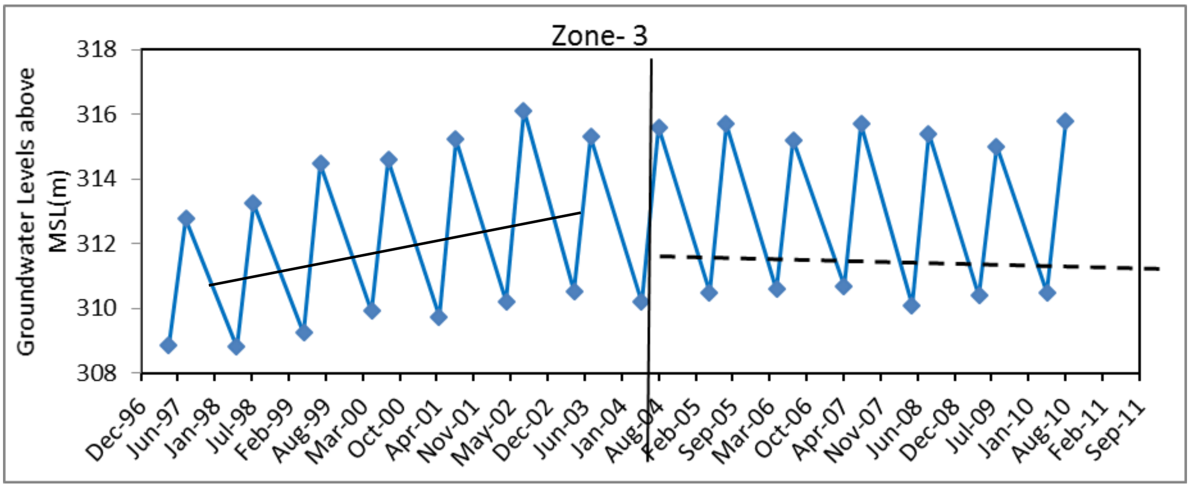


Figure 8.38 Groundwater behaviour in Zone-3 with resources allocation for Strategy-19

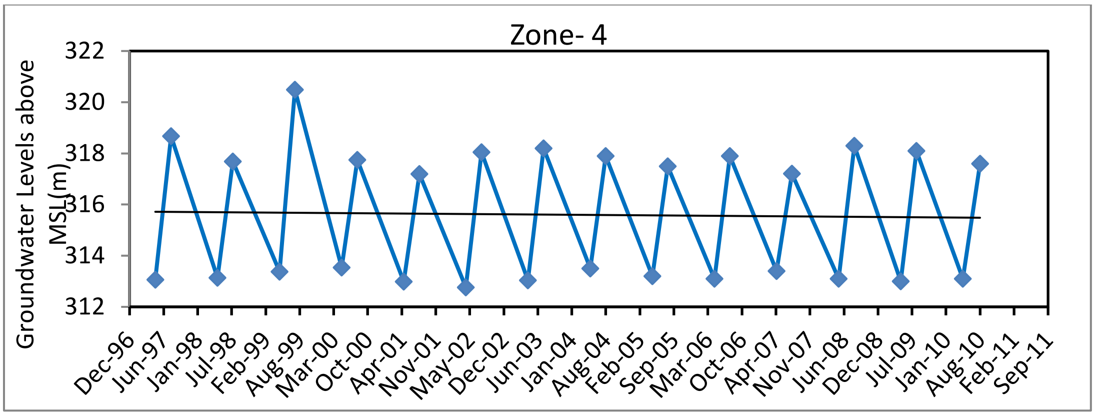


Figure 8.39 Groundwater behaviour in Zone-4 with resources allocation for Strategy-19

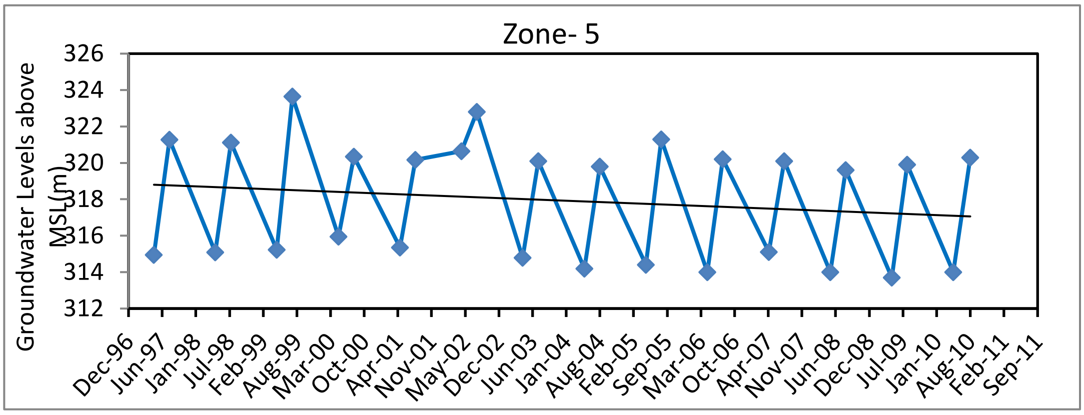


Figure 8.40 Groundwater behaviour in Zone-5 with resources allocation for Strategy-19

It is observed from Fig. 8.38 that if the spatio-temporal conjunctive use approach is implemented, the trend in groundwater rise in Zone-3 will slowly stabilize and reverses within a span of six years. On the other hand, if 100% surface water from Zone-3 is diverted to Zone-1, the additional recharge in this zone will improve the depleting groundwater condition in the zone, as can be seen in Fig.8.36

The spatio-temporal conjunctive use scenario is not only economically vibrant but also environmentally sustainable, as it tackles both the rising and depleting groundwater levels in different parts of Tawa Command.

8.5 COMPARISON BETWEEN DIFFERENT STRATEGIES

The accrued benefits, surface water utilization, groundwater utilization and area under cultivation in each strategy are listed in Table 8.12. The benefit per unit of water utilized is highest in spatio-temporal conjunctive use scenario (Strategy-19)

Table 8.12 Consolidated results from all strategies (S1 to S19)

S. No.	Benefits			Irrigated Area (ha)	Water Utilizes (ha-m)		Water Utilization Level (%)	
	Total (Rs)	Rs/ha	Rs/ha-m		SW	GW	SW	GW
S1	9223555000	25999	40488	354764	110473	**117333**	84.36	**83.33**
S2	8899792000	24692	43877	360436	112191	90643	85.67	64.37
S3	8899790000	24692	43877	360436	110330	92504	84.25	65.69
S4	8900917000	24695	43883	360436	112191	90643	85.67	64.37
S5	8899785000	24692	43877	360436	107569	95265	82.14	67.66
S6	8902041000	24698	43888	360436	111290	91544	84.98	65.01
S7	8899780000	24692	43877	360436	104454	98379	79.77	69.87
S8	8902946000	24700	43893	360436	109676	93157	83.75	66.16
S9	8899056000	24690	43874	360436	101285	101549	77.34	72.12
S10	8902969000	24701	43893	360436	107795	95039	82.32	67.49
S11	8896842000	24684	43863	360436	98225	104609	75.01	74.29
S12	8901258000	24696	43884	360436	105511	97323	80.57	69.12
S13	9678892000	25209	43959	383943	118122	102060	90.20	72.48
S14	9742168000	25374	44172	383943	118327	102222	90.36	72.60
S15	9743291000	25377	44177	383943	117073	103476	89.40	73.49
S16	9744414000	25380	44182	383943	115818	104730	88.44	74.38
S17	9744739000	25381	44184	383943	114435	106114	87.39	75.36
S18	9743272000	25377	44218	383943	112554	107794	85.95	76.55
S19	**9747532000**	**25388**	**44237**	**383943**	**119581**	100767	**91.32**	71.56

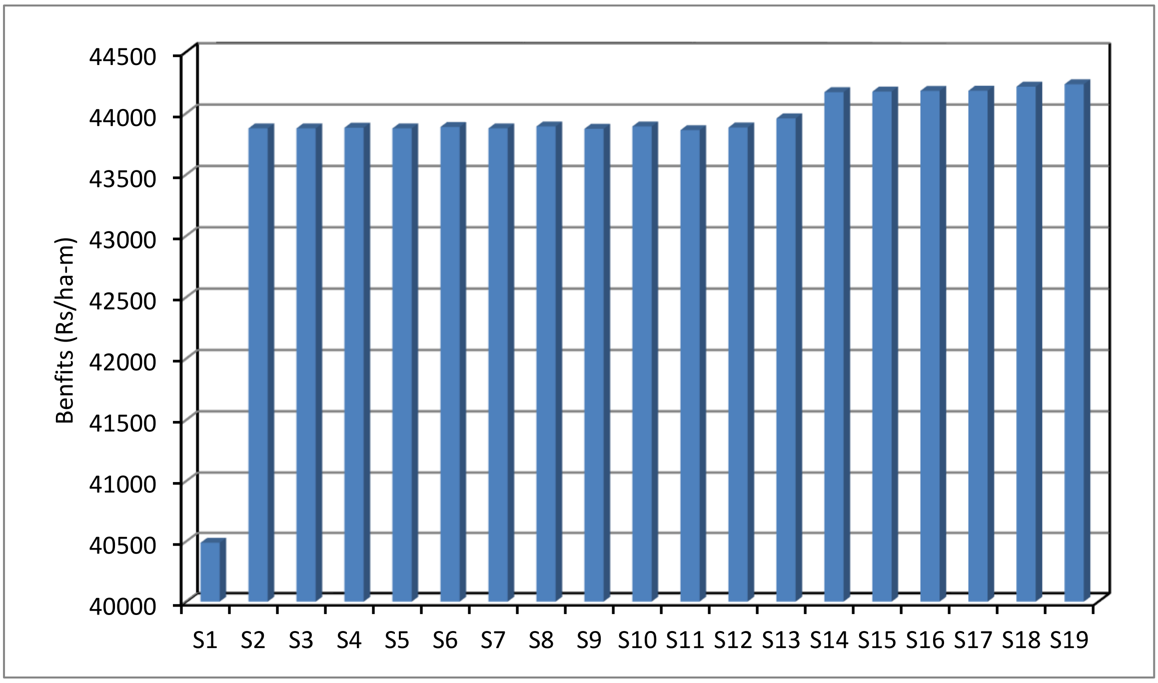


Figure 8.41 Benefits per unit water utilized in all strategies

It can be seen from the Table 8.12 that the highest surface water utilization is in Strategy-19 (91.32%). The groundwater utilization in case of Strategy-19 is lowest among all strategies considering increase in irrigation intensity in Rabi season to 80% (S13, S14, S15, S16, S17, S18 and S19). This reduction in groundwater pumping/utilization is as a result of proper utilization of surface water. On the basis of benefits (total, per unit cultivated area and per unit water utilized) and utilization levels of surface water and groundwater, Strategy-19 is the optimal strategy to manage all available resources in the Tawa Command (Fig. 8.41).

The zone wise surface water and groundwater utilized in all strategies is given in Tables 8.13 and 8.14 Zone-1 and Zone-3 were of special interest in the present study due to groundwater problems prevalent in these zones. Hence, the utilization of surface water and groundwater in Zone-1 and Zone-3 are presented separately in Figs. 8.42 and 8.43. Lower values of surface water utilization in Strategies 1 to 12 indicate the under utilization of surface water resources and scope for further expansion in irrigation intensity in Rabi season. After increase of 13% in irrigation intensity in Rabi season the value of total surface water utilization is increased in Strategies 13 to 19 and highest is achieved in spatio-temporal conjunctive use scenario (Strategy-19).

Table 8.13 Surface water allocations in all strategies (S1 to S19)

Surface Water Utilized (ha-m)						
S. No.	Zone-1	Zone-2	Zone-3	Zone-4	Zone-5	Total
S1	38497.7	34388.4	13594.9	16746.7	7246.0	110473.7
S2	38497.7	35458.5	13965.6	16746.7	7522.5	112191.0
S3	38497.7	35458.5	12105.2	16746.7	7522.5	110330.5
S4	40358.1	35458.5	12105.2	16746.7	7522.5	112191.0
S5	38497.7	35458.5	9344.1	16746.7	7522.5	107569.4
S6	42218.4	35458.5	9344.1	16746.7	7522.5	111290.2
S7	38497.7	35458.5	6229.4	16746.7	7522.5	104454.7
S8	43719.7	35458.5	6229.4	16746.7	7522.5	109676.8
S9	38497.7	35458.5	3060.1	16746.7	7522.5	101285.5
S10	44953.0	35458.5	3114.7	16746.7	7522.5	107795.4
S11	38497.7	35458.5	0.0	16746.7	7522.5	98225.4
S12	45783.3	35458.5	0.0	16746.7	7522.5	105511.0
S13	40211.9	38585.2	14534.4	16746.7	8044.0	118122.1
S14	42072.3	38585.2	12458.7	16746.7	8464.6	118327.5
S15	43932.7	38585.2	9344.0	16746.7	8464.6	117073.2
S16	45793.1	38585.2	6229.4	16746.7	8464.6	115818.9
S17	47524.3	38585.2	3114.7	16746.7	8464.6	114435.5
S18	48757.7	38585.2	0.0	16746.7	8464.6	112554.1
S19	55785.2	38585.2	0.0	16746.7	8464.6	119581.7

Groundwater is the only source of irrigation in Kharif season, the groundwater utilization in all strategies from S2 to S19 is less than the designed cropping pattern scenario (Strategy-1). This reduction in groundwater pumping/utilization is observed due to shift from Paddy to Soyabean in Kharif season. The groundwater pumping/utilization in Zone-1 is lowest (46% of groundwater pumping in Strategy-1) in Strategy-19, whereas groundwater pumping in Zone-3 is highest in Strategy-18 and 19 (100% surface water diversion from Zone-3 to Zone-1). This altered surface water supply scenario will counter the problem of rising groundwater level in Zone-3 and depleting water table in Zone-1.

Table 8.14 Groundwater allocations in all strategies (S1 to S19)

Groundwater Utilized (ha-m)						
S. No.	Zone-1	Zone-2	Zone-3	Zone-4	Zone-5	Total
S1	45363.7	28429.7	14230.8	23379.3	5929.7	117333.2
S2	35459.5	19940.6	10573.8	20094.6	4574.7	90643.2
S3	35459.5	19940.6	12434.2	20094.6	4574.7	92503.6
S4	33599.1	19940.6	12434.2	20094.6	4574.7	90643.2
S5	35459.5	19940.6	15195.4	20094.6	4574.7	95264.7
S6	31738.7	19940.6	15195.4	20094.6	4574.7	91543.9
S7	35459.5	19940.6	18310.0	20094.6	4574.7	98379.4
S8	30237.4	19940.6	18310.0	20094.6	4574.7	93157.3
S9	35459.5	19940.6	21479.3	20094.6	4574.7	101548.7
S10	29004.1	19940.6	21424.7	20094.6	4574.7	95038.7
S11	35459.5	19940.6	24539.4	20094.6	4574.7	104608.8
S12	28173.9	19940.6	24539.4	20094.6	4574.7	97323.1
S13	40070.7	21552.1	12103.8	23245.4	5087.9	102059.9
S14	38210.3	21552.1	14179.5	23245.4	5034.6	102221.9
S15	36349.8	21552.1	17294.1	23245.4	5034.6	103476.1
S16	34489.4	21552.1	20408.8	23245.4	5034.6	104730.4
S17	32758.2	21552.1	23523.5	23245.4	5034.6	106113.8
S18	31524.9	21552.1	26557.9	23124.9	5034.6	107794.4
S19	24497.4	21552.1	26557.9	23124.9	5034.6	100766.9

Figs. 8.42 and 8.43 highlights the linear relation existing between water diverted from Zone-3 and increase in groundwater pumping from Zone-3. Almost same amount of increase in groundwater pumping is observed with reduction in surface water in Zone-3. In case of Zone-1, the amount of reduction in groundwater pumping is less compared to amount of diverted surface water supplied to this zone. This indicates the under utilization of diverted water due to temporal disparity in demand and supply of water. This temporal difference in demand and supply calls for rescheduling of supply in the canal system.

The surface water supply rescheduling has been proposed in spatio-temporal conjunctive use scenario (Strategy-19). The diverted surface water from Zone-3 is supplied to Zone-1 in the months of highest demand (March and October). Comparing all aspects (economy, resources utilization levels and environmental sustainability), Strategy-19 (spatio-temporal conjunctive use) has been found as the most optimal and suitable for Tawa Command Area.

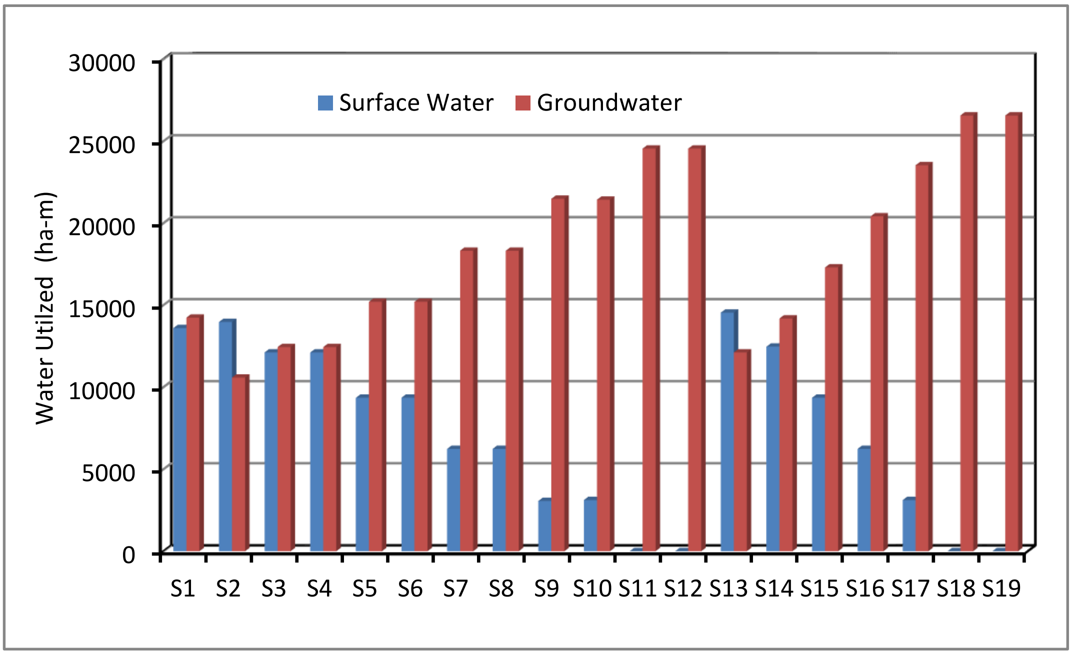


Figure 8.42 Surface water and groundwater allocations in Zone-3 for all strategies

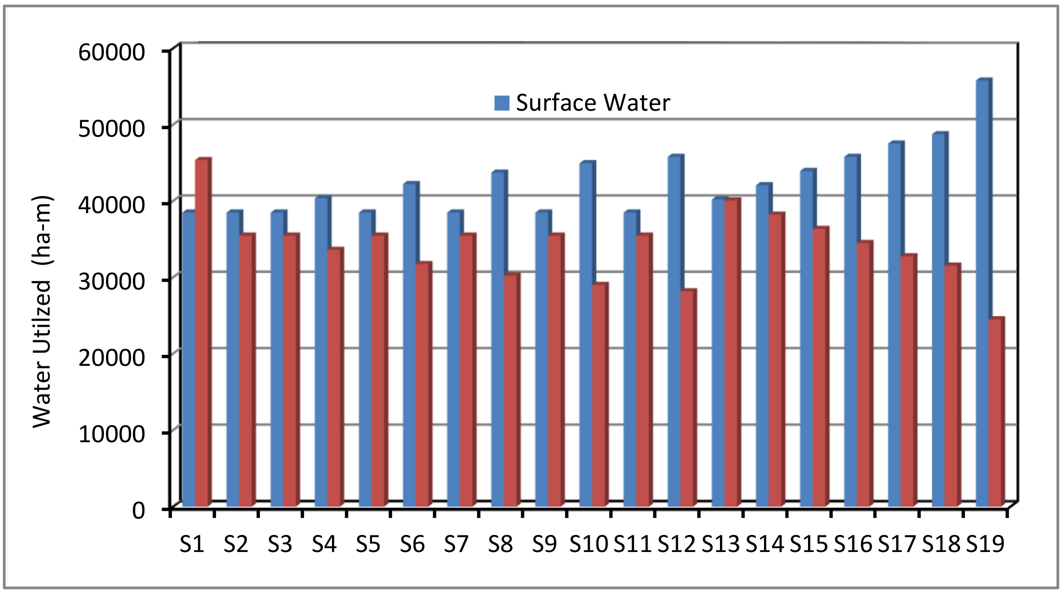


Figure 8.43 Surface water and groundwater allocations in Zone-1 for all strategies

8.6 OPTIMAL MANAGEMENT OF WATER DEFICIT SCENARIO

The distributed conjunctive use model developed in the present study has been integrated with Crop Production Response Functions (CPRF). The basic objective of CPRF is to predict the yield of respective crop as a response to water supplied. This structure of conjunctive use model gives an added advantage of managing the water deficit scenario optimally in the command. To demonstrate the capability of developed model to optimally manage the water deficit scenario, groundwater availability in the command has been reduced to 80000 ha-m, and the surface water availability, cropping pattern and irrigation intensity of existing cropping pattern scenario as in Strategy-2 have been used to solve the water deficit scenario. The water requirement constraints have been modified to allow deficit water supply to any crop in any month. The model has been solved and detailed results are given in Table 8.16. Total benefits achieved in this scenario are around 8838.661 Million Rupees, 0.70% (61.131 Million Rupees) less than that in existing cropping pattern scenario (Strategy-2). The benefits from water deficit scenario are compared with benefits from Strategy-2 as the cropping pattern in water deficit scenario has been assumed to be same as in case of Strategy-2. The benefits per unit cultivated area have come down to 24522 Rs/ha, around 170 Rs/ha less than that in Strategy-2, whereas benefits per unit water utilized in present scenario (45989 Rs/ha-m) have increased by 2112 Rs/ha-m as compared to the benefits per unit of water utilized in Strategy-2. The increase in benefits per unit of water utilized indicates the optimal management of deficit water resources.

Surface water utilization in present scenario is around 85.67% (112191 ha-m), same as the utilization in Strategy-2. The month zonal water allocations in water deficit scenario and normal supply scenario (Strategy-2) are shown in Figs. 8.44 whereas monthly water allocations for Tawa Canal Command in water deficit scenario and normal supply scenario are presented in Fig. 8.45. It is clearly visible from Fig.8.44 that groundwater pumping/utilization is reduced in all the zones. The amount and percentage reduction in each zone is estimated and given in Table. 8.16. The range of percent reduction varies approximately from 10% to 17%. The overall reduction in groundwater pumping is around 11.7% as compared to Strategy-2. In Strategy-2, only 64.37% (90643 ha-m) of total available groundwater resources (140809 ha-m) is utilized, hence in water deficit scenario the effective deficit is around 11.7% as given in Table 8.16

Table 8.15 Allocations of surface water and groundwater in water deficit scenario

						BENEFITS (Million Rs)=8838.661
AREA UNDER DIFFERENT CROPS (ha)						
	ZONE-1	ZONE-2	ZONE-3	ZONE-4	ZONE-5	TOTAL
PADDY	4761.7	3566.8	1579.9	2372	778.9	12280.626
COTTON	4761.7	3566.8	1579.9	2372.0	778.9	12280.6
JAWAR	6666.3	4993.5	2211.9	3320.8	1090.4	17192.6
GROUND NUT	4761.7	3566.8	1579.9	2372.0	778.9	12280.4
MAIZE	7618.7	5706.9	2527.9	3795.2	1246.2	19648.8
PULSES	4761.7	3566.8	1579.9	2372.0	778.9	12280.4
SOYABEAN	30474.6	22827.6	10111.7	15180.7	4984.7	78594.7
PERENNIAL	3809.3	2853.5	1264.0	1897.6	623.1	8549.9
WHEAT	52378.2	39235.0	17379.4	26091.8	8567.5	135084.5
GRAM	6666.3	4993.5	2211.9	3320.8	1090.4	17192.6
PEAS	1904.7	1426.7	632.0	948.8	311.5	4274.9
VEGETABLE	952.3	713.4	316.0	474.4	155.8	2137.6
LINSEED	1904.7	1426.7	632.0	948.8	311.5	4274.9
KHARIF CROPS	63806.4	47795.2	21171.1	31784.7	10436.9	
RABI CROPS	63806.2	47795.3	21171.3	31784.6	10436.7	
OPTIMAL ALLOCATION OF SURFACE WATER (ha-m)						
JANUARY	7148.2	5354.5	2371.8	3371.8	1169.2	19415.6
FEBRUARY	8239.3	8218.7	3135.6	3371.8	1794.7	24760.0
MARCH	3570.3	4213.8	1358.7	1461.1	821.4	11425.3
OCTOBER	4394.3	5186.2	1672.3	1798.3	1010.9	14062.0
NOVEMBER	8239.3	7312.0	3135.6	3371.8	1596.7	23655.4
DECEMBER	6906.3	5173.3	2291.6	3371.8	1129.7	18872.7
TOTAL	38497.7	35458.5	13965.6	16746.7	7522.5	**112191.0**
OPTIMAL ALLOCATION OF GROUNDWATER (ha-m)						
JANUARY	0.00	0.00	0.00	0.00	0.00	0.00
FEBRUARY	2732.5	0.0	504.9	2093.7	0.0	5331.1
MARCH	5074.0	2261.4	1509.5	2845.0	592.5	12282.5
APRIL	826.6	619.2	274.3	411.8	135.2	2267.1
MAY	1089.5	816.1	361.5	542.7	178.2	2988.0
JUNE	1200.9	899.6	398.5	598.2	196.4	3293.6
JULY	2002.8	1500.2	664.5	997.7	327.6	5492.7
AUGUST	1829.4	1370.4	607.0	911.3	299.3	5017.4
SEPTEMBER	6655.9	4985.7	2208.4	3315.6	1088.7	18254.3
OCTOBER	9006.9	4117.4	2774.3	4877.4	1181.1	21957.2
NOVEMBER	1522.1	0.0	103.3	1490.7	0.0	3116.1
DECEMBER	0.0	0.0	0.0	0.0	0.0	0.0
TOTAL	31940.6	16569.9	9406.2	18084.1	3999.1	**80000.0**

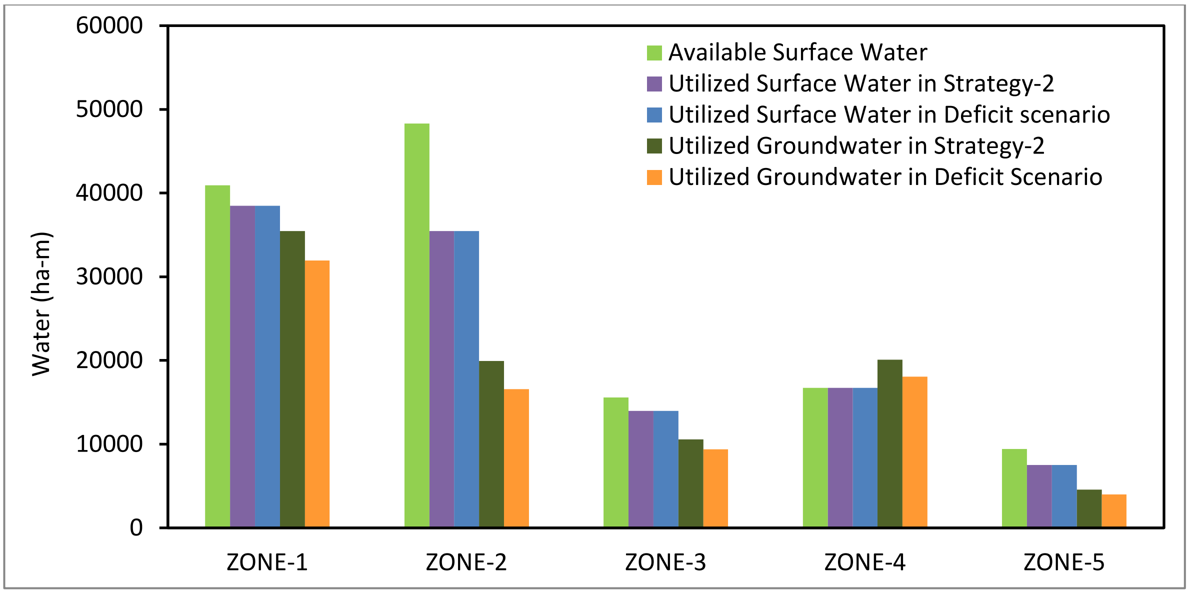


Figure 8.44 Surface water and groundwater allocations in each zone for water deficit and normal supply scenarios

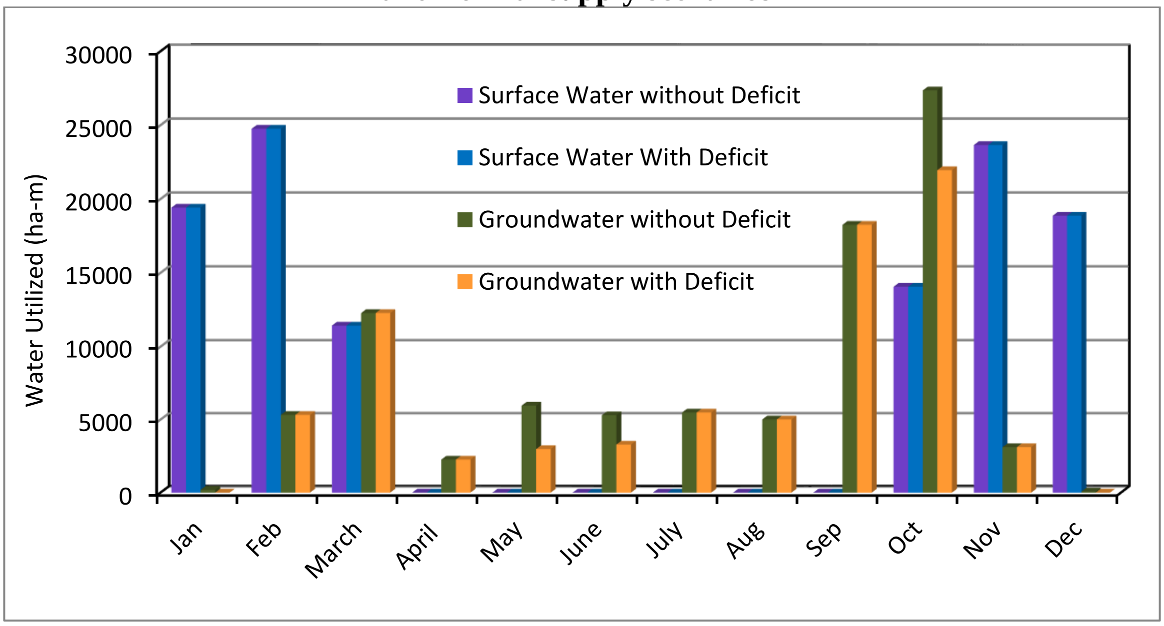


Figure 8.45 Monthly surface water and groundwater allocations for water deficit and normal supply scenarios

In Tawa Command, surface water for irrigation is supplied during Rabi season only (October -March) and the groundwater is used to supplement the irrigation supply in case of excess demand. In Kharif season, groundwater is the only source for irrigation. It is clear from Figs. 8.44 and 8.45 that groundwater pumping/utilization is high in March, September and October in normal supply scenario (Strategy-2) as well as in deficit supply scenario. The groundwater pumping is reduced in January, May, June and October months in water deficit scenario. The month wise groundwater pumping/utilization and amount of reduction are given in Table 8.17. Highest reduction is observed in October (5397 ha-m).

Table 8.16 : Groundwater allocations in different zones for water deficit and normal supply scenario

	Zone-1	Zone-2	Zone-3	Zone-4	Zone-5	Total
GW in Strategy-2	35459.5	19940.6	10573.8	20094.6	4574.7	90643.2
GW in Water deficit Scenario	31940.6	16569.9	9406.2	18084.1	3999.1	80000.0
Reduction in GW	3518.9	3370.7	1167.5	2010.4	575.6	10643.2
Percent Reduction	9.9	16.9	11.0	10.0	12.6	11.7

* GW - groundwater

Table 8.17 Difference between groundwater allocations in deficit and normal supply scenario

Months	GW Allocation in Deficit Scenario (ha-m)	GW Allocation in Normal Case (ha-m)	Reduction in supply (ha-m)
January	0.0	189.0	189.0
February	5331.1	5331.1	0.0
March	12282.5	12282.5	0.0
April	2267.1	2267.1	0.0
May	2988.0	5965.5	2977.5
June	3293.6	5304.7	2011.1
July	5492.7	5492.7	0.0
August	5017.4	5017.4	0.0
September	18254.3	18254.3	0.0
October	21957.2	27354.2	5397.0
November	3116.1	3116.1	0.0
December	0.0	68.5	68.5
Total	80000.0	90643.2	10643.2

The CPRF discussed in Chapter 6, are directly integrated in the framework of mathematical model developed for conjunctive use modelling in canal command. The CPRF finally estimates total yield of crop based on relative water deficit and yield response factor (K_y) given in Table 6.8 (Chapter 6). The objective function of developed conjunctive use model is formulated to maximize the total benefits from the command. So, the conjunctive use model integrated with CPRF will try to optimize the water deficit scenario in the command in an economical manner i.e. the deficit water will be given in time period when, effect of deficit supply is minimum on the crop yield. The combined analysis of Table 8.17 and Table 6.8 (Chapter 6) highlights that the values of yield response factor (K_y) are minimum in the months of January, May, June and October for the crops grown during these periods. The reduction in groundwater supplied in each zone to each crop in the January, May, June and October, compared to the groundwater supply in case of normal supply scenario is given in

Table 8.18 Reduction in groundwater supply (m) compared to normal supply scenario

Month \ Crop	PADDY	COTTON	JAWAR	GROUNDNUT	MAIZE	PULSES	SOYABEAN	PERENNIAL	WHEAT	GRAM	PEAS	VEGETABLE	LINSEED
ZONE-1													
JANUARY	0	0	0	0	0	0	0	0	0	0	0	0	0
MAY	0	0.228	0	0	0	0	0	0	0	0	0	0	0
JUNE	0	0	0	0	0	0.154	0	0	0	0	0	0	0
OCTOBER	0	0	0.22	0	0.058	0.1	0.044	0	0	0	0.1	0.1	0.08
ZONE-2													
JANUARY	0	0	0	0	0	0	0	0	0	0	0	0	0
MAY	0	0.228	0	0	0	0	0	0	0	0	0	0	0
JUNE	0	0	0	0	0	0.154	0	0	0	0	0	0	0
OCTOBER	0.102	0	0.184	0	0	0.1	0	0	0.005	0.02	0	0.1	0
ZONE-3													
JANUARY	0	0	0	0	0	0	0	0	0	0	0	0	0
MAY	0	0.228	0	0	0	0	0	0	0	0	0	0	0
JUNE	0	0	0	0	0	0.154	0	0	0	0	0	0	0
OCTOBER	0.102	0	0	0	0	0.1	0	0	0.011	0	0	0	0
ZONE-4													
JANUARY	0	0	0	0	0	0	0	0	0	0	0	0.2	0.099
MAY	0	0.228	0	0	0	0	0	0	0	0	0	0	0
JUNE	0	0	0	0	0	0.154	0	0	0	0	0	0	0
OCTOBER	0	0	0	0.019	0.047	0.1	0	0	0	0.08	0	0.1	0.08
ZONE-5													
JANUARY	0	0	0	0	0	0	0	0	0	0	0	0	0
MAY	0	0.228	0	0	0	0	0	0	0	0	0	0	0
JUNE	0	0	0	0	0	0.154	0	0	0	0	0	0	0
OCTOBER	0.102	0	0	0	0	0.1	0	0	0.0066	0	0.1	0.1	0

Table 8.19 Relative water deficit in all zones for January, May, June and October

Month \ Crop	PADDY	COTTON	JAWAR	GROUNDNUT	MAIZE	PULSES	SOYABEAN	PERENNIAL	WHEAT	GRAM	PEAS	VEGETABLE	LINSEED
ZONE-1													
JANUARY	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
MAY	0.0	1.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
JUNE	0.0	0.0	0.0	0.0	0.0	1.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
OCTOBER	0.0	0.0	1.0	0.0	1.0	1.0	0.4	0.0	0.0	0.0	1.0	1.0	1.0
ZONE-2													
JANUARY	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
MAY	0.0	1.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
JUNE	0.0	0.0	0.0	0.0	0.0	1.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
OCTOBER	1.0	0.0	0.8	0.0	0.0	1.0	0.0	0.0	0.1	0.2	0.0	1.0	0.0
ZONE-3													
JANUARY	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
MAY	0.0	1.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
JUNE	0.0	0.0	0.0	0.0	0.0	1.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
OCTOBER	1.0	0.0	0.0	0.0	0.0	1.0	0.0	0.0	0.1	0.0	0.0	0.0	0.0
ZONE-4													
JANUARY	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.0	1.0
MAY	0.0	1.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
JUNE	0.0	0.0	0.0	0.0	0.0	1.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
OCTOBER	0.0	0.0	0.0	0.1	0.8	1.0	0.0	0.0	0.0	0.8	0.0	1.0	1.0
ZONE-5													
JANUARY	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
MAY	0.0	1.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
JUNE	0.0	0.0	0.0	0.0	0.0	1.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
OCTOBER	1.0	0.0	0.0	0.0	0.0	1.0	0.0	0.0	0.1	0.0	1.0	1.0	0.0

Table 8.20 Percent reduction in yield due to deficit water supply

Month \ Crop	PADDY	COTTON	JAWAR	GROUNDNUT	MAIZE	PULSES	SOYABEAN	PERENNIAL	WHEAT	GRAM	PEAS	VEGETABLE	LINSEED
ZONE-1													
JANUARY	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
MAY	0.0	20.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
JUNE	0.0	0.0	0.0	0.0	0.0	20.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
OCTOBER	0.0	0.0	30.0	0.0	20.0	20.0	17.7	0.0	0.0	0.0	20.0	57.0	20.0
ZONE-2													
JANUARY	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
MAY	0.0	20.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
JUNE	0.0	0.0	0.0	0.0	0.0	20.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
OCTOBER	30.0	0.0	25.1	0.0	0.0	20.0	0.0	0.0	1.2	4.0	0.0	57.0	0.0
ZONE-3													
JANUARY	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
MAY	0.0	20.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
JUNE	0.0	0.0	0.0	0.0	0.0	20.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
OCTOBER	30.0	0.0	0.0	0.0	0.0	20.0	0.0	0.0	2.8	0.0	0.0	0.0	0.0
ZONE-4													
JANUARY	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	80.0	9.9
MAY	0.0	20.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
JUNE	0.0	0.0	0.0	0.0	0.0	20.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
OCTOBER	0.0	0.0	0.0	4.0	16.0	20.0	0.0	0.0	0.0	16.0	0.0	57.0	20.0
ZONE-5													
JANUARY	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
MAY	0.0	20.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
JUNE	0.0	0.0	0.0	0.0	0.0	20.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
OCTOBER	30.0	0.0	0.0	0.0	0.0	20.0	0.0	0.0	1.4	0.0	20.0	57.0	0.0

Detailed analysis of Tables 8.18 to 8.20 and Table 6.6 (Chapter 6) reveals that deficit supply to each crop is given in the time period (month) in which the yield reduction factor (K_y) is minimum (i.e. the yield reduction due to water deficit is minimum). In case of Paddy, value of K_y is minimum in October, therefore, deficit water supply is given in the same month in all the zones. Similarly, K_y for cotton is minimum in the month of May and June. The groundwater utilization in May is higher than the groundwater utilization in June (Fig.8.7), hence groundwater supply for Cotton is reduced in the month of May. Tables 8.18 to 8.20 indicate that developed conjunctive model has applied the deficit water after considering its impact on total yield and water utilization for a particular time period (month in present case).

The total benefits, benefits per unit of water utilized and temporal and spatial adjustment of deficit groundwater supply achieved using distributed conjunctive use model indicates that the developed model has the capability to optimally manage the water deficit scenario also. This capability makes the developed model a useful decision making tool in case of water deficit in a functional project.

8.7 OPTIMAL MANAGEMENT BASED ON REMOTE SENSING DERIVED SPATIAL AND TEMPORAL CROPPING PATTERN CHANGE

In the study, a separate scenario has been considered in solving the optimization model considering the existing cropping pattern estimated based on identified crops using remote sensing satellites for the *Rabi* season. The required data, as already described in previous Chapters, is used while solving the problems of resources allocations in different scenarios.

It has been already discussed in earlier chapter that significant changes in cropping pattern have been occurred in the Tawa canal command. New crop such as Soyabean has been introduced in the area. Also the crop acreage for few crops have been altered. It has been seen that the cropping intensity during *Rabi* season has been changed from 67% in the design cropping pattern to 74% in the existing cropping pattern as reported. Based on the satellites imageries (RS based) crop identified for the *Rabi* season, it has been seen that the cropping intensity has been further extended to 81%. The zone-wise crop acreage for the existing (RS based) is given in Table 8.21.

Table 8.21: Existing cropping pattern for the Tawa canal command (RS based)

Zone(s)	CCA	Wheat	Gram	Peas	Linseeds	Vegetables	Sugarcane	Total
Zone 1	90042.4	43220.3	13506.4	9004.2	1800.8	5402.5	2251.1	75185.4
Zone 2	67448.1	32375.1	6744.8	6744.8	1349.0	4046.9	1686.2	52946.8
Zone 3	29791.5	14299.9	1787.5	2979.2	595.8	1787.5	744.8	22194.7
Zone 4	44853.8	21529.8	897.1	4485.4	897.1	2691.2	1121.3	31621.9
Zone 5	14728.2	7069.5	368.2	1472.8	294.6	883.7	368.2	10457.0
Total	**246864.0**	**118494.7**	**23303.9**	**24686.4**	**4937.3**	**14811.8**	**6171.6**	**192405.8**

8.7.1 Resource allocation as per RS based existing cropping pattern (S-3)

This scenario (S-3) was considered to analyse the resources allocations to the existing cropping pattern of Tawa project based on the identified crops actually grown using satellite based remote sensing techniques. It was observed that the existing irrigation intensity in *Rabi* season in all the zones is increased by 7% to that of existing intensity as reported in DPR. Now, the cropping intensity is about 81% in the Tawa canal command. The major crops grown in *Rabi* season in LBC and RBC are listed below in Table 8.22.

Table 8.22: Existing cropping pattern of Tawa project (RS based)

Season	Crops	Irrigation intensity (%)	Irrigated cropped area (ha)
Rabi	Wheat	48	118494.7
	Gram	15	37029.6
	Peas	10	24686.4
	Vegetables	06	14811.8
	Linseed	02	4937.3
	Total	**81**	**199959.8**

The results obtained (Table 8.23) indicates that in existing cropping pattern and irrigation intensity scenario total benefit from the command was to the tune of 5096.31 Million Rupees. The total benefit was converted in terms of benefit per unit of land cultivated (Rs./ha) and benefit per unit of water utilized (Rs./ha-m). Accordingly, the benefit per unit of cultivated area was found to be 24723.61 Rs./ha and benefit per unit of water utilized was around 42640.63 Rs/ha-m. The available water and utilization is shown in Figure 8.46. The monthly surface water and groundwater utilization is presented in Figure 8.47.

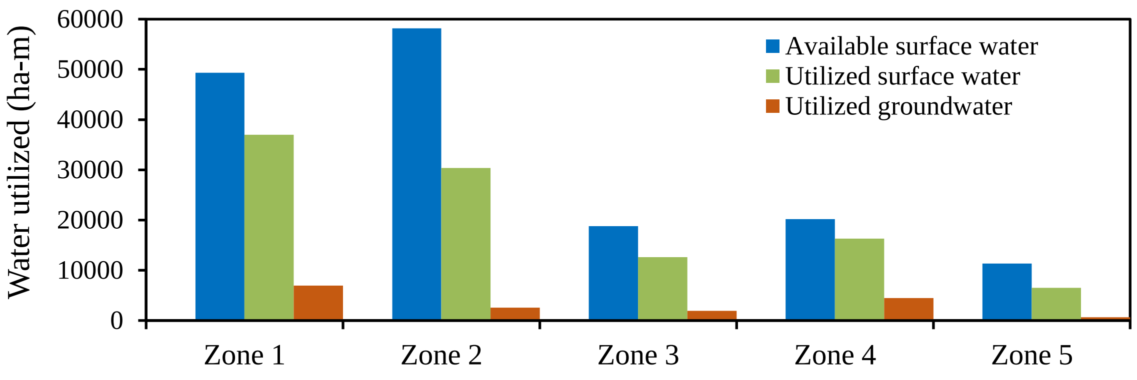


Figure 8.46 Surface water and groundwater utilization as per S-3

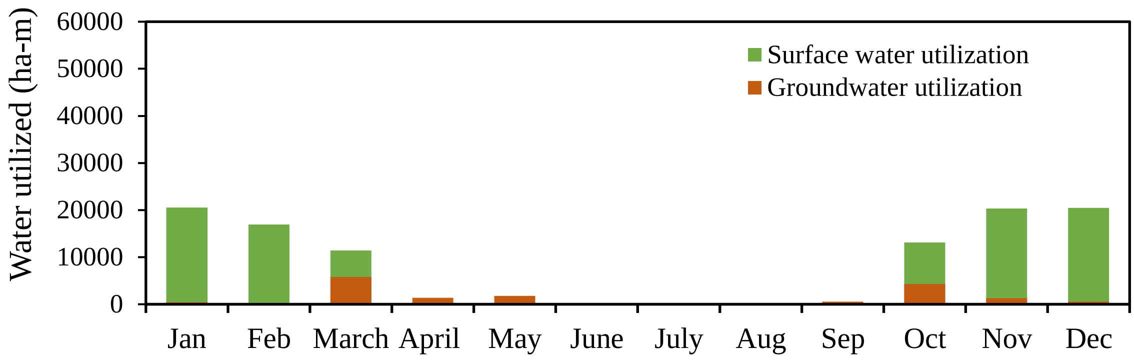


Figure 8.47 Month-wise surface water and groundwater utilization as per S-3

Table 8.23: Allocations of different resources and benefits for the existing cropping pattern as from identified crops (S-3)

CROPS						**BENEFITS (Million Rs)= 5096.31**
	ZONE-1	ZONE-2	ZONE-3	ZONE-4	ZONE-5	TOTAL
WHEAT	43220.3	32375.1	14299.9	21529.8	7069.5	118494.6
GRAM	13506.4	10117.2	4468.7	6728.1	2209.2	37029.6
PEAS	9004.2	6744.8	2979.2	4485.4	1472.8	24686.4
VEGETABLE	5402.5	4046.9	1787.5	2691.2	883.7	14811.8
LINSEED	1800.8	1349	595.8	897.1	294.6	4937.3
PERENNIAL	2251.1	1686.2	744.8	1121.3	368.2	6171.6
RABI CROPS	75185.3	56319.2	24875.9	37452.9	12298	206131.3
OPTIMAL ALLOCATION OF SURFACE WATER (Hectare-Meter)						
Jan	7642.79	5725.00	2528.70	3371.82	1250.12	20518.44
Feb	6185.46	4633.35	2046.53	3081.21	1011.75	16958.30
March	3570.30	4213.80	1358.70	1461.10	821.41	11425.31
Oct	4394.30	4402.34	1672.30	1672.30	961.30	13102.54
Nov	7563.11	5665.31	2502.34	3371.83	1237.09	20339.67
Dec	7632.43	5717.24	2525.28	3371.83	1248.43	20495.21
TOTAL	36988.39	30357.03	12633.85	16330.09	6530.11	**102839.48**
OPTIMAL ALLOCATION OF GROUNDWATER (Hectare-Meter)						
Jan	0.00	0.00	0.00	435.36	0.00	435.36
Feb	0.00	0.00	0.00	0.00	0.00	0.00
March	2702.96	485.31	716.88	1663.84	204.70	5773.69
April	488.49	365.91	161.62	243.32	79.90	1339.24
May	643.81	482.25	213.01	320.69	105.31	1765.08
June	81.04	60.70	26.81	40.37	13.26	222.18
July	58.53	43.84	19.36	29.15	9.57	160.46
Aug	40.52	30.35	13.41	20.18	6.63	111.09
Sep	207.10	155.13	68.52	103.16	33.87	567.79
Oct	2005.02	391.20	444.99	1389.44	85.42	4316.07
Nov	479.48	359.16	158.64	238.84	78.43	1314.55
Dec	245.37	183.80	81.18	122.22	40.13	672.70
TOTAL	6952.32	2557.65	1904.43	4606.58	657.22	16678.21

It can be seen from the water utilization that the surface water is again under-utilized in all the zones during *Rabi* season. This under-utilized water can be further used in increasing the irrigation intensity in the Tawa canal command.

8.8 CONCLUDING REMARKS

Application of distributed conjunctive use model has been demonstrated for realistic water resources system in Tawa Command Area. Different strategies have been formulated with the objectives of increasing the total benefits, solving problems of rising groundwater levels in Zone-3, and depleting groundwater table in Zone-1. The model has been run for different strategies and optimal allocations of resources have been estimated. Simultaneously, the response of groundwater system has been evaluated for existing conditions of resources allocation in the command and optimal scenario of resources allocations. Designed and existing resources allocation scenarios are evaluated considering conjunctive use approach. The effect of land use dynamics has been incorporated in different strategies by changing the irrigation intensity and increasing area under Wheat crop in Rabi season and by introducing shift from Paddy to Soyabean in Kharif season.

Two water supply approach i) percent reduction in Zone-3, ii) percent diversion from Zone-3 to Zone-1 have been tested over existing cropping pattern and irrigation intensity scenario. The surface water from Zone-3 has been reduced by 20% to 100% in first approach and then the same amount has been diverted to Zone-1 in addition to its regular supply in second approach. Observing the potential for expansion in irrigation intensity in Rabi season, its value has been increased by 13% and the water diversion strategies have been tested with additional irrigation intensity scenario.

Further, all strategies have been compared with respect to the criteria, like total benefits, benefits per unit cultivated area, benefits per unit water utilized, surface water and groundwater utilization levels along with special emphasis on groundwater pumping from Zone-1 and Zone-3. The comparison of obtained results shows that the scenario of increased irrigation intensity in Rabi season and 100% diversion from Zone-3 to Zone-1 are optimal and practically feasible. To improve the surface water utilization level, a spatio-temporal conjunctive use approach has been proposed and evaluated. This approach has been found to be the best suited for Tawa Command Area.

Potential of developed distributed conjunctive use model in optimally managing the water deficit scenario has been evaluated by reducing the groundwater availability. The model results indicate reduction of only 61.131 Million Rupees (0.7%) in total benefits and increase in benefits per unit water utilized. The analysis of amount of deficit supply given by the model indicates that developed model allocates deficit water in the time period when it will have minimum effect on yield of particular crop. The study also analysed the existing cropping pattern based on the remote sensing derived crops. The optimal allocation for the RS derived cropping pattern was separately done. Finally, the study concludes that the proposed optimal strategy (Strategy-19) based on distributed conjunctive use model has a capability to transform the Tawa Command into a profitable, environmentally sustainable water resources system, subject to implementation of suggestions and strategies by the concerned command authority.

CHAPTER 9

CROP IDENTIFICATION, AND ASSESSMENT OF WATER AVAILABILITY, UTILIZATION AND YIELD

9.1 INTRODUCTION

Agricultural crop water management at command level requires huge involvement of manpower, infrastructure and money. Optimal management of available water resources in a command primarily requires correct assessment of water requirement by different crops i.e. crop water requirement. When water supplies are abundant and environmental pollution and degradation is of least concerned, water managers can afford to be lax in its management. But, with ever increasing population and subsequent need for water for food, there will be few places in the country where we have water luxury. This calls for integrated water management where all pertinent factors can be considered in the decision making process. Such a holistic approach requires not only supply management, but also demand management. But for sound management and planning of water resources, one requires good and reliable information on water use. The task of providing reliable and accurate information from scales of farmer fields to entire river basins, encompassing millions of hectares of irrigated land, is far from trivial. Until 1960s, this information was acquired solely by conventional methods using topographic and cadastral maps as a base. The availability of aerial photographs and the development of interpretation techniques in the late 1960s accelerated these survey efforts to a considerable extent. With the development of aerial and space borne multispectral sensors, it is now possible to acquire multispectral data from a fairly large area in the narrow and discrete bands of the electromagnetic spectrum on a repetitive basis.

Remote sensing is the art and science of obtaining information about an object, area or phenomenon through the analysis of data acquired by a device that is not in contact with the object, area or phenomenon under investigation. Remote sensing can produce high spatial coverage of important components in the water balance for large areas, but at the cost of a rather sparse temporal resolution. Remote sensing data acquired from space-borne platforms, owing to their wide synoptivity and multispectral acquisition, offer unique opportunities for the study of soils, land use/land cover and other parameters required for water demand assessment of large command areas. Water demand assessment of an area requires a thorough understanding of the water balance components. As water is highly manageable in irrigation systems, a thorough knowledge of all terms of the water balance is essential for understanding how the system functions hydrologically, and how productivity and sustainability can be improved. For a pragmatic water balance study, the availability of accurate and up-to-date land use/land cover information is central to water resources management, planning and monitoring programmes. The hydrological land use maps are helpful in finding out the spatial distribution of various land use or land cover categories and their percentage area coverage, to act as the basic information needed for efficient utilization and management. Information on the rate and kind of changes in the use of land resources is essential for proper planning and to regularize the use of such resources. Traditional methods of land cover mapping have been limited to field surveys that are time consuming and uneconomical with data collected over long time intervals. The methods are particularly inefficient and impractical for real-time large area land use/land cover mapping. Satellite remote sensing images due to their synoptic view, map like format and repetitive coverage are a viable source of gathering effective land cover information. Typically, the pixels of the remote sensing image are grouped into meaningful and homogenous land cover classes using digital image classification.

The evaporation of moisture from the soil and transpiration from vegetation (termed collectively Evapotranspiration, or ET) of a catchment is related to the systematic distribution of moisture and land cover over its extent. Knowing the way moisture and ET are distributed is a key factor in the successful use of water balance studies in catchment. A large number of empirical and semi-empirical methods have been developed to estimate the component of the water balance attributable to ET. The standard methods use climatological data to estimate a potential ET that would occur if water were not limiting and use simple water balance methods to both modify the potential to an actual ET as well as to estimate the available water. However, in catchments with reasonable topographic variation, even if the regional potential ET based on the state of the atmosphere and intensity of solar radiation could be estimated accurately, the actual ET will not be uniform spatially. Estimation of crop evapotranspiration is essential for computing the soil water balance and irrigation scheduling. Crop evapotranspiration is governed by weather and crop condition. Most of the current water demand models are a non-spatial model, which uses point data of reference evapotranspiration and the crop coefficient values from available literature (Doorenbos and Pruitt, 1977). However, the climatic data used to measure ET are highly spatially variable. Also the land use and the crop condition can vary from field to field, thus affecting the crop coefficients and there by crop evapotranspiration rates. Hence, using crop coefficient values from available literature may provide a practical guide for scheduling irrigation, but considerable error in estimating crop water requirement can occur due to their empirical nature (Jagtap and Jones, 1989). The advantage of remote sensing derived crop coefficient over traditional crop coefficient is that it represents a real-time crop coefficient that responds to actual crop conditions in the field and captures the between field variability. Also the identification of different crops and their acreage is a prerequisite in estimating the actual crop water requirement.

In this chapter, major crops were identified using satellite imageries and GPS sampling and then relationships were developed between crop coefficients of identified crops in the command and normalized difference vegetation Index (NDVI) from remote sensing data, as both are affected by leaf area index and fractional ground cover, before estimating the crop evapotranspiration. Finally, the supply (rainfall, canal irrigation) and demand (crop evapotranspiration) has been analyzed for the Tawa canal command before suggesting optimal allocations of the water.

9.2 MATERIALS AND METHODS

9.2.1 Tawa canal system

Tawa canal system, with a gross command area of about four lakhs hectare, comprises of two irrigation systems viz. Left bank canal (LBC) and Right bank canal (RBC). LBC is originated from the left bank of the Tawa dam running towards west and RBC towards east. It is a gravity based irrigation system draining north and north-west up to the Narmada river flowing east to west in the northern part of the command (Figure 9.1). The tail end of the LBC reaches Harda district irrigating about 1,86,162 ha of land. There are three distinct crop seasons practiced in the command. Kharif crop season is overlapped with the monsoon months and mainly rainfed. The sowing for the kharif crops (kharif paddy; kharif soyabean) are generally started in the months of June-July and harvested by October-November. Immediately after harvesting of kharif crops, people go for Rabi crops (Winter crops). The Rabi season starts by the months of October-November up to the months of February-March. Rainfall during this time is scanty in the command area, and hence, the Rabi crops are mainly dependent on the canal water supply and groundwater. Apart from the two major crop seasons, summer crops (vegetables) are grown in the command where ever provisions of irrigation available. The design cropping intensity in the LBC is 138% of the CCA (Kharif-67%; Rabi-67%; Summer-4%), whereas the cropping intensity in the RBC is about 125%

(Kharif-58%; Rabi-67%; Summer-nil). The existing cropping intensity in the LBC and RBC is about 165% and 154% respectively. The design and existing cropping intensity with corresponding crop acreage of the two irrigation canals is provided in Table 9.1 and Table 9.2 respectively.

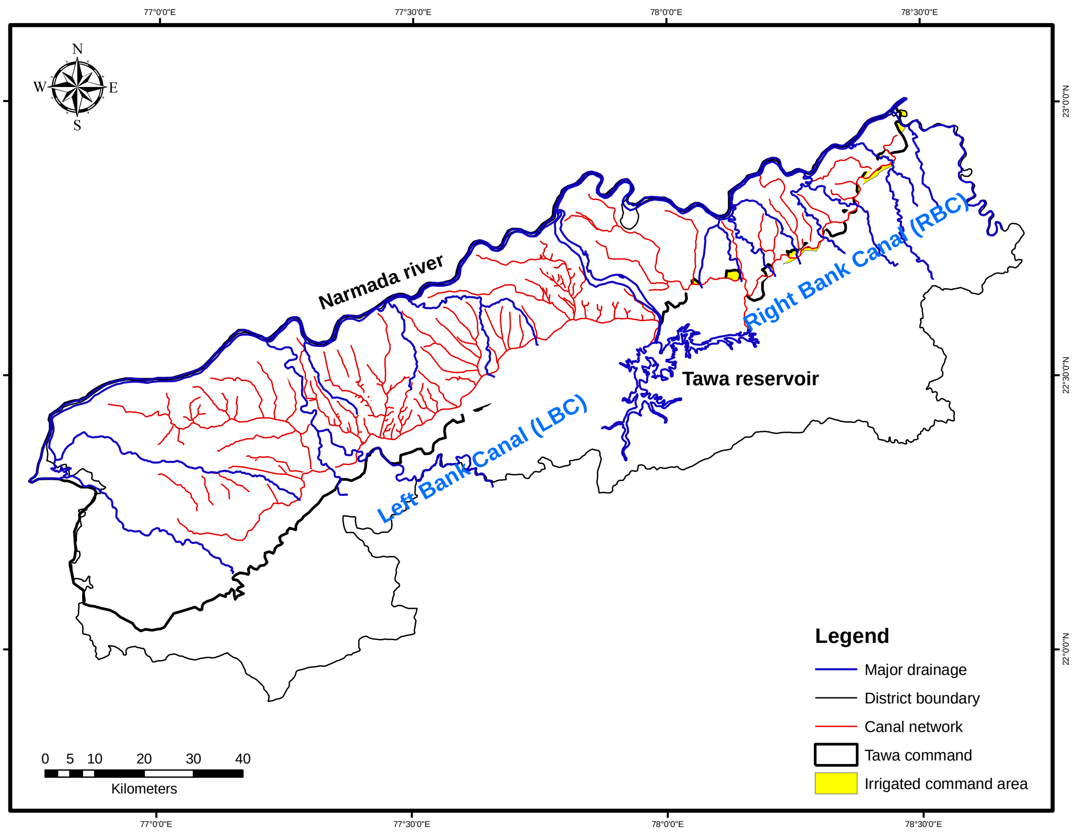


Figure 9.1 Tawa irrigation system

Table 9.1 Design cropping intensity in the Tawa command

Sl. No.	Name of Canal	Design crop intensity		
		Season(s)	% of ICA	Area in hectare
1.	Left Bank Canal C.C.A. 1,86,162 ha; G.C.A. 3,04,736 ha;	Kharif	67	124,729
		Rabi	67	124,729
		Summer	4	7,446
	Sub-total =		*138*	*256,904*
2.	Right Bank Canal C.C.A. 60,702 ha; G.C.A. 96,949 ha;	Kharif	58	35,207
		Rabi	67	40,670
	Sub-total =		*125*	*75,878*
	Grand Total =			**332,781**

Table 9.2 Existing cropping intensity in the Tawa command

Sl. No.	Name of Canal	Existing crop intensity		
		Season(s)	% of ICA	Area in hectare
1.	Left Bank Canal C.C.A. 1,86,162 ha; G.C.A. 3,04,736 ha;	Kharif	87	161,961
		Rabi	74	137,760
		Summer	4	7,446
	Sub-total =		*165*	*307,167*
2.	Right Bank Canal C.C.A. 60,702 ha; G.C.A. 96,949 ha;	Kharif	80	48,562
		Rabi	74	44,919
	Sub-total =		*154*	*93,481*
	Grand Total =			**400,648**

The cropping pattern is an important component of any farming system. It is the proportion of area under various crops at a point of time. The Tawa irrigation system commissioned in the year 1978. The design cropping pattern during conceptualization of the project was given in Table 9.3. The major crops planned in the design cropping pattern were paddy (30%), jowar (15%), cotton (5%), groundnut (5%), pulses (5%), sugarcane (4%), fodder (2%), and vegetables (1%) during kharif seasons, whereas wheat (55% of CCA) replaced paddy during rabi season. With time, due to several factors, deviation is found in the cropping pattern of a command area. The primary factor determining a farmer’s choice of cropping pattern is the rate of return; other contributing factors include agro-climatic conditions, farm programmes, conservation programmes, and environmental regulations (Rao and Rajput 2009; Pakhale et al., 2010). In the Tawa canal command, not only the cropping intensity has been raised but also the variety of crops grown are also changed. Kharif soyabean, maize, and other profitable crops are introduced in place of paddy and wheat. The existing cropping pattern presently followed in the command is provided in Table 9.4

Table 9.3 Design cropping pattern of Tawa command

Season	Crops	LBC		RBC	
		Percent of Crop	Area (ha)	Percent of Crop	Area (ha)
Kharif	Paddy	30	55849	30	18211
	Cotton	5	9308		0
	Jowar	15	27924	15	9105
	Groundnut	5	9308	5	3035
	Pulses	5	9308	5	3035
	Vegetables	1	1862	1	607
	Sugarcane	4	7446		0
	Fodder	2	3723	2	1214
Total		**67**	**124729**	**58**	**35207**
Rabi	Wheat	55	102389	55	33386

Gram	7	13031	7	4249
Peas	2	3723	2	1214
Vegetables	1	1862	1	607
Linseed	2	3723	2	1214
Total	**67**	**124729**	**67**	**40670**

Table 9.4 Existing cropping pattern of Tawa command

Season	Crops	LBC		RBC		Tawa command	
		Percent of Crop	Area (ha)	Percent of Crop	Area (ha)	Percent of Crop	Area (ha)
Kharif	Paddy	25	46541	25	15176	25	61716
	Cotton	5	9308	-	-	4	9308
	Jowar	7	13031	7	4249	7	17280
	Groundnut	5	9308	5	3035	5	12343
	Maize	8	14893	8	4856	8	19749
	Pulses	5	9308	5	3035	5	12343
	Soyabean	30	55849	30	18211	30	74059
	Sugarcane	2	3723	-	-	2	3723
Total		**87**	**161961**	**80**	**48562**	**85**	**210523**
Rabi	Wheat	42	78188	42	25495	42	103683
	Gram	20	37232	20	12140	20	49373
	Soyabean	10	18616	10	6070	10	24686
	Vegetables	1	1862	1	607	1	2469
	Linseed	1	1862	1	607	1	2469
Total		**74**	**137760**	**74**	**44919**	**74**	**182679**

9.2.2 Data used

9.2.2.1 Satellite data

Two LISS III (24m x 24m) images and Nine AWiFS (60m x 60m) images on-board IRS P6 were procured from NRSA, Hyderabad for generating land use/ land cover map. Maximum likelihood supervised classification technique was used to separate the interest class (irrigated agriculture) and NDVI. One scene for each month of *Rabi* season was used for the development of spatially and temporally distributed ET_c map. The dates of nine AWiFS images covering entire rabi period are 23rd October 2011, 11th November 2011, 21st November 2011, 10th December 2011, 24th December 2011, 12th January 2012, 05th February 2012, 20th February 2012 and 10th March 2012. These images were used for NDVI profiling. The temporal dates have been considered based on quality image availability starting from pre-sowing period (23rd October 2011) to crop harvest (10th March 2012).

9.2.2.2 Rainfall data

Daily rainfall data of six consecutive months (from 1st October 2011 to 31st March 2012) were collected from the Tawa canal command authority.

9.2.2.3 Canal Flow data

Canal flow data of six consecutive months (from 1st October 2011 to 31st March 2012) of the head regulators were collected from the Tawa Reservoir Authority and were used in the water demand and supply analysis of the command.

9.2.2.4 Crop data

Crop data of six consecutive months (from 1st October 2011 to 31st March 2012) were collected from the District Authority.

9.2.2.5 Ground truth data

The Survey of India topographical sheets of 55 series nos. F/2, F/3, F/6, F/7, F/9, F/10, F/11, F/13, F/14, F/15, J/1, J/2, J/3, J/5, J/6, J/9, J/10, B/15 and the command area map supplied by Tawa canal command authority, Bhopal were used to prepare the base map and to finalize the different land use/land cover classes.

A field visit of the study area (Tawa command, Madhya Pradesh) was also carried out for collecting information about the location of the various land use and land cover classes present in the area including different crops grown during Rabi season (December 25, 2011). A hand-held GPS was utilized to capture location specific crop details for different crops on sample basis in and around the command area. The GPS sample points collected during field visit is presented in Appendix II. The coding used during the visit is given in Appendix III.

9.2.2.6 Image Processing System used

The following computational systems were utilized for image processing and computational work.

1. ARC/INFO version 9.3 and ERDAS imagine version 9.2 GIS software.
2. Contex FSS (8000) scanner.

9.2.3 Concepts and methods

9.2.3.1 Preparation of land use/land cover map

The following activities are particularly relevant to successful transformation of remotely sensed data into different land use/land cover classes.

1. Collection of Remote Sensing data (cloud-free and of appropriate time)
2. Collection and study of collateral data
3. Ground truth collection
4. Digital Image Processing and post-classification verification
5. Generation of output

Two scenes of IRS P6 LISS III of 27th January 2011 were selected for the land use/land cover mapping of (*Rabi)* seasons for the command area. The different steps involved to generate land use/land cover map is shown in Fig. 9.2. The Survey of India (SOI) topographical sheets covering the present study area were scanned and geometrically rectified. The satellite data were geometrically corrected with respect to the SOI toposheets to impart proper projection, uniform scale and orientation. Supervised classification technique with maximum likelihood algorithm was used for image classification. Here the ground truth information is fed to the computer which is called training process. Ground Truth (GT) information acquired from field visits and topographical sheets was fed to the computer in the form of spectral signatures and there by the segmentation of the categories for the entire scene was performed. Finally the class statistics of the training classes were used to compute the probability density function for each pixel of the input scene. Pixels having the maximum probability of falling into a particular class are assigned the same class value. Thus using this algorithm the entire input scene was classified into various land use/land cover categories. But very often-spectral confusion is conceivable due to high moisture content and concomitant greenery, which are likely to get away without notice and misplaced into different classes. Hence, recoding of different categories was done with respect to the ground truth information generated from toposheets and a final output map representing the land use/land cover map was developed. A proper colour combination was then assigned to different categories.

9.2.3.2 Identification of crops

The methodology consisted of selection of the datasets, pre-processing of the satellite data, generating LULC map and NDVI map, Mapping NDVI profile, accuracy assessment of classified images, and finally crop map for discriminated crops. Flowchart showing broad methodology followed in the study is shown in Fig.9.3. The nine AWiFS scenes were pre-processed using image to image registration and atmospheric corrections. Nine temporal AWiFS images were stacked in chronological order of their dates (each image represents as a band in the stacked image) before generating NDVI map. Pixels of the interest class i.e. irrigated agriculture were masked to the stacked NDVI temporal image where every band represents to a particular temporal dates. Sample NDVI values were collected to develop the

NDVI profile corresponding to the GPS points of sample crops collected during field visit. Finally, major crops were identified and discriminated based on the NDVI profile and crop calendar of different crops grown in the command area. The main principle of detecting vegetation using NDVI is the high absorptivity of vegetation pigments (chlorophyll) in the red spectral region and high reflectance in the near infrared spectral region. NDVI is highly correlated to the photosynthetic activity and indicates the greenness of the vegetation. Hence NDVI has been used for this temporal and multispectral data set for enhancement of the vegetation class and discriminating specific crops. The NDVI is calculated as given in Eq. (9.1):

$$NDVI = \frac{\rho_{NIR} - \rho_{RED}}{\rho_{NIR} + \rho_{RED}} \qquad (9.1)$$

Where, ρ_{NIR} = near infra-red band of sensor, and ρ_{RED} = red band of sensor.

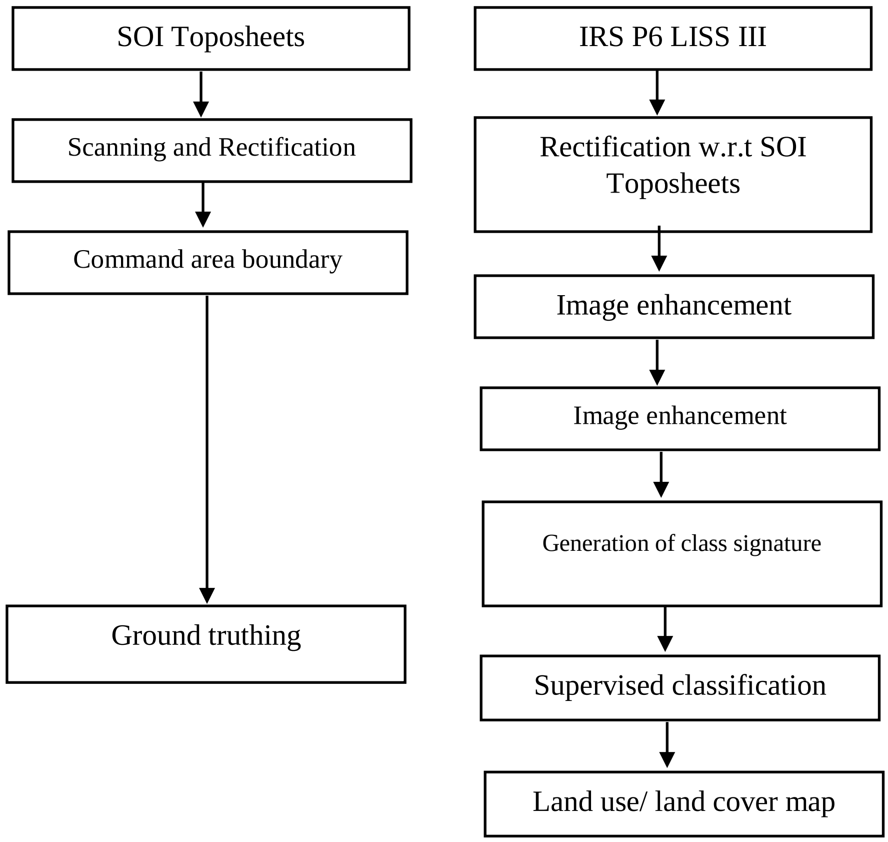


Figure 9.2 Flow chart for land use/land cover mapping

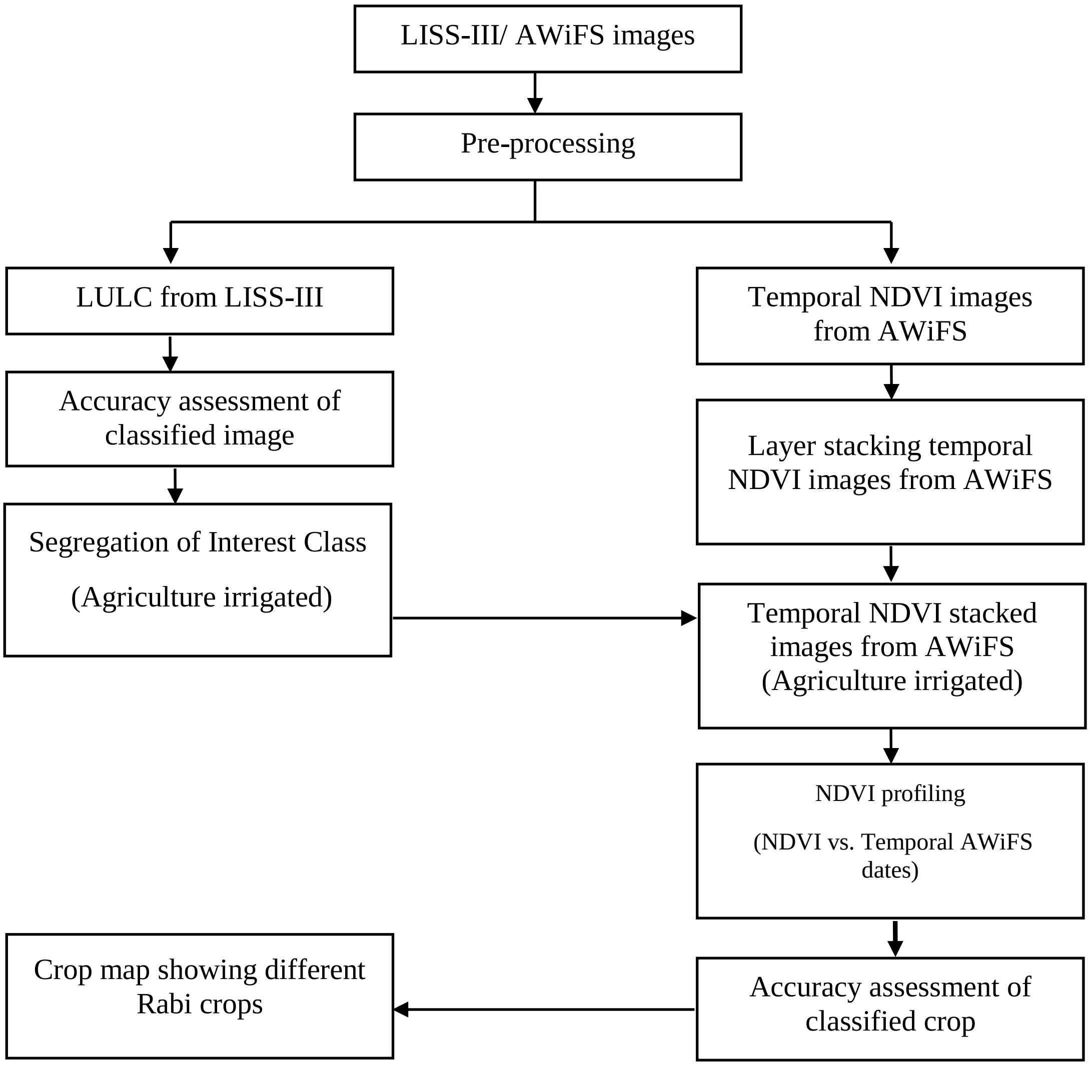


Figure 9.3 Flowchart showing methodology for the temporal crop discrimination

9.2.3.3 Evapotranspiration estimation using RS and GIS

The following steps were carried out to estimate the crop evapotranspiration (ETc map) from the remotely sensed data.

1. Collection of Multidate Remote Sensing (RS) data
2. Image rectification and atmospheric correction
3. Vegetation index model development
4. Crop coefficient (Kc) map generation
5. ETc map generation

Multidate remote sensing data of AWiFS were taken for the evaluation of the evapotranspiration. One scene(s) for six consecutive months of *Rabi* season were taken for the study. The satellite data were geographically registered onto one another, with respect to LISS III data. From the classified scene representing the *Rabi* season, only the pixels representing the identified crops were chosen by a process called masking. NDVI values were calculated for each pixel representing identified crop.

For each scene(s) five-sample areas, and from each area few pixels were chosen and corresponding NDVI values were noted down. The average of the NDVI values picked from each scene(s) was considered to be the representative value of NDVI for that scene(s). Thus for nine scenes, nine NDVI values were obtained. Regression equations between the NDVI values and corresponding crop coefficients of identified crop taken from literature for the six consecutive months were developed. Using these empirical equations, crop coefficient maps (Kc map) were generated. Daily reference evapotranspiration (ET_0) values for the six months were calculated using the FAO-56 Penmann-Monteith equation (CROPWAT 8.0). Monthly average value of the ET_0 was multiplied with the crop coefficient maps developed, and thus corresponding crop evapotranspiration maps (ETc map) were generated for six different months involving nine scenes. The flowchart indicating steps to generate Kc and ETc maps is shown schematically in Fig. 9.4 and Figure.9.5.

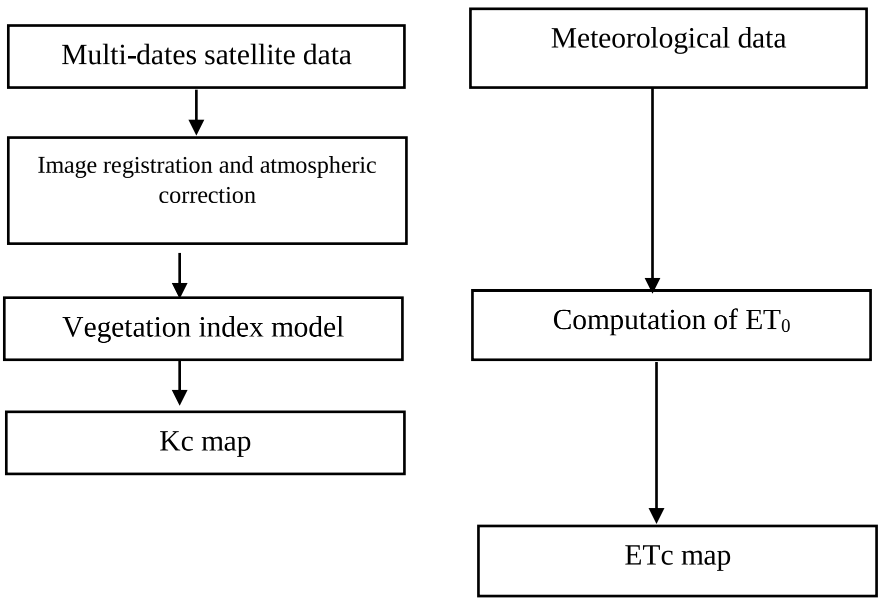


Figure 9.4 Flow chart for crop evapotranspiration (ETc) estimation using RS and GIS

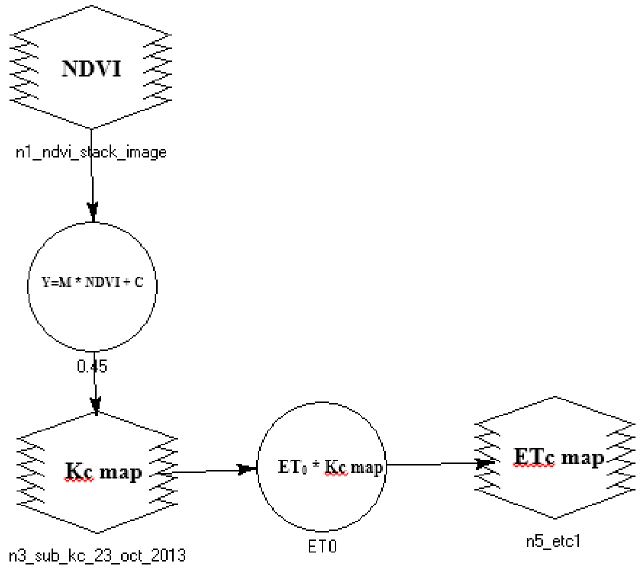


Figure 9.5 Model showing the generation of Kc map and ETc map

9.2.3.4 Water demand and supply assessment

Water demand and supply analysis for the Tawa command was done for the six consecutive months of *Rabi* season (October 2011 to March 2012). In the present study, water demand, which refers to the crop evapotranspiration, was computed from remote sensing. The spatial resolution of AWiFS sensor is 60 m, that means a pixel represents 60 × 60 m^2 in the real ground situation. Spatially distributed pixel-wise crop evapotranspiration computed from satellite image when multiplied with the pixel area gives the total volume of water requirement for that particular pixel. Thus total demand (in volume unit) in the command for each scene was estimated. It was assumed that each scene represents the real ground condition for the whole day on which the satellite passed. There by, total crop evapotranspiration estimated for a particular scene was equivalent to the water requirement for the whole day. Monthly water demand was computed simply by multiplying the total number of days in the month with the scene-wise total water demand for the whole command area. In the months of November, December, and February, two scenes were used. Hence, each scene represents the fortnight of the month.

1.1.1 ETc Map

The water supply of the study area was estimated from daily rainfall and daily canal flow data obtained from Canal Authority. Thus, total daily supply of water (rainfall + canal flow) to the command area was computed taking into account the conveyance losses from the canal. Subsequently, monthly supply was estimated by summing up the daily canal supply and rainfall data. Then monthly water deficit i.e. supply (rainfall + irrigation) and demand (ETc from remote sensing) gap of the command area was computed separately for each month of the *Rabi* season.

9.2.3.5 Water availability and utilization assessment in future

Water availability and crop water demand assessment in the future has been done using the techniques of downscaling, in which GCM based future rainfall and temperature projections are made corresponding to different scenarios. The downscaling techniques has already been discussed in Chapter 5 for the Tawa canal command. The downscaled rainfall and temperature (maximum and minimum) are used while estimating reference evapotranspiration for the present and future periods (2020s, 2050s, 2080s) using Hargreaves method and FAO 56 (CROPWAT 8.0) method.

9.3 RESULTS AND DISCUSSION

9.3.1 Land use/ land cover map

Land use/ land cover map for the Tawa command was generated using LISS-III image (Fig.9.6). Eight land use classes have been considered viz. dense forest, sparsed vegetation, water bodies, waste land, built-up area, exposed river bed including sand, and agriculture which further segregated into irrigated and non-irrigated. Agriculture is the dominant of all the classes with 78% coverage of total area. Built-up area includes major dwelling regions such as Hoshangabad, Itarsi and Harda. Tawa river is meeting Narmada river near Hoshangabad. Left bank canal (LBC) and Right bank canal (RBC) are emerging from the two end of Tawa reservoir irrigating about 60% of the total grossed command area with an irrigation intensity of more than 150%. The different land use classes with their area coverage in the command are presented in Table 9.5. The drainage and canal network in the command indicating northward slope.

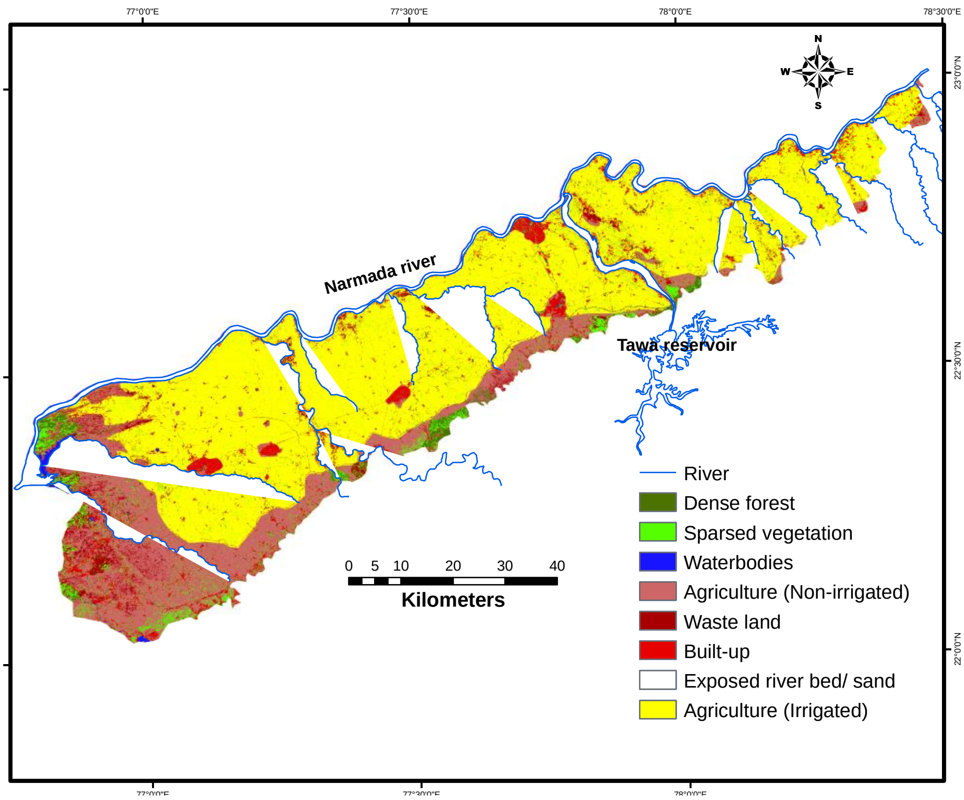


Figure 9.6 Land use/ land cover map of Tawa canal command

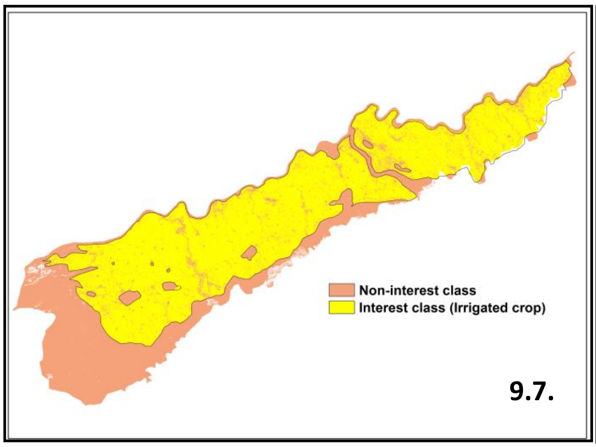
Table 9.5 Area statistics of land use/ land cover of the Tawa canal command

LULC type	Area (km^2)	% cover
Dense forest	58.89	1.46
Sparse vegetation	239.44	5.94
Water-bodies	148.18	3.68
Agriculture (Non-irrigated)	575.76	14.29
Waste land	387.71	9.62
Built-up	423.17	10.50
Exposed river bed/ sand	139.4	3.46
Agriculture (Irrigated)	2057.49	51.05
Total	**4030.04**	**100**

9.3.2 Identification of crops and generation of crop map

9.3.2.1 Development of crop NDVI profile

NDVI profiling is the process of plotting mean NDVI values of different crops for different temporal dates during the entire crop period. In the study, temporal NDVI images from AWiFS data of different dates were generated for the interest class i.e. irrigated agriculture (Fig.9.7 & 9.8)



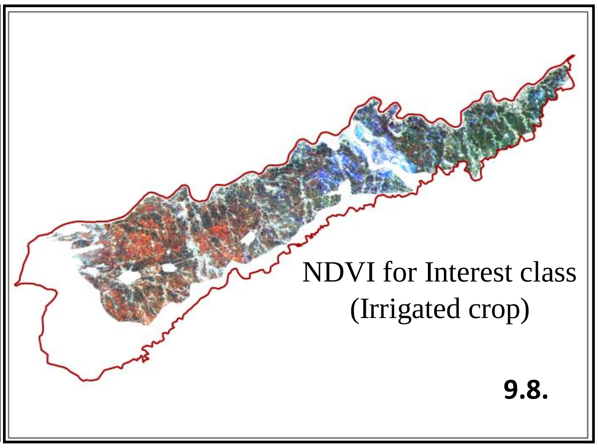


Figure 9.7 Segregation of Interest and Non-interest class. **Figure 9.8 NDVI for Interest class (Irrigated crop)**

All the NDVI images were stacked chronologically to their dates such that every temporal date becoming a respective band in the stacked image. GPS sample points of different crops collected during field visit on 25th November 2011 were superimposed over the image as shown in Fig.9.9. Sample NDVI values were collected from nine scenes from different probable crop signatures from the GPS superimposed images (Figs. 9.10-13). Mean NDVI values was then derived as given in Table 9.6. NDVI values of different crops for different temporal dates have been plotted to develop the NDVI profile for the entire crop period during rabi season (Fig.9.14). Major crops grown in the Tawa command with their crop period is presented in Fig.9.15.

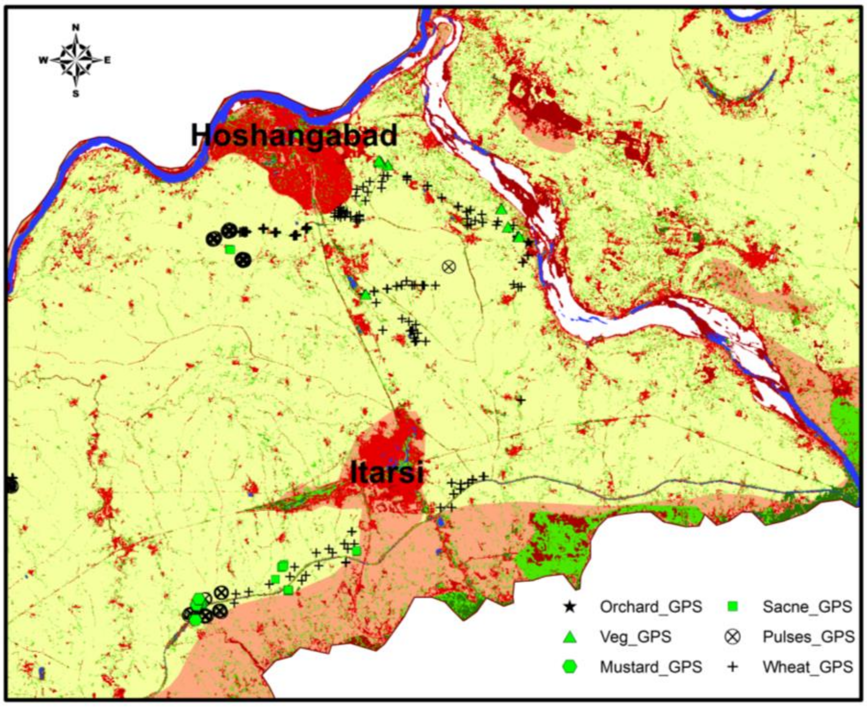
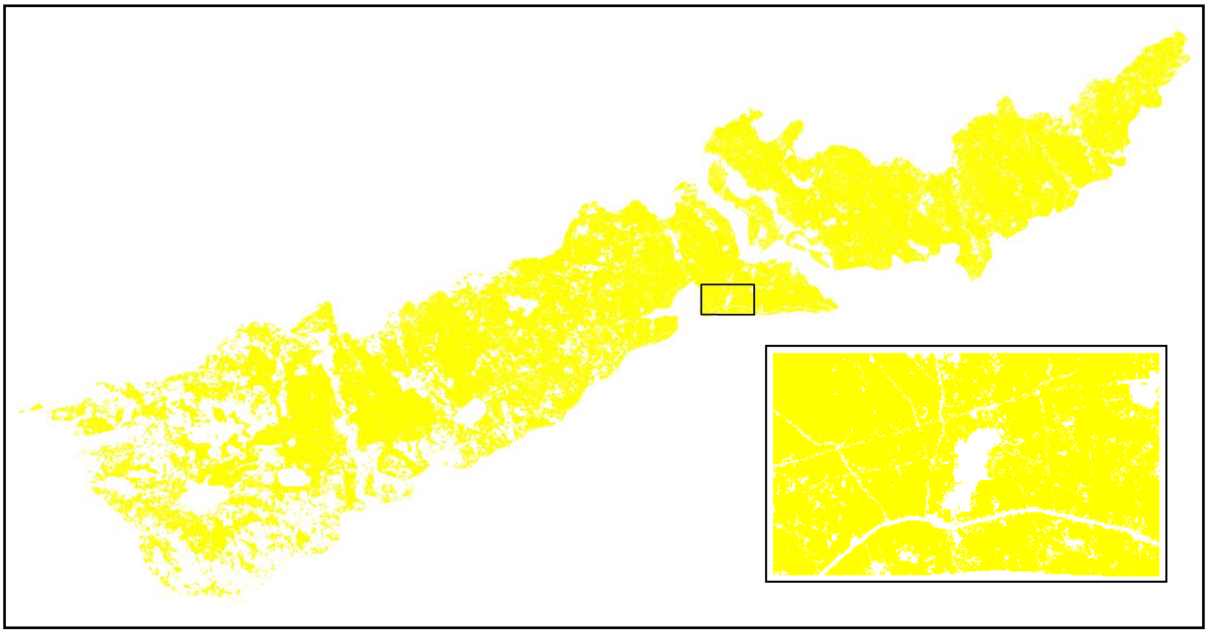


Figure 9.9 Sample crop points taken through GPS superimposed over LULC

Table 9.6 Mean NDVI values of different crops

Temporal AWiFS dates	Wheat	Pulses	Oilseeds	Sugarcane	Others
23rd October 2011	0.1169	0.1766	0.2067	0.3560	0.2260
11th November 2011	0.1392	0.1707	0.2214	0.3585	0.1871
21st November 2011	0.1944	0.3285	0.4672	0.3660	0.2493
10th December 2011	0.2521	0.6895	0.6422	0.4136	0.3495
24th December 2011	0.5125	0.7787	0.7543	0.5522	0.5975
12th January 2012	0.7230	0.7851	0.7318	0.5764	0.3652
05th February 2012	0.6999	0.5771	0.6515	0.6438	0.3909
20th February 2012	0.6487	0.3402	0.5540	0.6519	0.5574
10th March 2012	0.5527	0.2395	0.2659	0.6142	0.3919



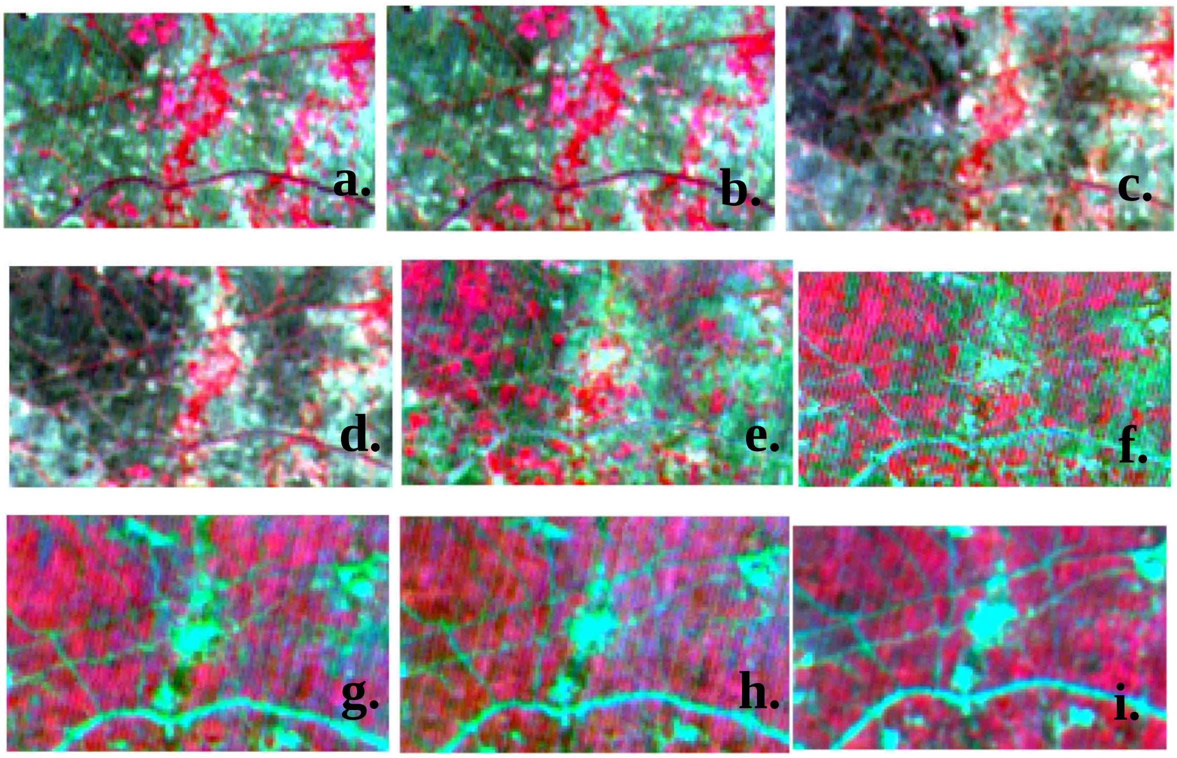


Figure 9.10 Temporal FCC of sample wheat pixel: a. 23rd Oct’11, b. 11th Nov’11, c. 21st Nov’11, d. 10th Dec’11, e. 24th Dec’11, f. 12th Jan’12, g. 05th Feb’12, h. 20th Feb’12, i. 10th Mar’12

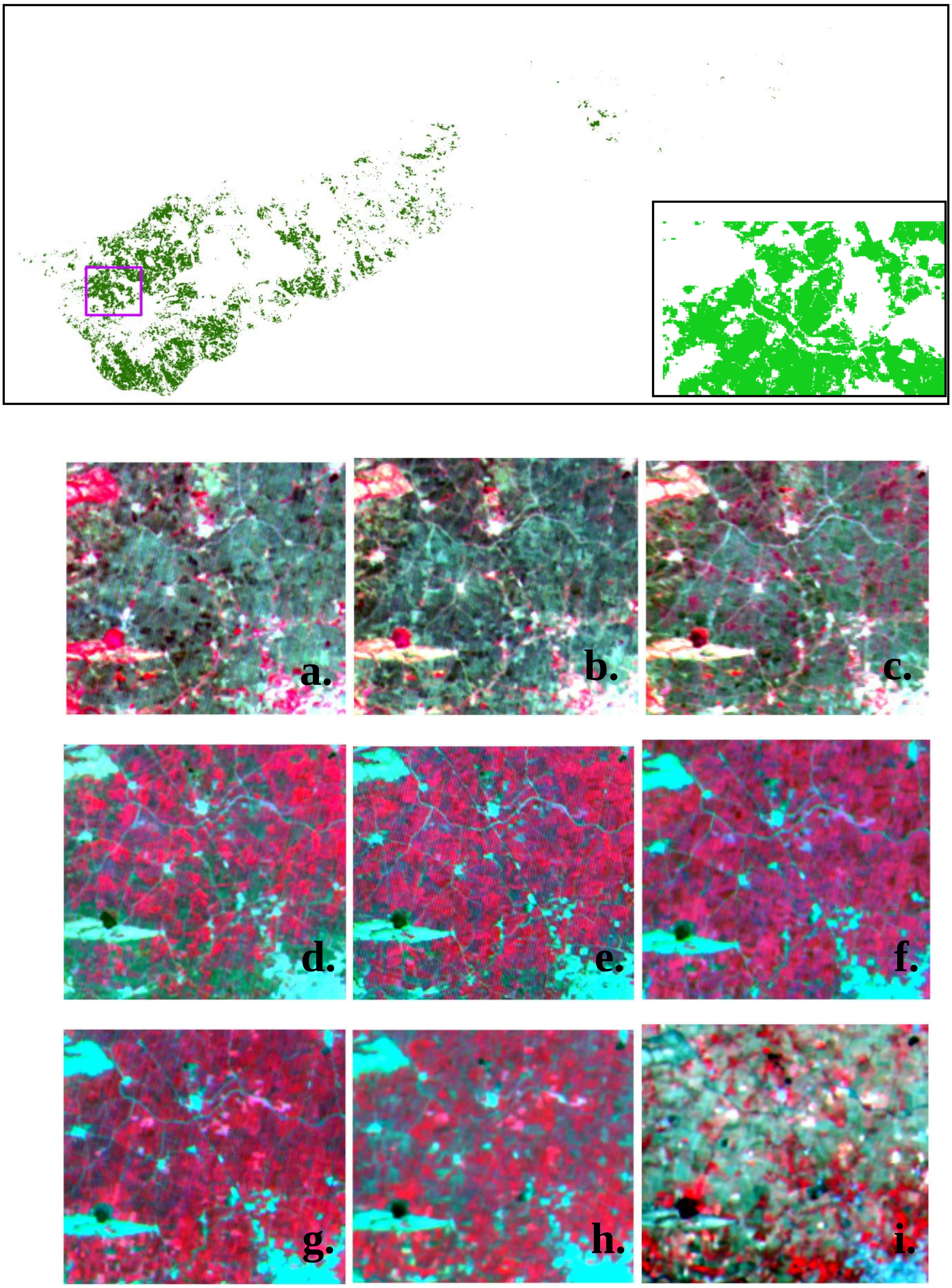


Figure 9.11 Temporal FCC of sample chick-pea pixel: a. 23rd Oct'11, b. 11th Nov'11, c. 21st Nov'11, d. 10th Dec'11, e. 24th Dec'11, f. 12th Jan'12, g. 05th Feb'12, h. 20th Feb'12, i. 10th Mar'12

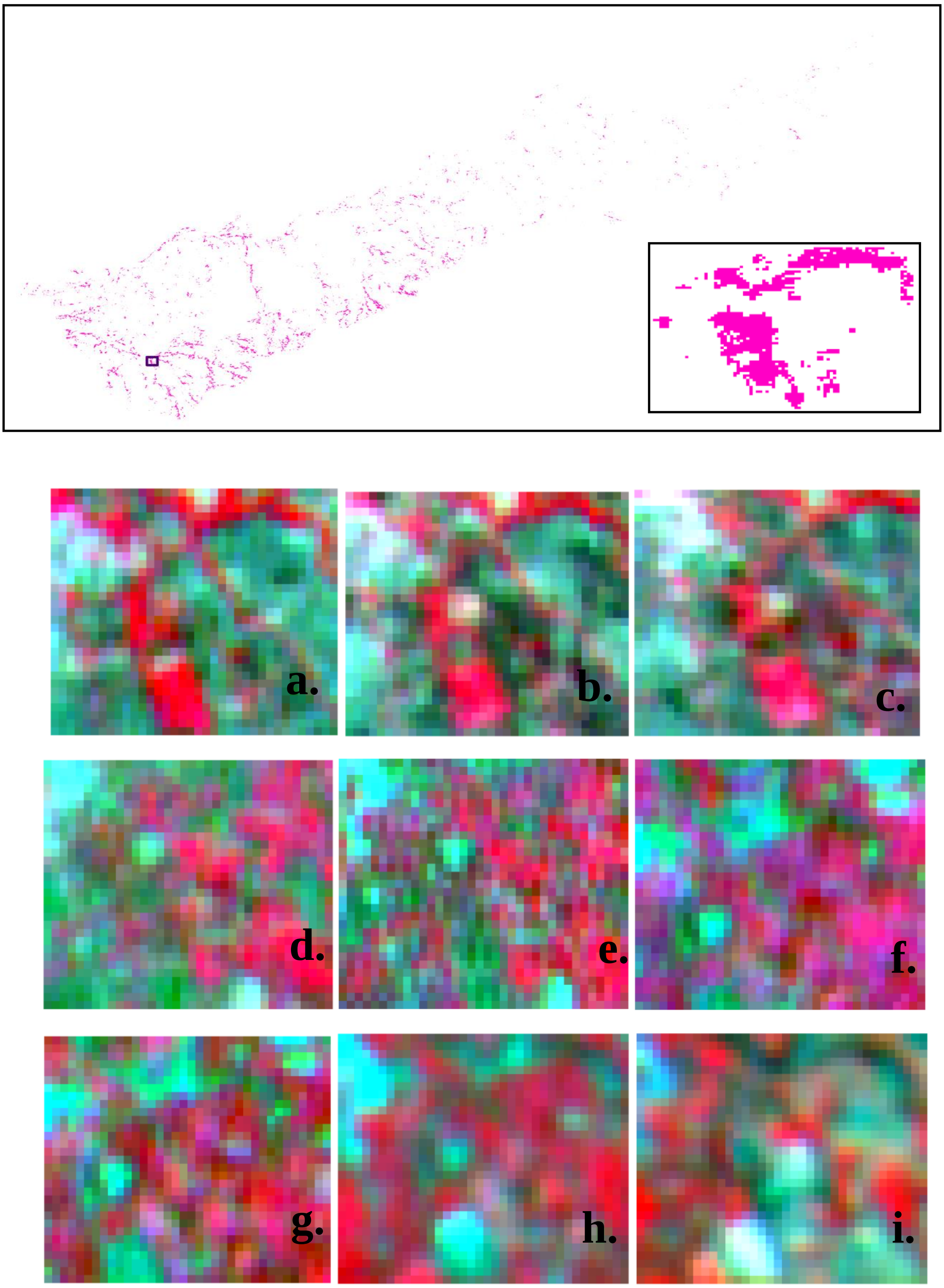
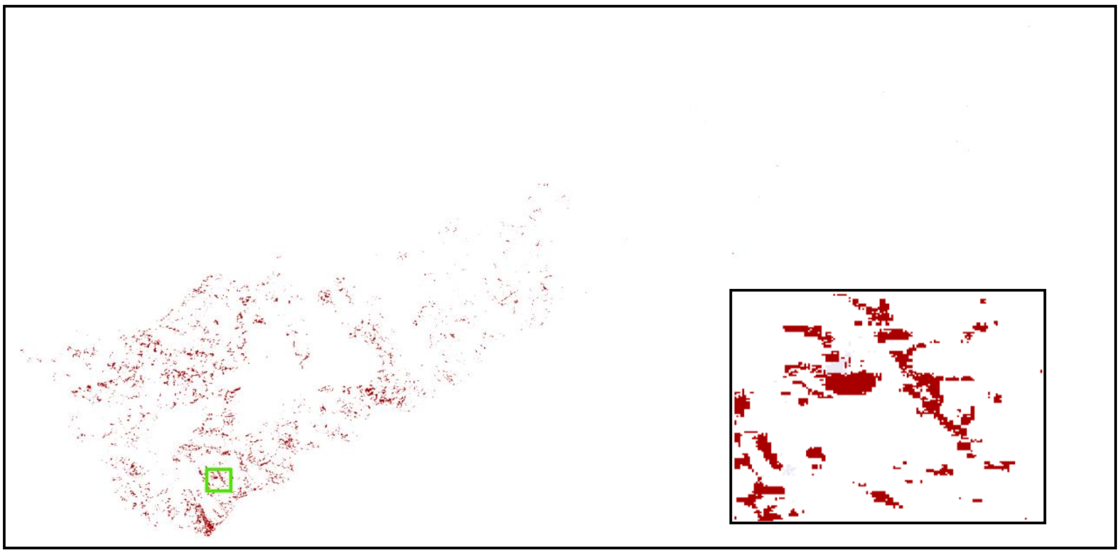


Figure 9.12 Temporal FCC of sample sugarcane pixel: a. 23rd Oct'11, b. 11th Nov'11, c. 21st Nov'11, d. 10th Dec'11, e. 24th Dec'11, f. 12th Jan'12, g. 05th Feb'12, h. 20th Feb'12, i. 10th Mar'12



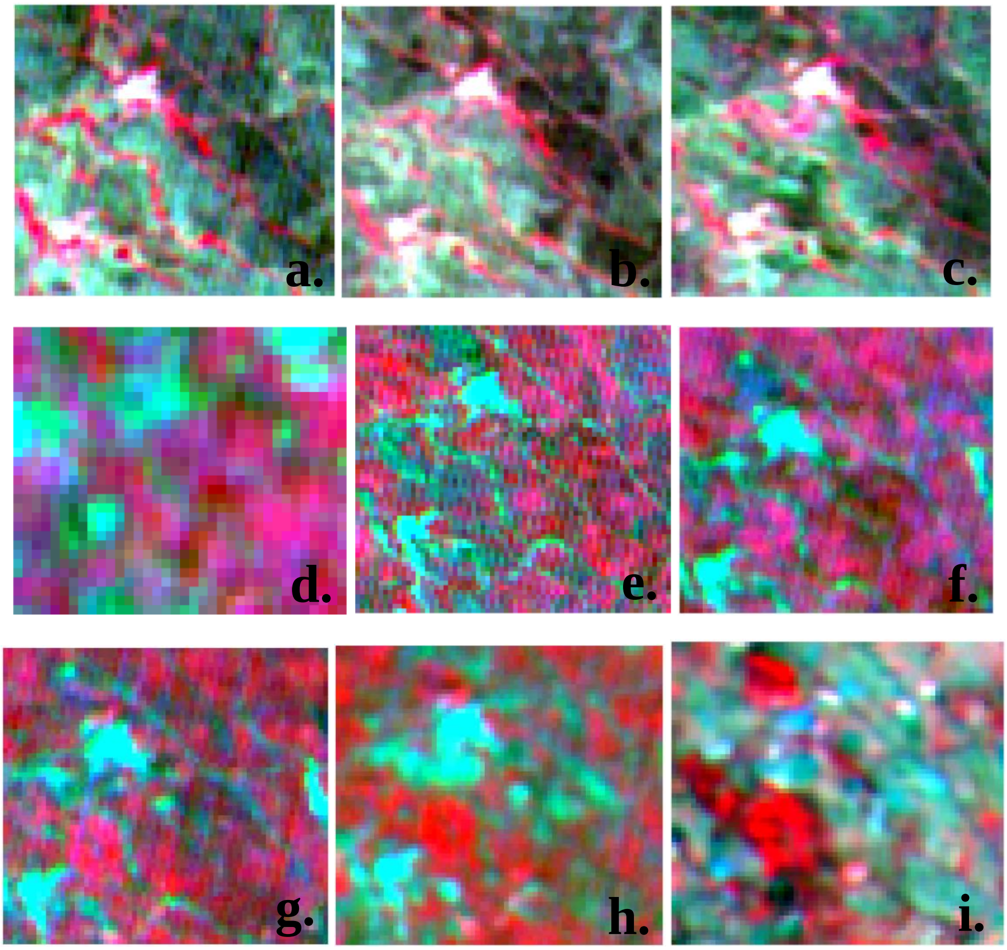


Figure 9.13 Temporal FCC of sample oilseeds pixel: a. 23rd Oct'11, b. 11th Nov'11, c. 21st Nov'11, d. 10th Dec'11, e. 24th Dec'11, f. 12th Jan'12, g. 05th Feb'12, h. 20th Feb'12, i. 10th Mar'12

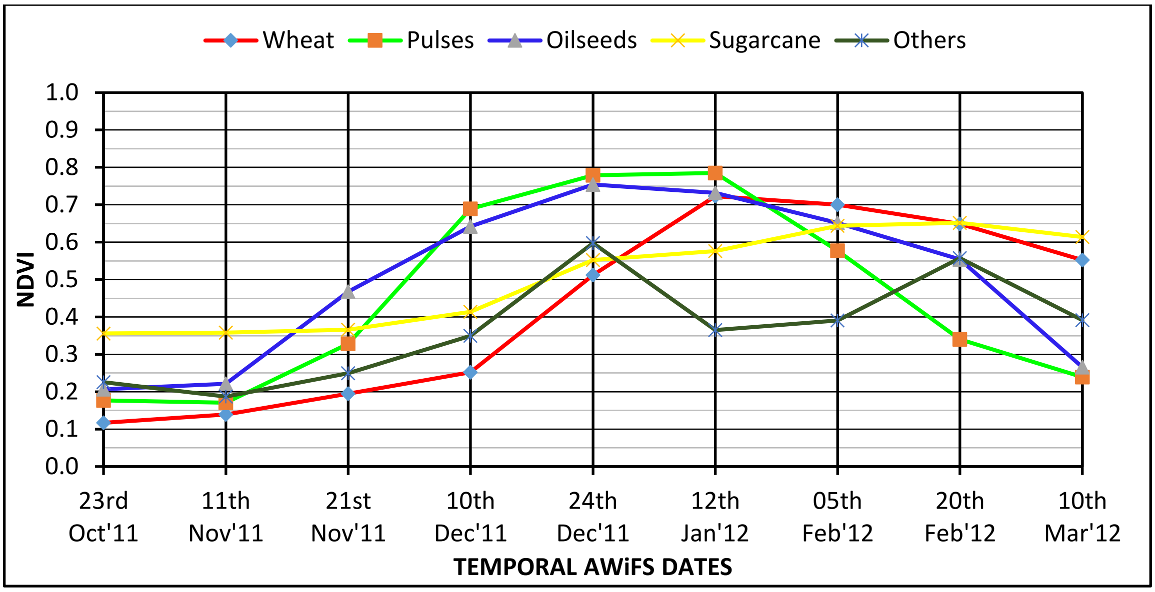


Figure 9.14 NDVI profile of different crops

Crop type/ Crop period	October	November	December	January	February	March
Wheat						
Peas						
Linseed						
Mustard						
Vegetables						
Sugarcane						

Figure 9.15 Crop period for major crops grown during rabi season in the command area

9.3.2.2 Identification of crops for the rabi season

Different crops exhibit different reflectance properties at different growing stages. Further, it is also true that short duration crops (pulses) will achieve early maturity than long duration crops (sugarcane). Keeping these points in mind, NDVI profile indicates following major crops in the command during rabi season: (i) wheat, (ii) chick-pea, (iii) sugarcane, (iv) linseed and (v) crops such as vegetables and orchards. As can be seen in the NDVI profiling (Fig.9.14), short duration crops such as pulses and oilseed are attaining early maturity (higher mean NDVI values) then wheat and sugarcane. Sugarcane is exhibiting a rather straight profile. Spatial distribution of major crops (Fig.9.15) indicates highest coverage for wheat (75%) followed by chick-pea (15%), sugarcane (2.42%) and linseed (2.32%). The details on the spatial distribution of different crops are presented in Table 9.7.

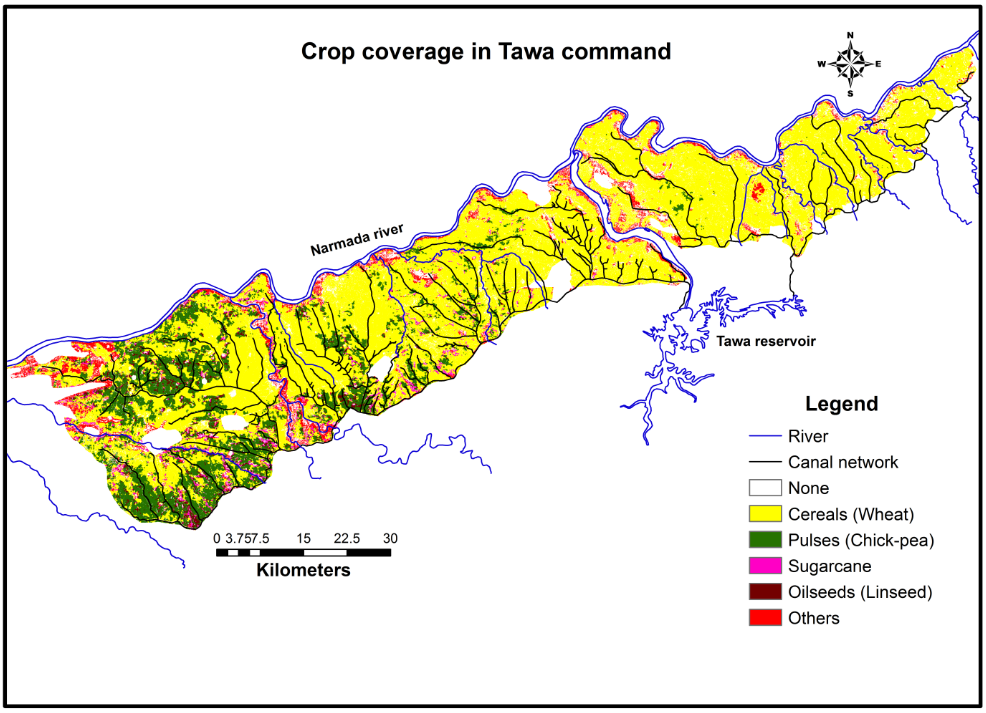


Figure 9.16 Crop map showing major rabi crops

Table 9.7 Area coverage of identified crops

Crop type	Area (Km^2)	% cover
Cereals (Wheat)	1166.15	59.33
Pulses (Chick-pea)	561.87	28.59
Sugarcane	55	2.80
Oilseeds (Linseeds)	36.82	1.87
Others (mainly vegetables, orchards, etc.)	145.73	7.41
Total	**1965.57**	**100.00**

9.3.2.3 Classification accuracy assessment

Any classification is incomplete without assessing its accuracy. Thereby, the study assessed the classification accuracy of the land use land cover from LISS-III image and identified major crops from NDVI profiling from AWiFS images in the command area. Accordingly, 120 sample points were randomly selected from the classified image and comparison was made with the sample GPS points as ground truth. The error matrix, accuracy total with over all classification accuracy and kappa statistics of the classified land use land cover map from LISS-III image is presented in Table 9.8, Table 9.9 and Table 9.10 respectively. Similarly, the error matrix, accuracy total with over all classification accuracy and kappa statistics of the classified crop coverage map of the identified crops from AWiFS images is presented in

Table 9.11, Table 9.12 and Table 9.13 respectively. The overall classification accuracy and kappa statistics for both the classified images suggest a good classification.

Table 9.8 Error matrix of the 120 sample points randomly selected from the classified land use land cover map from LISS-III

Classes	Dense forest	Sparse vegetation	Water-bodies	Agriculture (Non-irrigated)	Waste land	Built-up	Exposed river bed/ sand	Agriculture (Irrigated)	Row Total
Dense forest	3	1							**4**
Sparse vegetation	1	8							**9**
Water-bodies			5				1		**6**
Agriculture (Non-irrigated)				17				3	**20**
Waste land					7	1			**8**
Built-up					1	8			**9**
Exposed river bed/ sand			1				3		**4**
Agriculture (Irrigated)				5				55	**60**
Column Total	**4**	**9**	**6**	**22**	**8**	**9**	**4**	**58**	**120**

Table 9.9 Accuracy totals with overall classification accuracy of the classified land use land cover map from LISS-III

Classes	**Reference totals**	**Classified totals**	**Number correct**	**Producers accuracy**	**Users accuracy**
Dense forest	4	4	3	75.00%	75.00%
Sparse vegetation	9	9	8	88.89%	88.89%
Water-bodies	6	6	5	83.33%	83.33%
Agriculture (Non-irrigated)	22	20	17	77.27%	85.00%
Waste land	8	8	7	87.50%	87.50%
Built-up	9	9	8	88.89%	88.89%
Exposed river bed/ sand	4	4	3	75.00%	75.00%
Agriculture (Irrigated)	58	60	55	94.83%	91.67%
Totals	**120**	**120**	**106**	**-**	**-**
			Overall Classification Accuracy = 88.33%		

Table 9.10 Kappa statistics of the classified land use land cover map from LISS-III

Class Name	Kappa coefficient
Dense forest	0.7414
Sparse vegetation	0.8799
Water-bodies	0.8246
Agriculture (Non-irrigated)	0.8163
Waste land	0.8661
Built-up	0.8799
Exposed river bed/ sand	0.7414
Agriculture (Irrigated)	0.8387
	Overall Kappa statistics = 0.8351

Table 9.11 Error matrix of the 120 sample points randomly selected from the classified crop coverage map from AWiFS

Classes	Cereals (Wheat)	Pulses (Chick-pea)	Sugarcane	Oilseed (Linseed)	Others (Vegetables)	**Row Total**
Cereals (Wheat)	78	6		1	1	**86**
Pulses (Chick-pea)	2	15			1	**18**
Sugar cane	1		3			**4**
Oilseed (Linseed)				3	1	**4**
Others (Vegetables)			1		7	**8**
Column Total	**81**	**21**	**4**	**4**	**10**	**120**

Table 9.12 Accuracy totals with overall classification accuracy of the classified crop coverage map from AWiFS

Classes	**Reference totals**	**Classified totals**	**Number correct**	**Producers accuracy**	**Users accuracy**
Cereals (Wheat)	81	86	78	96.30%	90.75%
Pulses (Chick-pea)	21	18	15	71.43%	83.33%
Sugar cane	4	4	3	75.00%	75.00%
Oilseed (Linseed)	4	4	3	75.00%	75.00%
Others (Vegetables)	10	8	7	70.00%	87.50%
Totals	**120**	**120**	**106**	**-**	**-**
					Overall Classification Accuracy = 86.67%

Table 9.13 Kappa statistics of the classified crop coverage map from AWiFS

Class Name	Kappa coefficient
Cereals (Wheat)	0.7138
Pulses (Chick-pea)	0.7980
Sugar cane	0.7414
Oilseed (Linseed)	0.7414
Others (Vegetables)	0.8636
	Overall Kappa statistics = 0.7581

9.3.3 NDVI based ETc estimation

9.3.3.1 Development of Kc map and ETc map

In this study, a procedure was developed to estimate the realistic spatial crop coefficient based on NDVI. Further, these crop coefficients were used for estimation of spatially and temporally distributed crop evapotranspiration. The pixel level crop coefficient values were estimated from the satellite RS-based crop reflectance values. For the present study, six consecutive months of agricultural season i.e. *Rab*i season was chosen for the estimation of evapotranspiration. The Kc map and ETc map for different months were generated by the digital image analysis of 2011-2012 agricultural season of IRS-P6 AWiFS data of dated 23rd October 2011, 11th November 2011, 21st November 2011, 10th December 2011, 24th December 2011, 12th January 2012, 05th February 2012, 20th February 2012 and 10th March 2012.

9.3.3.1.1 Estimation of NDVI

The average of the NDVI values picked from each scene was considered to be the representative value of NDVI for that scene for a particular crop. Thus for nine scenes, nine NDVI values were obtained for each crop (Table 9.6). The corresponding crop coefficients of each crop were taken from literatures. NDVI values obtained in the month of October and November were minimum since crops were in its initial phase of development. It then increases linearly and touches maximum in the month of January-February signifying maximum crop coverage over the ground. It was also observed that NDVI values decreases as the crop attains maturity.

9.3.3.1.2 Relationship between Kc and NDVI

Regression equations between the NDVI values and corresponding crop coefficient of identified crops taken from literature (FAO 56) for the six consecutive months were developed. The Kc and NDVI values for different scenes used in regression relationship are given in Table 9.14. The regression equations developed for each crop are presented in Figs.9.17. The coefficient of determination (R^2) obtained between Kc-NDVI relations were in the range of about 0.65-0.95. The analysis of regression showed that the equations were highly significant with high R^2 values.

Table 9.14Kc* and NDVI values for different scenes used in regression relationship

Months	Kc_wheat	NDVI_wheat	Kc_chick pea	NDVI_chick pea	Kc_sugar cane	NDVI_sugar cane	Kc_linseed	NDVI_linseed	Kc_Others	NDVI_Others
23-Oct					0.6	0.356				
11-Nov	0.5	0.34	0.25	0.3285	0.8	0.3585			0.27	0.3085
21-Nov	0.6	0.45	0.4	0.6895	1.0	0.366	0.35	0.2272	0.42	0.6395
10-Dec	0.75	0.5125	0.6	0.7787	1.0	0.4136	1.0	0.4422	0.64	0.7287
24-Dec	1.0	0.723	0.45	0.5751	1.15	0.5522	1.15	0.6543	0.45	0.5151
12-Jan	1.15	0.6999	0.35	0.3771	1.25	0.5764	0.35	0.3515	0.32	0.3271
5-Feb	1.0	0.6487			1.25	0.6438				
20-Feb	0.75	0.5527			1.25	0.6519				
10-Mar	0.67	0.5321			1.0	0.6142				

*****Source: FAO 56

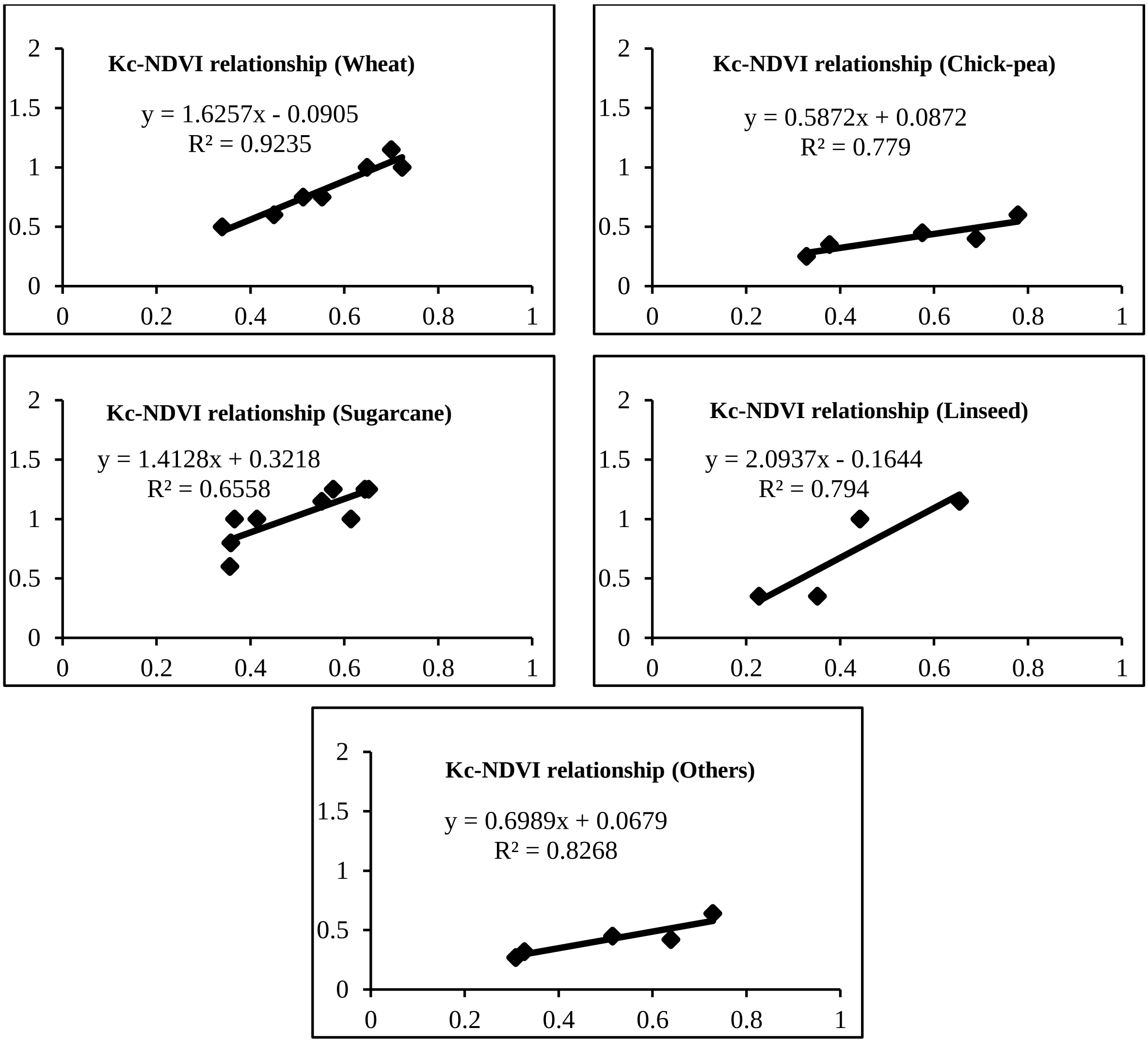


Figure 9.17 Regression curves between Kc and NDVI values for different crops

Using this empirical equations, pixel-wise crop coefficient values from the corresponding NDVI values for six months were computed. Crop coefficient maps (Kc map) generated for different months based on NDVI is given in Fig. 9.18. Climatic data collected from nearest weather station were used to compute the reference evapotranspiration. Daily reference evapotranspiration (ET_0) values for the six months were calculated using the FAO-56 Penmann-Monteith equation. Monthly average value of the reference evapotranspiration was multiplied with the pixel-wise crop coefficient values, and thus corresponding crop evapotranspiration maps (ETc map) were generated for six different months. Crop evapotranspiration map (ETc) generated for six months based on NDVI were presented in Fig. 9.19.

9.3.3.1.3 Relationship between ETc and NDVI

The different crop coefficient and crop evapotranspiration values (scene wise) based on NDVI are given in Table 9.15.

Table 9.15 Scene wise range of Kc values and ETc values (mm) of different crops

Months	Wheat		Pulses		Sugarcane		Oilseeds		Others	
	Kc	ETc	Kc	ETc	Kc	ETc	Kc	ETc	Kc	ETc
23rd October 2011					0.3-1.05	2.25-3.15				
11th November 2011	0.25-0.77	1.35-2.25	0.35-0.45	1.15-2.35	0.4-1.15	1.57-4.19			0.11-0.45	1.0-2.3
21st November 2011	0.68-0.89	1.86-2.38	0.40-0.75	1.55-2.89	0.37-1.18	1.65-5.11	0.15-0.75	1.05-2.65	0.32-0.78	1.34-2.89
10th December 2011	0.93-1.17	2.10-2.75	0.61-0.98	1.87-3.5	0.55-1.25	1.18-5.28	0.33-1.05	1.55-3.25	0.51-0.98	1.37-4.5
24th December 2011	1.03-1.32	2.17-3.10	0.41-0.84	1.74-3.89	0.71-1.25	1.5-5.55	0.61-1.15	1.81-3.87	0.39-0.86	1.24-5.36
12th January 2012	1.10-1.16	2.55-3.76	0.31-0.78	1.35-3.15	0.61-1.31	1.87-5.76	0.3-0.74	1.74-3.39	0.31-0.78	1.35-4.15
05th February 2012	0.89-1.11	2.67-4.98			0.38-1.18	1.45-4.67				
20th February 2012	0.30-1.13	1.27-4.87			0.31-0.97	1.57-4.49				
10th March 2012					0.29-0.89	1.15-4.55				

It is observed from Table 9.15 that crop evapotranspiration values have an increasing trend as the season progress. It is minimum in the month of October-November and maximum in the month of February-March. Sometime the harvesting season extended to April also

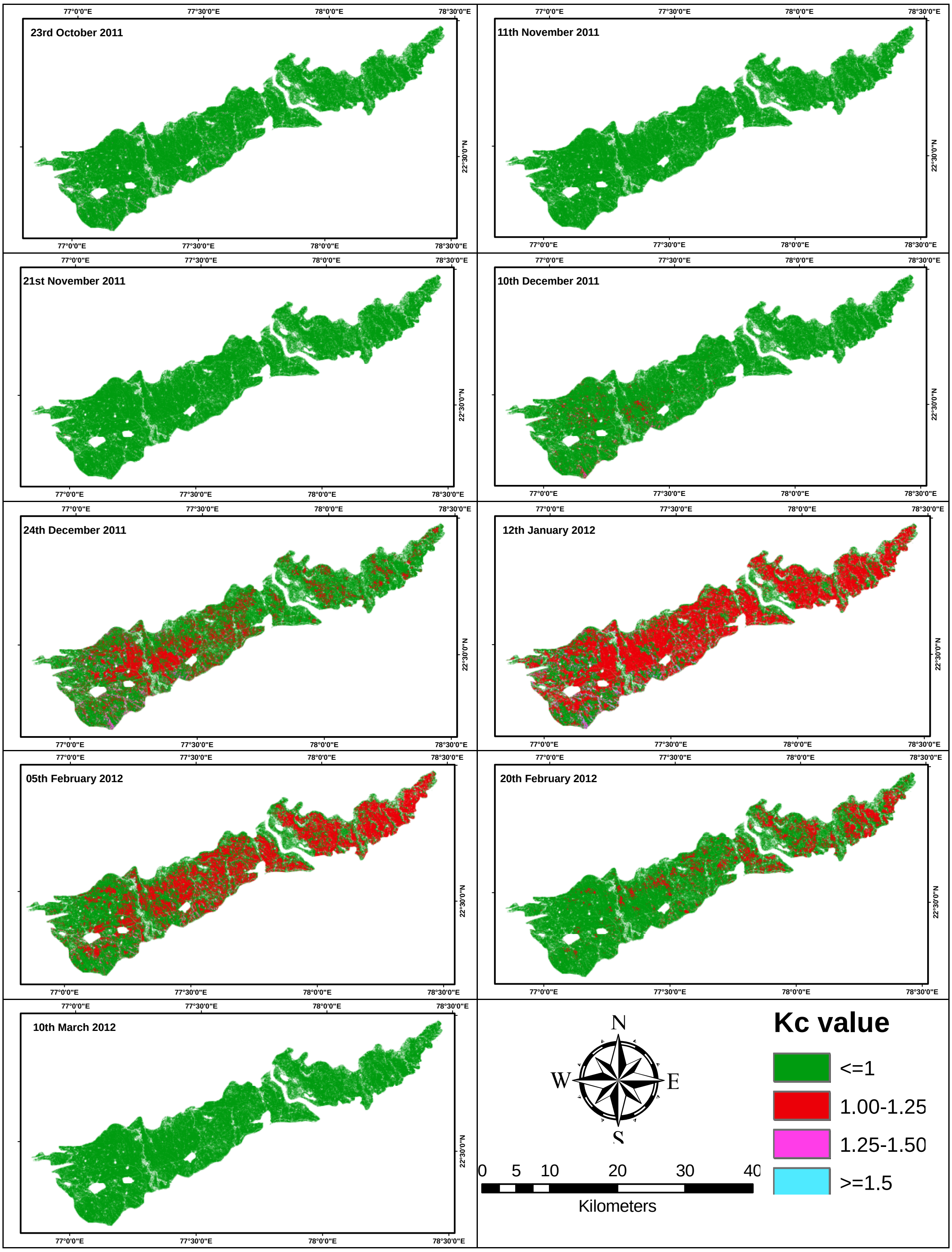


Figure 9.18 Spatially and temporally distributed Kc map (based on NDVI)

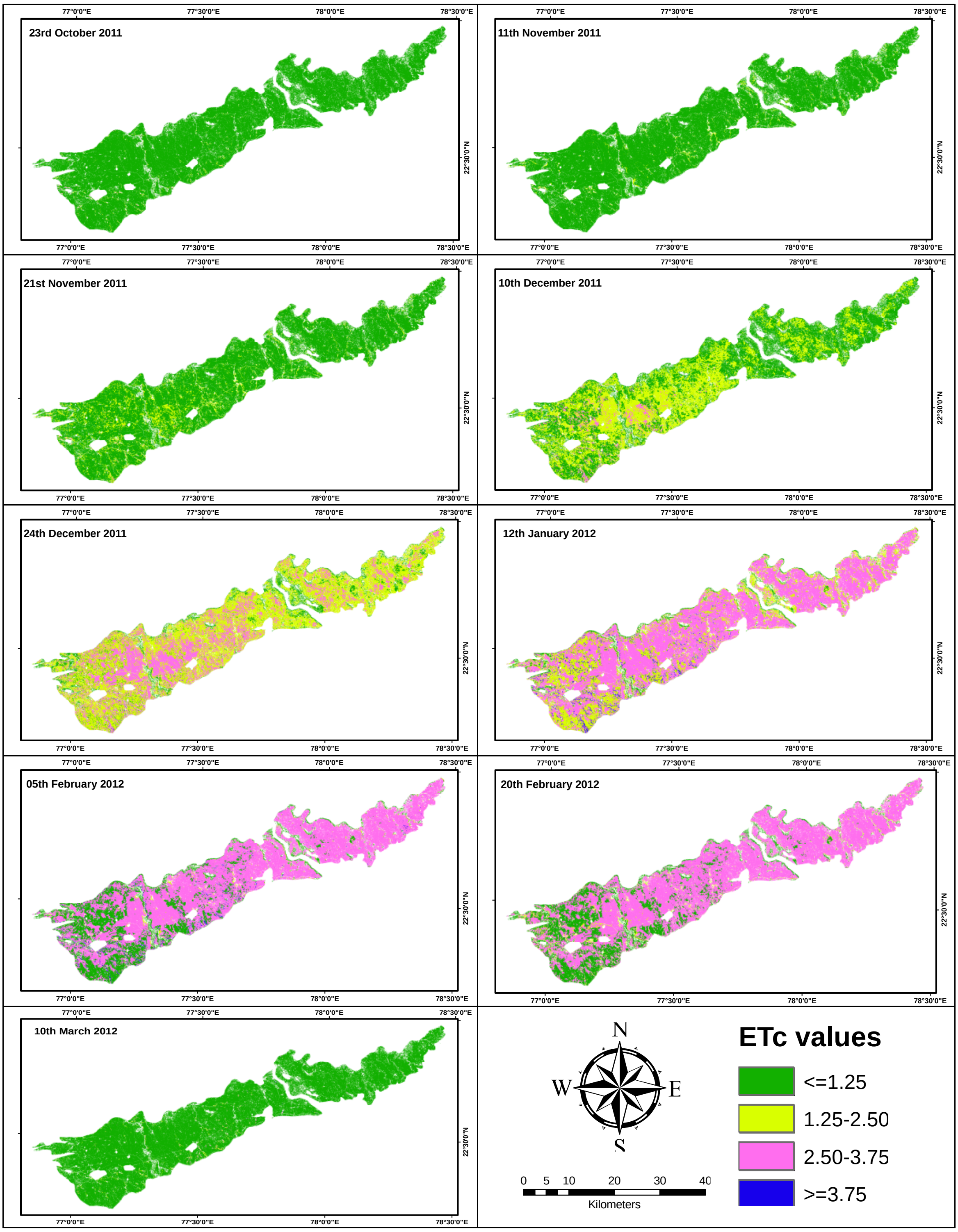


Figure 9.19 NDVI based spatially and temporally distributed ETc map for the current period

The maximum and minimum Kc and ETc values obtained for nine scenes based on NDVI are presented in Table 9.15. The spatial resolution of AWiFS sensor is 60 m, that means a pixel represents 60 $\times$60 m^2 in the real ground situation. Spatially distributed pixel-wise crop evapotranspiration computed from satellite image when multiplied with the pixel area gives the total volume of water requirement for that particular pixel. Thus total demand (in volume unit) in the command for each scene was estimated. The scene-wise ETc values (total demand) obtained for nine scenes based on NDVI are presented in Table 9.16. The crops grown in the command during the rabi season is given in Table 9.17.

Table 9.16 Scene wise ETc values based on NDVI

Months	Wheat ETc (mm)	Pulses ETc (mm)	Sugarcane ETc (mm)	Oilseeds ETc (mm)	Others ETc (mm)
23rd October 2011			2.25-5.15		
11th November 2011	1.35-2.25	1.15-3.35	1.57-4.19		1.15-4.3
21st November 2011	1.86-3.38	1.55-3.89	1.65-5.11	1.05-2.65	1.34-4.89
10th December 2011	2.10-2.75	1.87-4.50	1.18-5.28	1.55-3.95	1.37-4.5
24th December 2011	2.17-3.10	1.74-3.71	1.5-5.55	1.81-3.87	1.24-5.36
12th January 2012	2.55-3.76	1.35-3.15	1.87-5.76	1.74-3.39	1.35-4.15
05th February 2012	2.67-4.98		1.45-4.67		
20th February 2012	1.27-4.87		1.57-4.49		
10th March 2012			1.15-4.55		

Table 9.17 Crops grown in the Tawa canal command during Rabi season

Months	Crops grown during Rabi season (ha)					
	Wheat	Pulses (chick-pea)	Sugarcane	Linseed	Others (Veg.)	Total
Jan	116615	56187	5500	3682	3500	185484
Feb	116615		5500			122115
Mar	116615		5500			122115
Apr			5500			5500
May			5500			5500
Jun			5500			5500
Jul			5500			5500
Aug			5500			5500
Sep			5500			5500
Oct			5500	3682		9182
Nov	116615	56187	5500	3682	3500	185484
Dec	116615	56187	5500	3682	3500	185484

Total Cultivable Command Area (CCA) in the command should be always higher than the total crop acreage at any point of time throughout the crop calendar, which is = 261185 ha.

Based on the crop acreage and the NDVI based crop evapotranspiration, the ETc (ha-mm) is given in Table 9.18. The monthly crop water requirement is given in Table 9.19.

Table 9.18 ETc values during rabi season

Months	Wheat		Pulses		Sugarcane		Oilseeds		Others	
	ETc (ha-mm)	ETc (mm)	ETc (ha-mm)	ETc (mm)	ETc (ha-mm)	ETc (mm)	ETc (ha-mm)	ETc (mm)	ETc (ha-mm)	ETc (mm)
23rd October 2011					23375.00	4.25				
11th November 2011	389494.10	3.34	182607.75	3.25	20625.00	3.75			14875.00	4.25
21st November 2011	389494.10	3.34	210701.25	3.75	20625.00	3.75	8284.50	2.25	15750.00	4.5
10th December 2011	349845.00	3	224748.00	4	19250.00	3.5	14175.70	3.85	14000.00	4
24th December 2011	349845.00	3	182607.75	3.25	19250.00	3.5	12887.00	3.5	14000.00	4
12th January 2012	367337.25	3.15	176989.05	3.15	17875.00	3.25	10125.50	2.75	12250.00	3.5
05th February 2012	437306.25	3.75			17875.00	3.25				
20th February 2012	437306.25	3.75			17325.00	3.15				
10th March 2012					17325.00	3.15				

Table 9.19 Crop water requirement (m) of different crops during rabi season

Month(s)	Wheat	Gram	Peas	Linseeds	Vegetables	Sugarcane
January	0.098	0.098	0.098	0.085	0.109	0.204
February	0.116				0.109	0.259
March	0.116				0.109	0.298
October	0.050	0.105	0.105	0.068	0.131	0.232
November	0.090	0.105	0.105	0.068	0.131	0.213
December	0.093	0.112	0.112	0.110	0.120	0.109

CWR for the month of April, May, June, July, August, and September for the sugarcane crops has been considered as 0.217 m, 0.286 m, 0.036 m, 0.026 m, 0.018 m, and 0.092 m respectively (Source: Nikam, 2012).

9.3.4 Demand and Supply Analysis

It was assumed that each scene represents the real ground condition for the whole day on which the satellite passed. There by, total crop evapotranspiration estimated for a particular scene was equivalent to the water requirement for the whole day. Monthly water demand was computed simply by multiplying the total number of days in the month with the scene-wise total water demand for the whole command area.

Total rainfall for the whole month was recorded. Total supply of water through canal as supplementary irrigation was measured. Thus total supply of water (rainfall + canal flow) to the command area was computed taking into account the conveyance loss from the canal. Monthly supply (rainfall + irrigation) and demand (ETc from Remote Sensing) gap was computed for six different months separately. The supply and demand gap estimated for the six months are presented in Table 9.20.

Table 9.20 Supply and demand analysis based on NDVI

Months	Rainfall (ha-m)	Canal supply (ha-m)	Demand based on NDVI (ha-m)	Deficit (-)/ Surplus (+)
October-2011	227.44	22509.63	724.63	22012.44
November-2011	2272.18	23877.22	18786.85	7362.55
December-2011	1871.53	20513.13	18587.72	3796.95
January-2012	1022.02	20513.13	18121.88	3413.27
February-2012	467.70	17231.4	12737.38	4961.73
March-2012	663.08	17231.4	537.08	17357.41

From the supply and demand analysis, it was found that the Tawa canal is sufficient to meet the entire crop water requirement in the command during Rabi season. In all the months surplus supply was witnessed, and hence additional crops can be grown in the command.

9.4 CONCLUSIONS

Crop management at command level requires considerable efforts in terms of crop planning, water management, pest management, etc. When the area encompasses by the command is large the task becomes more difficult for the command area authority for proper planning and decision making. With the arrival of technologies such as remote sensing and geographical information systems, NDVI based crop identification and discrimination in large areas is helping planners in multiple of ways. These techniques support not only in discriminating different crops which are essential for crop yield assessment but also indicates the health of different crops at different growing stages helping command authority in taking timely measures for maximum crop yield. In the preset study, utility of LISS-III and multi-dates AWIFS images have been demonstrated for identifying and discriminating different crops during Rabi season in the Tawa command. Based on the NDVI profile and sample GPS points taken during field visits, four principal crops viz. wheat (74.68%), chick-pea (14.52%), sugarcane (2.42%), linseeds (2.32%) and others mainly vegetables (6.06%) are identified in the command. Also in the study, demonstration has been made how distributed crop evapotranspiration (ETc map) is prepared based on the relationship between crop coefficient and NDVI. This helps in estimating the demand and supply scenario in the canal command.

9.5 YIELD ESTIMATES

9.5.1 Introduction

Survey has been conducted in November End of Kharif season. It was planned to collect information from farmers and collection of GPS point and even Geotagged photos. All GPS data collected in digital format and crop attribute defined on the spot during survey. During survey, we have approached places which were difficult to approach. Interacted with farmers and collated photo and High definition video of all work. We have collected data from 24 villages of tawa command area, 541 GPS points with attributes, 550 Geotagged Photo and Videos and 91 form filled from selected farmers from survey area. Questionnaire and Survey code used and in Annuxure-1. Then all data collected from farmers converted to digital format for analysis. All GPS data is processed by GIS model and represent as spatial distribution of cropping pattern. Secondly, Crop distribution map is generated by combining field and satellite data. For kharif session it is very rare we get clout free satellite image when leaf area of crop is maximum, but we have carefully selected an image with minimum cloud cover. For Rabi season, we have also obtained cloud free image with maximum growth period. Then we have tested and developed various model for crop yield and distribution analysis. Our Model contain linear and experimental tested model. Both model provide almost same result and even we calibrated our model because have actual filed data. So, generated maps also shown in this report and methodology is also explained. It is found during survey yield production of crops is improving if we compare old data of govt. Satellite image also show health index of command are which is clearly visible in shown figures. Results for all question asked to farmers also shown. All GPS data shown in Appendix IV(A), Appendix IV(B). The photos taken where GPS sample points were obtained is given in Appendix V.

9.5.2 Study Area

Tawa canal command is a planned gravity major irrigation system started in the year 1978 on completion of the dam across the Tawa river, a tributary to Narmada river. Tawa command is spread over in an area of about 5273.12 km^2 falling in the district of Hoshangabad, Madhya Pradesh, India. It lies between 22º54' N to 23º00' N latitude and 76º457' E to 78º45' E longitude. Hoshangabad district lies in the south-west part of the Madhya Pradesh state, India. The district lies between north latitude from 21º54' to 23º00' N and longitude from 76º47' to 78º42' E. The district spans over an area of 10,037 km2. It is a longitudinal irregular strip of country with River Narmada being its northern boundary. South portion of the district occupied by Satpura Range whereas the northern plains include isolated knolls and low stony ridges. Tawa and Ganjal are the other main rivers of area. It is bounded by Sehore and Raisen districts in the North. In the East its boundary marches with Narsimahpur district. The two Satpura plateau districts Chindwara and Betul bound the district in the South, and Dewas district in the North-west (Figure 9.20). Hoshangabad town, the district head quarter is situated along the south bank of Narmada River overlooking Vindhya range lies 75 km South from State capital Bhopal. The area is well connected with rest of India by rail route and roads. Itarsi is the most important railway junction in the district. Hoshangabad and Itarsi lie on Delhi-Chennai, Delhi-Bangalore and Delhi-Mumbai railway routes. State Highway No 21 and 22 pass through the district. The villages in the district are approachable by fair motorable tracks. Tawa dam site is about 9 km from Bagra Tawa Railway station and 33 km from Itarsi railway station on Central Railway. 38 Tawa dam site is situated in Ranipur Town of Kesla Block of Itarsi Tehsil of Hoshangabad district. For administrative convenience, the district is divided into 10 blocks. The block headquarters are located at Khirkiya, Harda, Timrani, Seoni Malwa, Hoshangabad, Kesla, Babai, Sohagpur, Pipariya and Bankheri. Tawa Command area falls under Kesla, Hoshangabad, Seoni Malwa, Timrani, Harda, Babai, Sohagpur and Pipariya blocks of Hoshangabad District. The location map of the study area is presented in Figure 9.20.

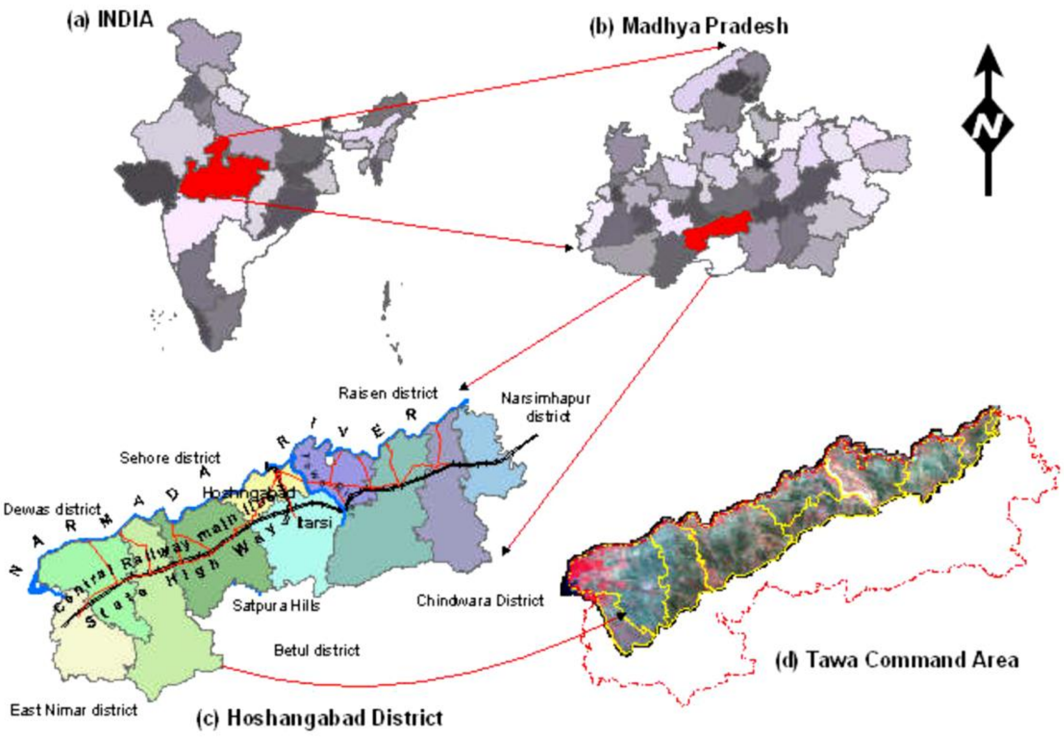


Figure 9.20 Location of tawa Canal command

9.5.3 Methodology

This data is sample survey, but data sites and form data is carefully selected. Then all data is converted to digital format and Geo Spatial format and satellite data is also used, Crop Health Index also derived. Various model also developed for crop yield spatial distribution based on collected field data and actual satellite data. All data linked with digital Geodatabase. All progress flowchart is shown in Figure 9.21. We have also did videography of whole survey.

Methodology Used for Yield Estimation using Remote Sensing and GIS

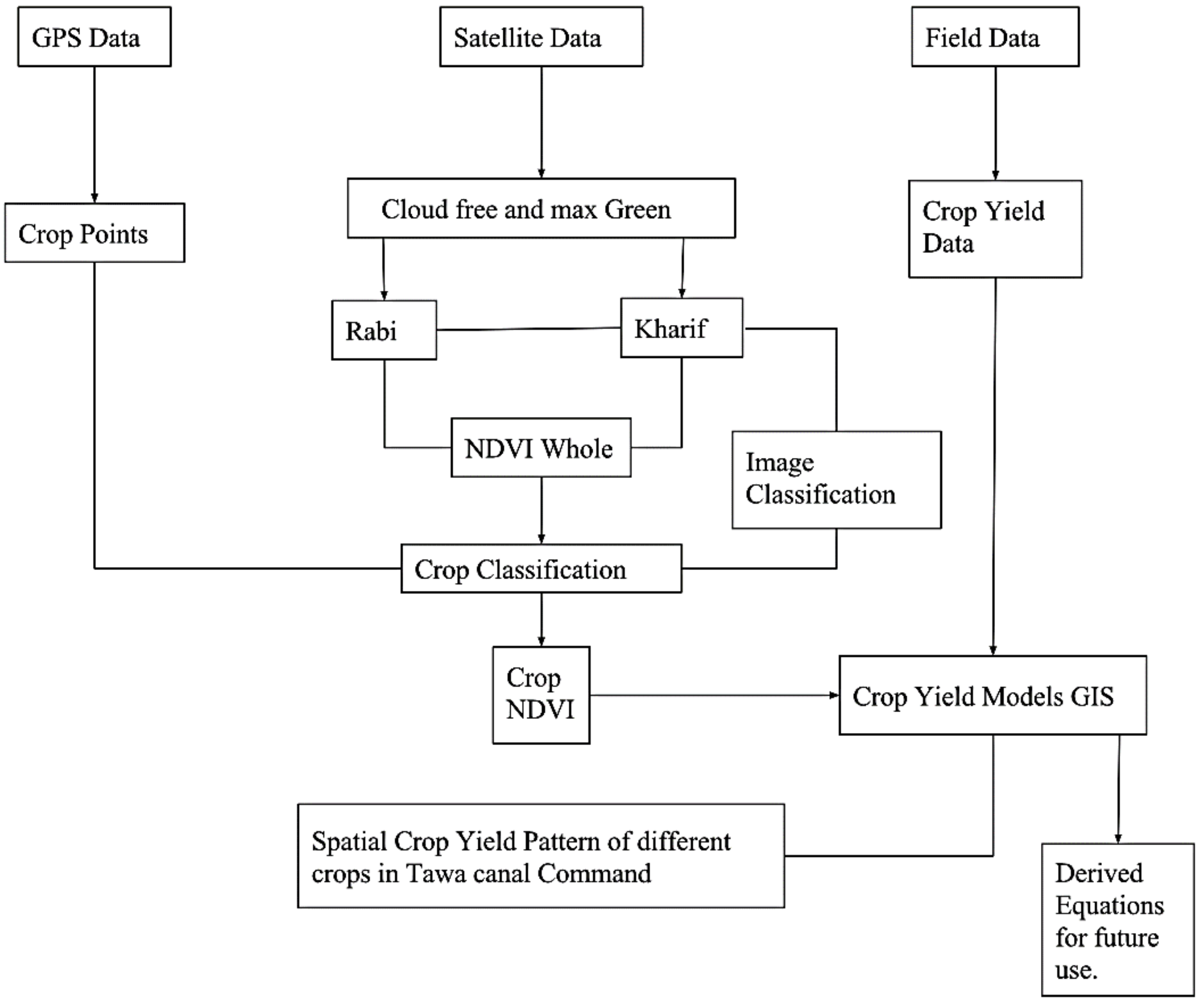


Figure 9.21 Methodology Used

From our actual data, we have also derived crop yield equation to predict yield of crop from satellite image taken during maximum green index, of number of days after sowing. There is direct relation found between crop yield and NDVI of crop. So after carefully separation of NDVI of specific crop and compare it with some samples of GPS actual data and same yield data it is possible to drive equation and develop equation specific models in GIS to predict crop yield and cropping pattern in command area. Error NDVI values are also corrected due to resolution of satellite image or mixed pixels i.e. Urban and crop in one pixel. So, accuracy of data will be near to 80% after validation. We have derived this relation for each crop and validated with actual data. We have also generated crop yield maps based on these equation and models as in result section of this report.

9.5.4 Equation Derived for Yield

Let Yield is the Function of NDVI, then selected crop yield based on NDVI will be estimated using relation between actual field value and related yield using liner equations.

$Yield = f(NDVI)$ (Valid if image is taken during maximum growth period, and NDVI values corrected not less than 0.3 Table 9.21 Show derived yield equation using actual data.

Table 9.21 Derived Equation for Yield estimate

Crop	**Equation (Q/Acre)**
Rice	Yield = 3.455+31.814(NDVI)
Mung Dal	Yield = 0.1520+13.659(NDVI)
Soybean	Yield = -0.94+33.33(NDVI)
Grams Urad/Arharhar	Yield = -0.560+13.968(NDVI)
Maze	Yield = -16.99+76.8935(NDVI)
Sugarcanes	Yield = -10.1095+71.9387(NDVI)
Wheat	Yield = 7.7645+19.852(NDVI)

9.5.5 Results and Discussion

During survey GPS Points and Geotagged photos are collected. We have collated 1091 Points total. Each point and combination of point represent different class. We have much points of validation of satellite pixel even on low resolution. As shown in Figure 9.22 We have collected maximum points for crops and also other category for separation like Natural vegetation, barren land and urban area. Because it’s found that sometime natural vegetation and specific crop has very less variation in pixel reflectance. But we have resolved this error by combing NDVI and crop classification from satellite image and field data. So accuracy is much higher as possible on 30 meter resolution of pixels. We have covered 24 villages with crop yield data direct from farmer location of survey villages is shown in Figure 9.23

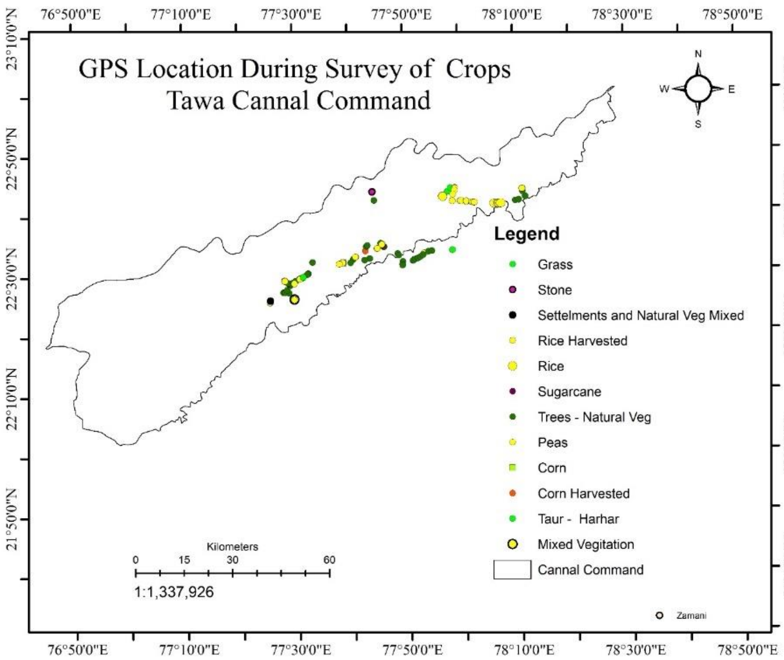


Figure 9.22 GPS Location of Survey Points

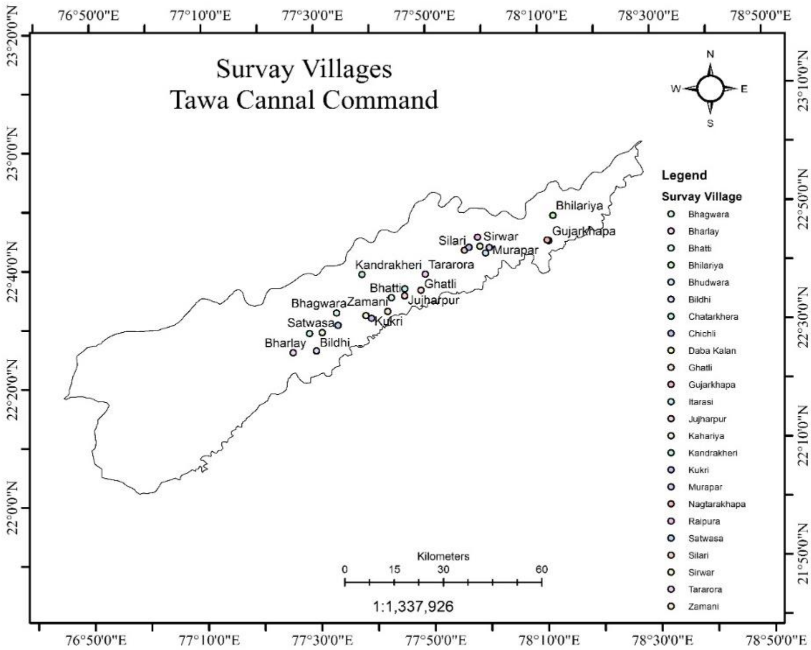


Figure 9.23 Village covered for data collection

Figure 9.24 Showing crop health index NDVI which is calculated using near infrared and infrared bands. This is acquired using Satellite image taken during maximum green period of crops. In February month. This index has value range between -1 to +1 where positive value denotes good health of crops. NDVI of specific crop also calculated by separation a specific crop using classification. NDVI has direct relation to crop growth. We can easily relate NDVI with crop yield if we have field and satellite data. This way we have accurate estimate of crop yield. From Fig.9.24 it is clear that irrigated command area has good crops. NDVI values are vary between -0.21 to +0.62, negative NDVI denotes urban area or rocks, or vegetation less area including roads and water. So, in this command area North-East region from East of Hoshangabad has goof crop index. But West side of command area has lower quality of crops. But area which is irrigated is in large extent and showing good health of crops. Western area lies between 0.18 to 0.38 values. It means this area also not have bad crops it as average good crops.

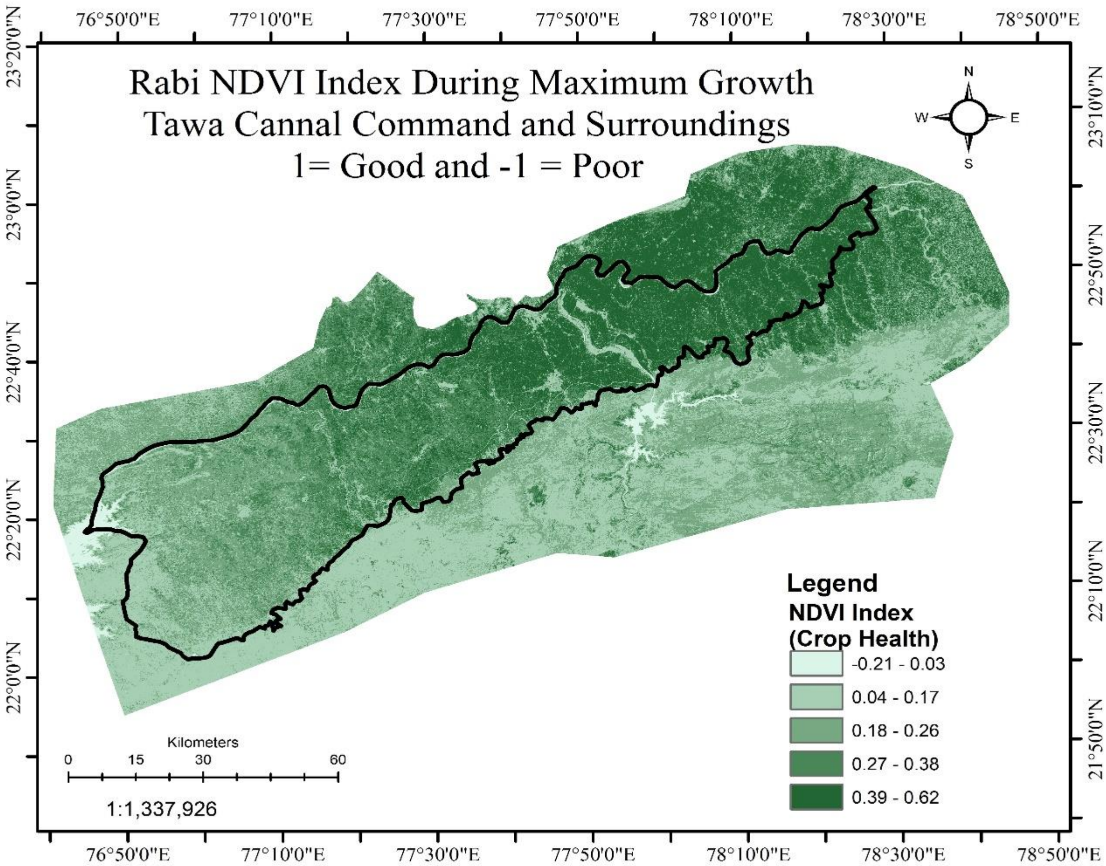


Figure 9.24 NDVI During Rabi Crops

This are having much of cloud during, kharif Green season but we have selected set of satellite image for irrigated area. Also, corrected some cloud effect on western part of area and corrected it with ground truth. Spatial pattern of kharif crops is shown in Figure 9.25 It is seen maximum are is covered by rice during kharif. Rest of part is covered by other crops, discussed separately in next chapters.

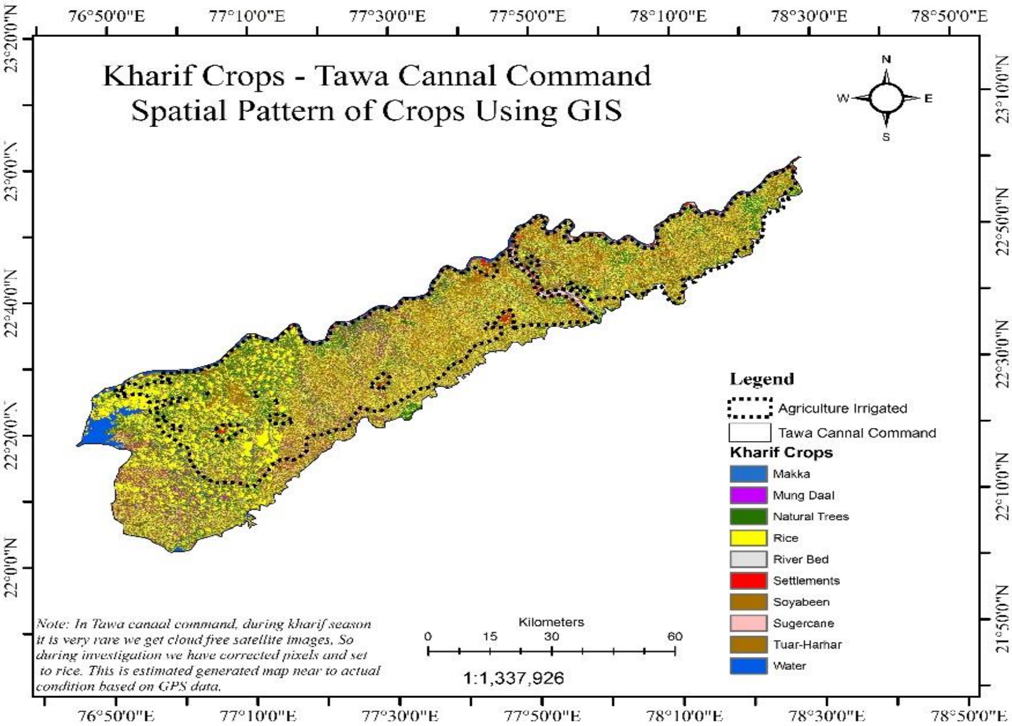


Figure 9.25 Kharif Crops

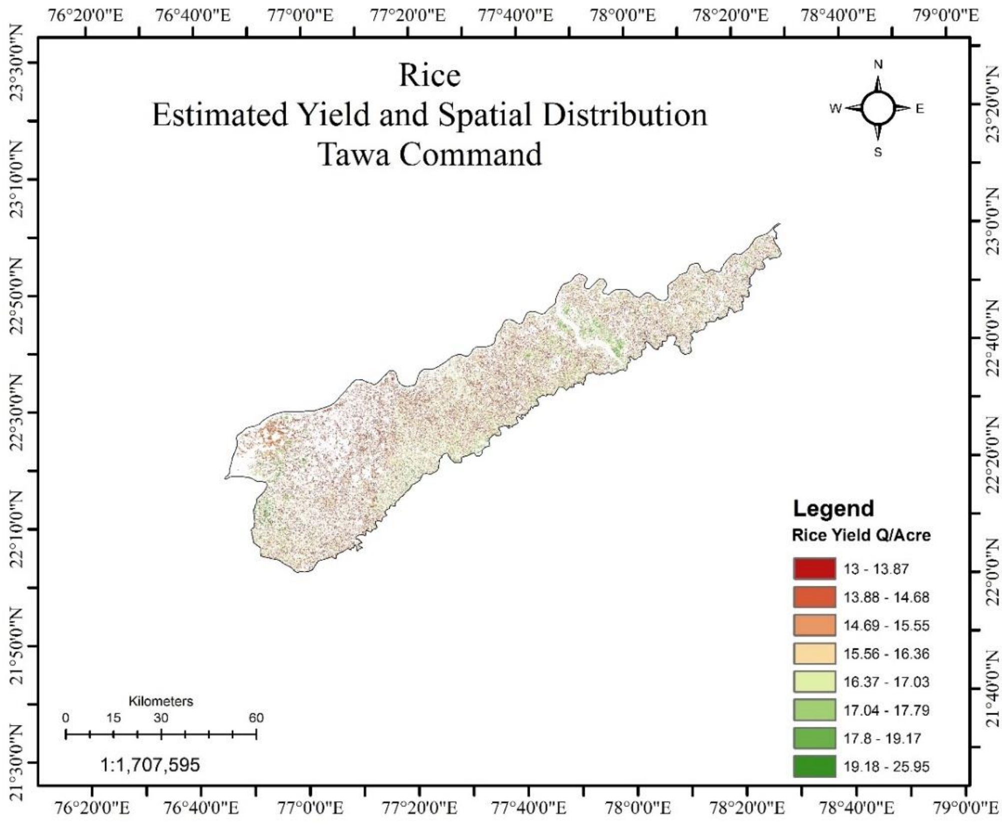


Figure 9.26 Rice yield pattern

Yield of rice is calculated in GIS based model. It required NDVI of maximum green growth period. Then relation of actual data is derived with field data and equation is generated for estimating yield in whole area. Later this equation is used in GIS. Accuracy of data is very dependent of resolution and reflectance properties of satellite sensors. But we have verified data with actual data and found around 80% accuracy is achieved.

<u>As per results shown in Fig.9.26 about yield of rice following are findings.</u>

(i) Yield of rice is lies between 13 q/Acre to 26 /Acre
(ii) Western past of area has lower yield, this is the part of command area where availability of irrigation water is poor.
(iii) South and East part of command area has good yield. It reaches up to maximum of 26 Q/Acre
(iv) Estimated area of cropped rice during image taken is 1500km^2
(v) Most area has yield in range of 15Q/Acre to 26Q/Acre.
(vi) Area near to Narmada river has more yield. Soil of this area is fertilize because it on the deposition of river which collected over thousands of years ago.

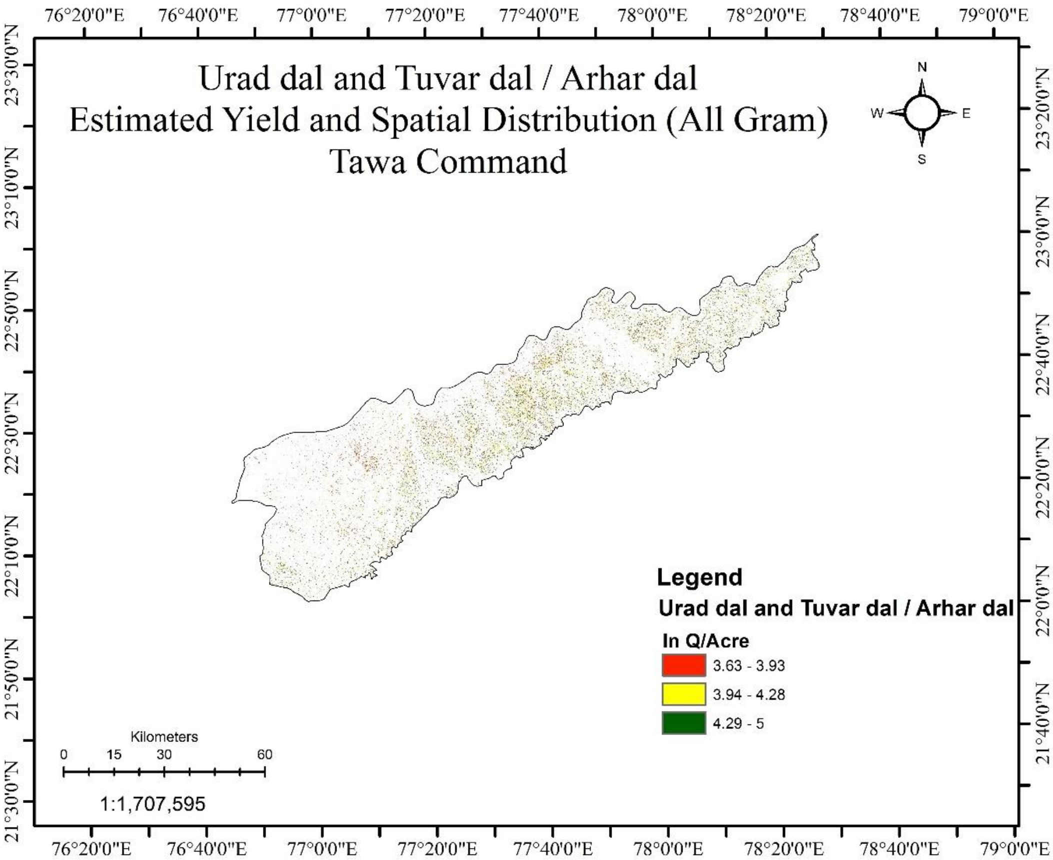


Figure 9.27 Grams yield pattern

This area has also cultivation of grams including Arhar and Urad gram. This are grown in area of 386 km^2. Arhar is sowing in both session in Rabi and Kharif. Pattern of crop is mixed with other crops. But most of grams are good production in north side of Narmada river. But western part of command area has very few field where cultivation of grams is being done. During our visit, we have find people are growing different vegetables in Narmada river bed. Figure 9.27 is showing pattern of Grams and also production. Same approach is used to estimate yield from satellite data i.e. combination of actual data, field data, NDVI and running model in GIS environment. Accuracy may be very depending of resolution and specification of satellite.

Our finding are as follows:

(i) Grams has not much variation in yield it has minimum of 3.63 Q/ Acre to 4.29 Q/Acre.
(ii) As per cropping pattern using GIS shown in Fig.9.27 it's clear that irrigated area has good yield, and this crop is only grown in irrigated area.
(iii) Most of Grams which has good yield are lies in north of Narmada river.
(iv) Grams are sown in both sessions Rabi and Kharif.

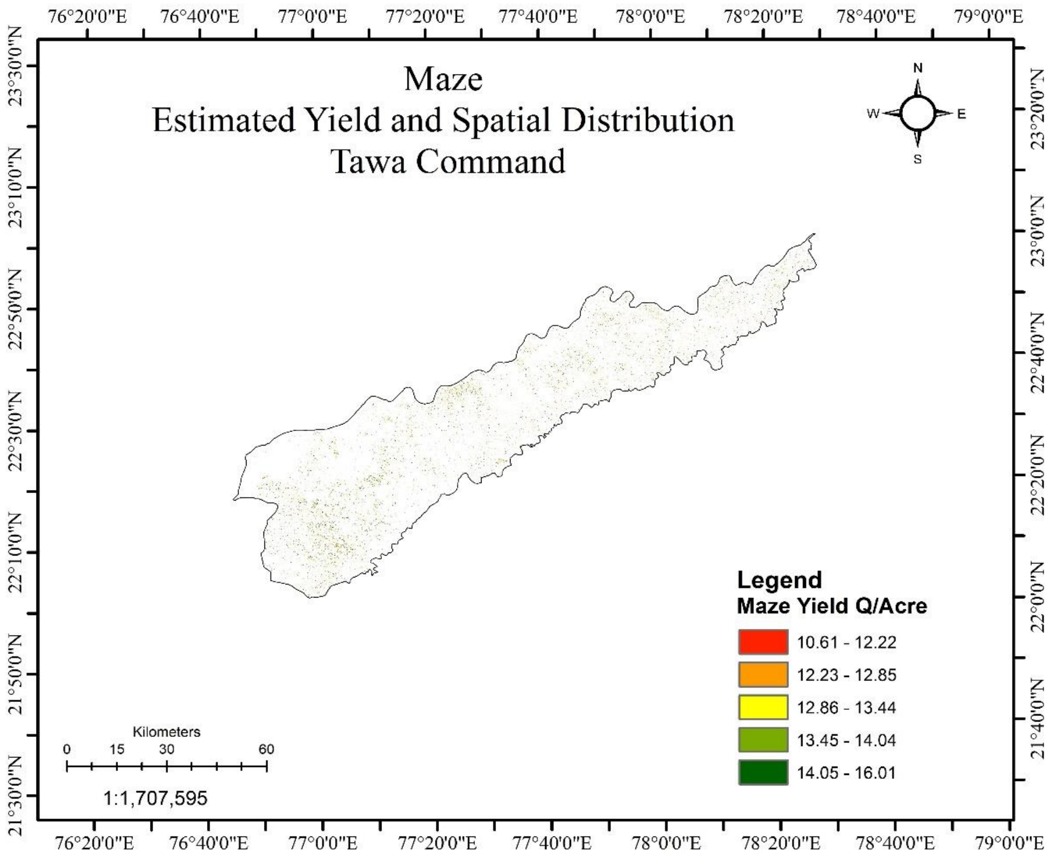


Figure 9.28 Maze Yield Pattern

Maize is also grown in better in this area from satellite data it is estimated to be grown in 153 km$^{2.}$ During our survey, we have found that farmers has grown Maze between other crops like all around other crops and vegetables and inside maze. But size of maze fields is not much large. Total estimate Yield is between 10 to 16 maze also has good yield in western part of command area weather other crops has not good in this area due to shortage of irrigation water. Shown in above Figure 9.28

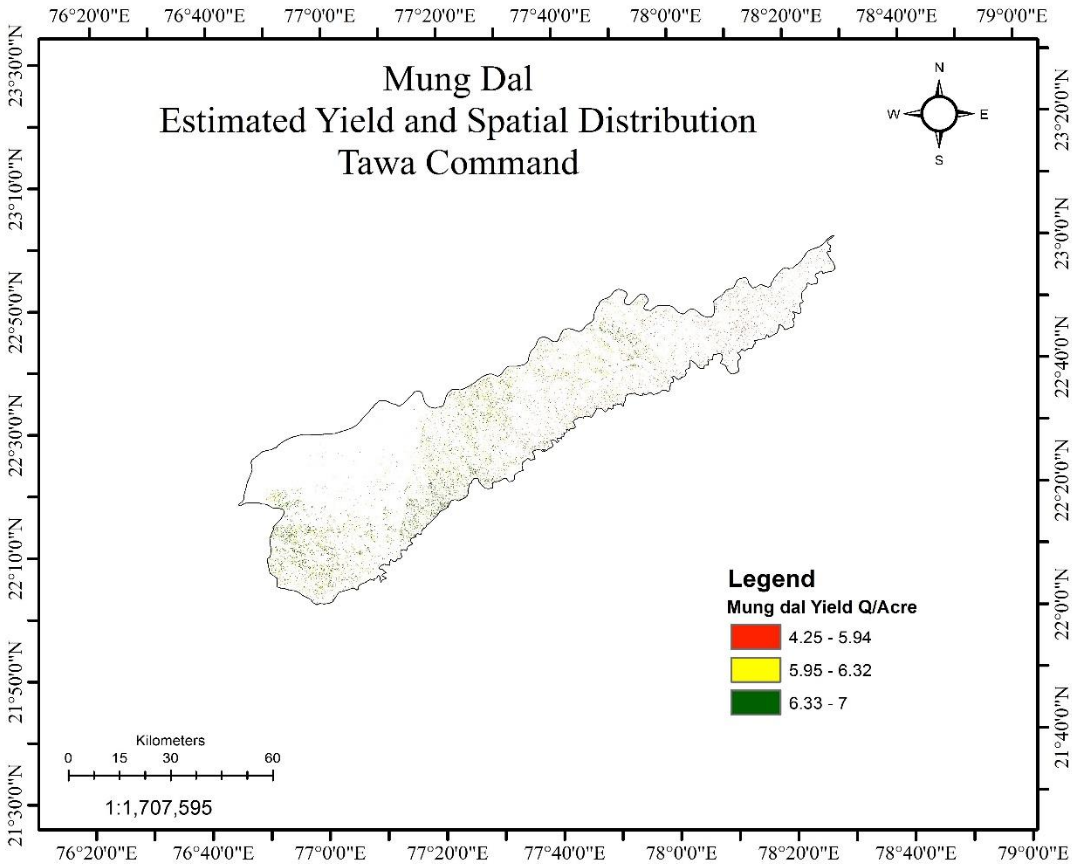


Figure 9.29 Mung Yield pattern

Mung gram is found in 244 km^2 of command area. It cultivate in whole area distributed with large difference and spread over whole area. It has production between 4.25 to 7 Q/Acre. But most of area has good production of mung daal (gram) around 6 to 7 Q/Acre. Lowes production area are lies at north side of command area. Pattern shown in above Figure 9.29

Soybean is cultivated around 290 km^2 of area. But currently it has very few field in command area. We can find very rarely a soybean fields. Most of farmers during survey reported us that they left soybean cultivation due to low production or loss in total crop. So as shown in Fig.9.30 most of irrigated area has lowest consternation of fields. It also has lowest to average production. Good production is found in few fields near to reserve forest and western part of area. Its production lies between 4.1 to 12 Q/Acre. It also includes poor production. Larger the difference between yield represent losses in crops at some area.

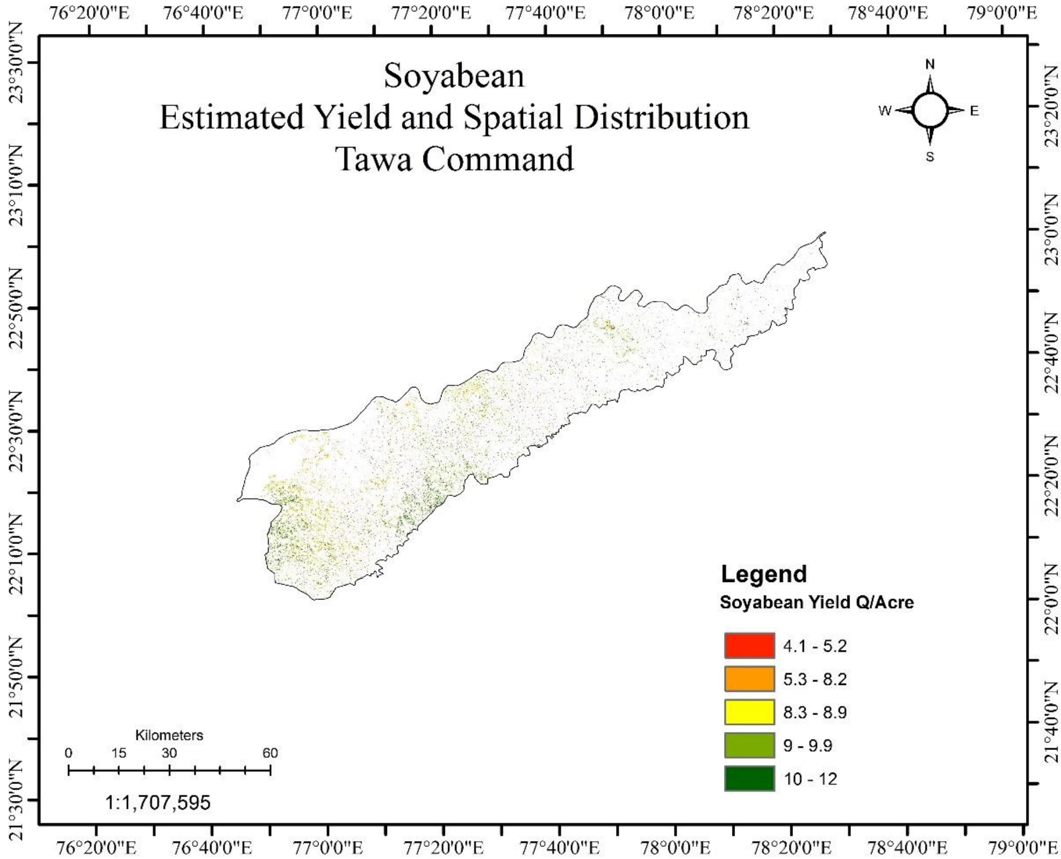


Figure 9.30 Soybean Pattern

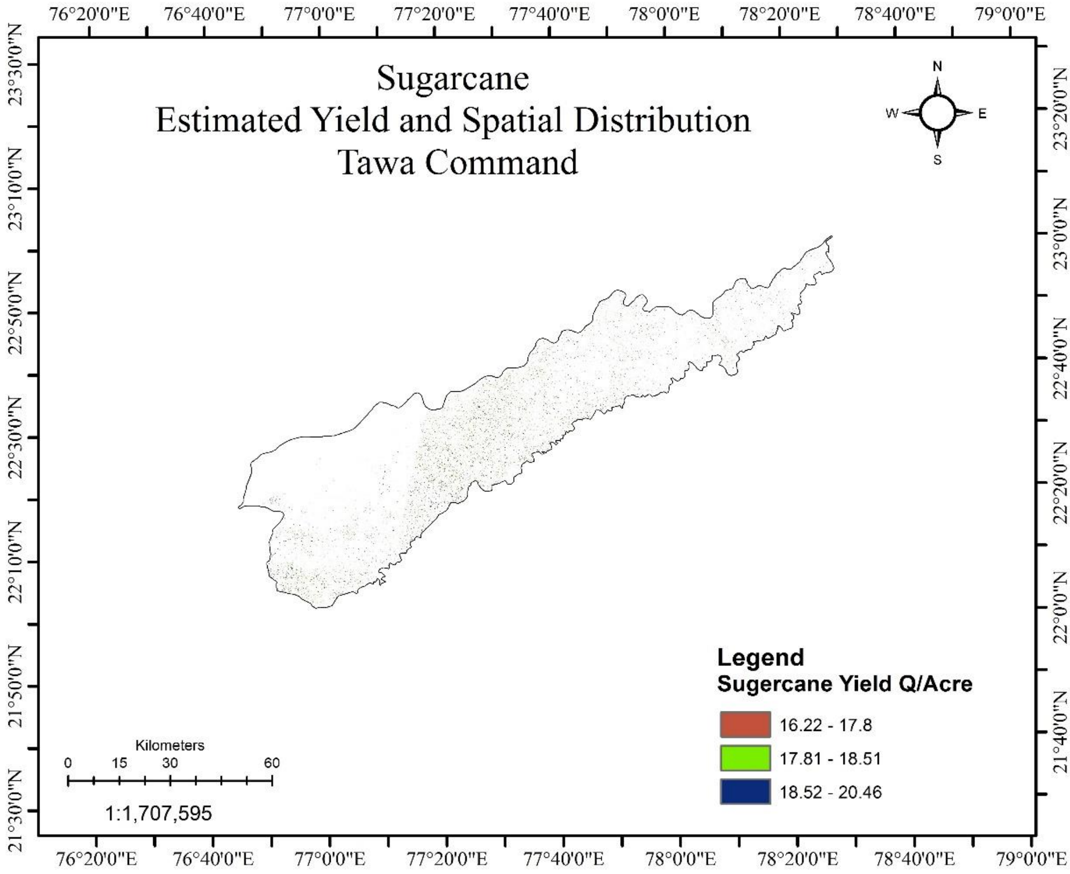


Figure 9.31 Sugarcane

Area of sugarcane is much less compare to total command area. At very few places sugarcane in visible. It cover total estimated area 129 km^2. But its production has not much variation because it has longer grown period. So much difference is not seen. The yield depends upon time to time growth of crop and NDVI image generally considered aft full green period of crop. Its pattern is shown in Figure 9.31

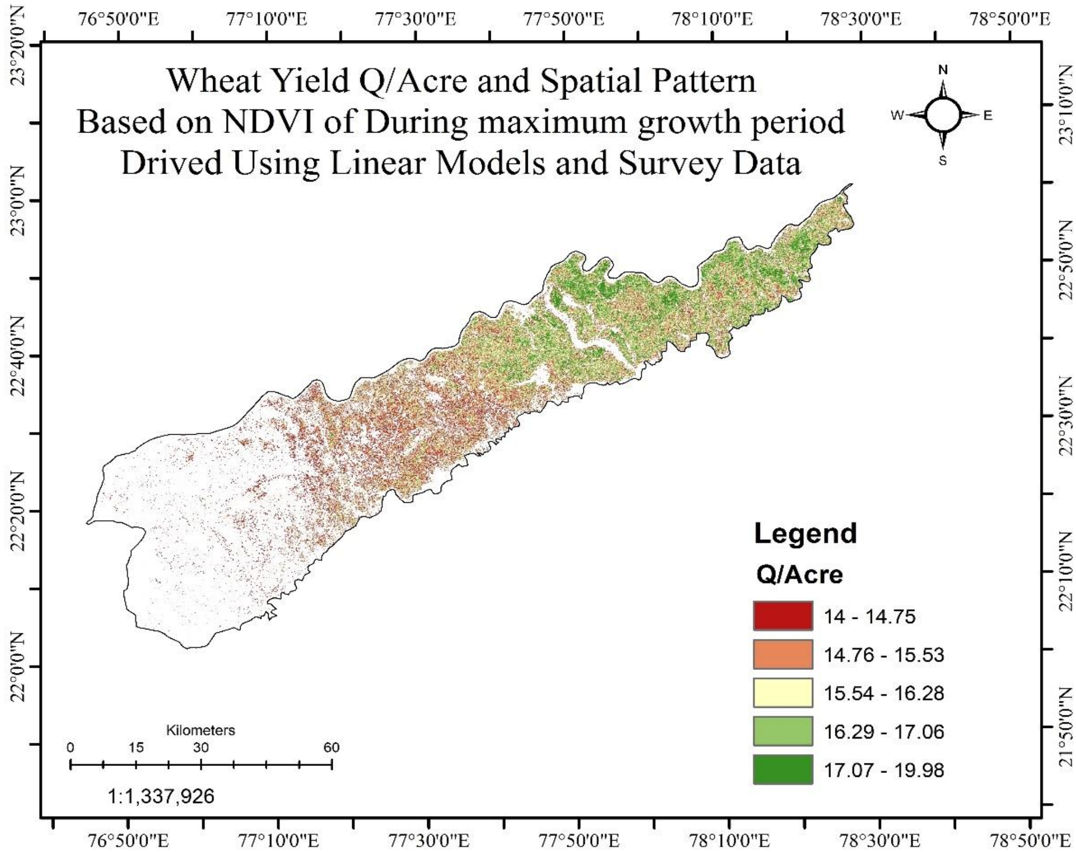


Figure 9.32 Wheat

Maximum are of canal command is covered by Wheat during Rabi session. Wheat is grown in area about 2190 km^{2}. It has production between 14 to 20 Q/Acre. It has good production on North side of Narmada river, and surrounding of it. All other area comes under average production. It has low production area on far west side of canal command area. Far side of command area preferred with vegetable and other crops. Pattern is shown in Figure 9.32

9.5.6 Land usage information

It is found during survey all farmers are utilizing whole agricultural land, for agriculture. Out of survey 2050 Acre of land total 1.5 is **banjar** and 5 Acre daldal , 20 Acre has shortage of water. Area covered under crops under sample survey shown in Table 9.22.

Table 9.22 Area under crops under survey

Crop	Area Under Crops in Acres (During Survey only)
Dhan	579
Taur	6
Soybean	794
Urad	181
Wheat	2022 (During Rabi)
Channa kala	17
Maze	67

9.5.7 Using of Fertilizer

It is found during survey all of farmers are using Urea and DAP for, we have found no farmer using Bio-Fertilizer

9.5.8 Instruments

Most of farmers are using instruments for agriculture rented or owned. But we have seen instruments on farmers' home. Which are their own. Some village has 200 Tractors, Almost tractor in each home. As per our survey result for usage of instruments. Shown in Table 9.29

Table 9.23 Instrument Used

Crop	Instruments
Tractor	79
Harvester	23
Thrasher	40

9.5.9 Irrigation Method

Most of farmers has both source of irrigation, some has all three sources. But if farmer has both source i.e. Canal water and Tube well then, they prefer to canal water of available at good time and schedule. Farmers has pumps are not dependent of canal water. Problems of farmers will be discussed later in problems section. Irrigation method results are shown in Table 9.30

Table 9.24 Method of irrigation

Source	Count
Canal	70
Well/Tubewell	72
Pump	20

9.5.10 Canal Water

During survey 29 farmers not required canal water. Most of farmer using irrigation water having distance of field from canal between 0.5 to 3.5 km. Out of 91 only 34 are getting complete water from canal.

9.5.11 Knowledge of Schemes and Loan

Total 69 farmers know about crop insurance. Loan is taken by 66 farmers, 63 knows about welfare schemes. 83 told good facility of market is available.

9.5.12 Climate change

Farmers are not familiar with term climate change or “जलवायु परिवर्तन” During our survey only one farmer knows about it. But when we asked is earth is becoming hot now then previous years then most of framers said yes, now days are going hot…. and this “hot” has negative impact on our crops leaves of vegetables going yellow before time.

So, farmers indirectly know about it. But does not know what it called and the have impact on their crops too.

9.5.13 Ground Water

Ground water varies between 70-150 feet for whole year. But it is good in Month of Jan to April and November, December.

9.5.14 Suggestion / Complaints

1. Crop diseases but no recovary
2. No full water is available from canal
3. Water theft, Rich farmer with force block small irrigation network and divert water to own fields. Show by one farmer, Photo Video attached (link)
4. Electric has power cut of 6 hrs and more, so they cannot use pumps.

9.5.15 Best Practices

During survey when we meet rich farmers we found that they are not selling their production to govt. they have contract with private companies and selling their production of higher quality at higher rate and getting much profit. I.e. Selling of Basmati rice of higher grade.

9.5.16 Average Yield from Field Data

Table 9.25 shows average yield from field data.

Table 9.25 Yield as per estimated from survey data.

Crop	Yield/Q/Acre (Average)
Dhan	13.02
Mung	4.26
Soyabeen	4.06
urad	3.63
makka	10.60
Wheat	15.47
channa	6.33

Following data in Table 9.26 is obtained from govt records. Shown Production of Each crop and Yield statics as per govt record. Shown in Table 9.26.

Table 9.26 Crop Yield As per Records

Crop Production Statistics as Per Govt Record

State/Crop/District	Year	Season	Area (Hectare)	Production (Tonnes)	Yield (Tonnes/Hectare)
Madhya Pradesh					
Arhar/Tur					
1.HOSHANGABAD	1997-98	Kharif	16100	19000	1.18
	1998-99	Kharif	11800	16400	1.39
	1999-00	Kharif	11343	15430	1.36
	2000-01	Kharif	9882	11258	1.14
	2001-02	Kharif	10221	13348	1.31
	2002-03	Kharif	9205	9592	1.04
	2003-04	Kharif	8180	8966	1.10
	2004-05	Kharif	8326	8702	1.05
	2005-06	Kharif	12153	12517	1.03
	2006-07	Kharif	8806	8583	0.97
	2007-08	Kharif	7300	6962	0.95
	2008-09	Kharif	6507	7317	1.12
	2009-10	Whole Year	6366	6787	1.07
	2010-11	Kharif	11004	6693	0.61
	2011-12	Kharif	8334	7750	0.93
	2012-13	Kharif	6461	6595	1.02
	2013-14	Kharif	3210	2361	0.74

Beans & Mutter(Vegetable)					
1.HOSHANGABAD	2002-03	Whole Year	306	0	0.00
	2003-04	Whole Year	227	0	0.00
Maize					
1.HOSHANGABAD	1997-98	Kharif	2300	3000	1.30
	1998-99	Kharif	1000	1300	1.30
	1999-00	Kharif	981	1674	1.71
	2000-01	Kharif	1339	2694	2.01
	2001-02	Kharif	1334	2883	2.16
	2002-03	Kharif	1959	4622	2.36
	2003-04	Kharif	1945	3906	2.01
	2004-05	Kharif	1941	2362	1.22
	2005-06	Kharif	1928	2973	1.54
	2006-07	Kharif	1621	1649	1.02
	2007-08	Kharif	1441	1886	1.31
	2008-09	Kharif	1338	1793	1.34
	2009-10	Whole Year	1251	1465	1.17
	2010-11	Kharif	999	1746	1.75
	2011-12	Kharif	1104	1341	1.21
	2012-13	Kharif	987	3948	4.00
	2013-14	Kharif	1425	2207	1.55
Masoor					
1.HOSHANGABAD	2004-05	Rabi	2590	1435	0.55
	2005-06	Rabi	2269	1277	0.56
	2006-07	Rabi	1967	1125	0.57
	2007-08	Rabi	1491	852	0.57
	2008-09	Rabi	1478	845	0.57
	2009-10	Whole Year	999	545	0.55
	2010-11	Rabi	678	335	0.49
	2011-12	Rabi	473	227	0.48
	2012-13	Rabi	293	218	0.74
	2013-14	Rabi	476	214	0.45
Moong(Green Gram)					
1.HOSHANGABAD	2005-06	Kharif	96	29	0.30
	2006-07	Kharif	152	47	0.31
		Rabi	337	129	0.38
		Total	489	176	0.36
	2009-10	Kharif	78	24	0.31
		Rabi	236	88	0.37
		Total	314	112	0.36
	2010-11	Kharif	136	50	0.37
		Rabi	370	115	0.31
		Total	506	165	0.33
	2011-12	Kharif	61	14	0.23
		Rabi	686	235	0.34
		Total	747	249	0.33

	2012-13	Kharif	98	29	0.30
		Rabi	284	104	0.37
		Total	382	133	0.35
	2013-14	Kharif	96	23	0.24
		Rabi	72449	33174	0.46
		Total	72545	33197	0.46
Other Kharif pulses					
1.HOSHANGABAD	1999-00	Kharif	247	75	0.30
	2000-01	Kharif	547	153	0.28
	2001-02	Kharif	275	81	0.29
	2002-03	Kharif	646	194	0.30
	2003-04	Kharif	408	113	0.28
	2006-07	Kharif	17	6	0.35
	2010-11	Kharif	1		0.00
	2011-12	Kharif	33	10	0.30
	2012-13	Kharif	200	68	0.34
	2013-14	Kharif	44	23	0.52
Paddy					
1.HOSHANGABAD	1997-98	Kharif	10000	12800	1.28
Peas & beans (Pulses)					
1.HOSHANGABAD	2005-06	Rabi	1189	569	0.48
	2006-07	Rabi	1160	572	0.49
	2007-08	Rabi	1131	532	0.47
	2008-09	Rabi	834	405	0.49
	2009-10	Whole Year	684	322	0.47
	2010-11	Rabi	589	249	0.42
	2011-12	Rabi	540	244	0.45
	2012-13	Rabi	534	300	0.56
	2013-14	Rabi	841	308	0.37
Rice					
1.HOSHANGABAD	1998-99	Kharif	7800	6300	0.81
	1999-00	Kharif	8677	13185	1.52
	2000-01	Kharif	9681	11178	1.15
	2001-02	Kharif	9667	11464	1.19
	2002-03	Kharif	9969	12880	1.29
	2003-04	Kharif	10526	13980	1.33
	2004-05	Kharif	11625	11298	0.97
	2005-06	Kharif	14052	18009	1.28
	2006-07	Kharif	15232	20226	1.33
	2007-08	Kharif	16540	26753	1.62
	2008-09	Kharif	17083	25152	1.47
	2009-10	Whole Year	19907	33040	1.66
	2010-11	Kharif	23719	54441	2.30
	2011-12	Kharif	25270	50110	1.98
	2012-13	Kharif	29322	194687	6.64
	2013-14	Kharif	40939	64662	1.58
Soyabean					
1.HOSHANGABAD	1997-98	Kharif	345800	437800	1.27

	1998-99	Kharif	204200	179300	0.88
	1999-00	Kharif	209618	139815	0.67
	2000-01	Kharif	203862	201008	0.99
	2001-02	Kharif	211385	216035	1.02
	2002-03	Kharif	204295	130340	0.64
	2003-04	Kharif	200517	205530	1.03
	2004-05	Kharif	203970	110756	0.54
	2005-06	Kharif	188495	198108	1.05
	2006-07	Kharif	194858	237142	1.22
	2007-08	Kharif	206698	225301	1.09
	2008-09	Kharif	211925	179077	0.85
	2009-10	Whole Year	214734	283019	1.32
	2010-11	Kharif	216702	138333	0.64
	2011-12	Kharif	220745	141498	0.64
	2012-13	Kharif	223664	192798	0.86
	2013-14	Kharif	213184	21105	0.10
Sugarcane					
1.HOSHANGABAD	1998-99	Whole Year	425	2920	6.87
	1999-00	Whole Year	187	6350	33.96
	2000-01	Whole Year	680	7710	11.34
	2001-02	Whole Year	269	9140	33.98
	2002-03	Whole Year	259	8260	31.89
	2003-04	Whole Year	402	12820	31.89
	2004-05	Whole Year	179	5800	32.40
	2005-06	Whole Year	817	27160	33.24
	2006-07	Whole Year	1783	59250	33.23
	2007-08	Whole Year	2002	62380	31.16
	2008-09	Whole Year	1090	36230	33.24
	2009-10	Whole Year	837	27820	33.24
	2010-11	Whole Year	1572	54690	34.79
	2011-12	Whole Year	1056	27210	25.77
	2012-13	Whole Year	1451	54610	37.64
	2013-14	Whole Year	984	31620	32.13
Urad					
1.HOSHANGABAD	1999-00	Kharif	121	36	0.30

		Rabi	3	1	0.33
		Total	124	37	0.30
	2003-04	Kharif	301	84	0.28
		Rabi	10	3	0.30
		Total	311	87	0.28
	2004-05	Kharif	219	66	0.30
		Rabi	6	2	0.33
		Total	225	68	0.30
	2005-06	Kharif	172	51	0.30
		Rabi	1		0.00
		Total	173	51	0.29
	2006-07	Kharif	155	47	0.30
		Rabi	5	2	0.40
		Total	160	49	0.31
	2007-08	Kharif	227	66	0.29
	2008-09	Kharif	269	81	0.30
		Rabi	7	2	0.29
		Total	276	83	0.30
	2009-10	Kharif	153	44	0.29
		Rabi	8	2	0.25
		Total	161	46	0.29
	2010-11	Kharif	226	78	0.35
		Rabi	8	3	0.38
		Total	234	81	0.35
	2011-12	Kharif	127	27	0.21
		Rabi	2	1	0.50
		Total	129	28	0.22
	2012-13	Kharif	143	41	0.29
		Rabi	2	1	0.50
		Total	145	42	0.29
	2013-14	Kharif	132	25	0.19
		Rabi	3	2	0.67
		Total	135	27	0.20
Wheat					
1.HOSHANGABAD	1997-98	Rabi	234600	348900	1.49
	1998-99	Rabi	157700	331900	2.10
	1999-00	Rabi	161391	428000	2.65
	2000-01	Rabi	159623	406129	2.54
	2001-02	Rabi	165938	439373	2.65
	2002-03	Rabi	166902	376038	2.25
	2003-04	Rabi	178476	439313	2.46
	2004-05	Rabi	192727	449691	2.33
	2005-06	Rabi	202628	450475	2.22
	2006-07	Rabi	209184	568680	2.72
	2007-08	Rabi	217612	698551	3.21
	2008-09	Rabi	219007	607398	2.77
	2009-10	Whole Year	232477	700109	3.01
	2010-11	Rabi	242251	853964	3.53
	2011-12	Rabi	250555	1186378	4.74
	2012-13	Rabi	259950	1015365	3.91
	2013-14	Rabi	260258	829182	3.19

9.5.17 Field Visit Photos

Data Collection During Visit (Kharif)At Babai Village

Bhati Village

Dhaba Kalan

Dorgada

Tirnoda Village

Village Gujar Khappa

Guradiyakalan

Hoshangabad

Itarsi

Jamani

Lalwani

Rajpura

Sirwar

<u>Visit Rabi</u>

Ankhmau Village

Babai

Diwala Khedi

Hoshangabad

Panoramic View of Field Near Hoshangabad

Jamani

Nimsadiya

Satwasa

Sukkarwada

CHAPTER 10
SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

This study is an attempt to develop a distributed conjunctive use model for optimal and sustainable management of resources in irrigation command area. To demonstrate applicability of developed model, a canal command system of Tawa project, Madhya Pradesh, India has been considered to solve the optimal resources allocation problem. The Crop Production Response Functions of all the crops grown in the command area have been integrated along with the cost functions for different resources in the main framework of conjunctive use model. The calibrated groundwater model has been externally coupled with conjunctive use model. Further, the formulated conjunctive use model has been applied to evaluate different management strategies of resources allocation in the Tawa Command. Summary and conclusions of major results of this study are presented in this chapter. Recommendations for the future research work are also discussed in the last part of the chapter.

10.1 SUMMARY AND CONCLUSIONS

Application of mathematical model developed in the present study has been successfully demonstrated for resources allocation problem of Tawa Command. The developed model has been found capable in achieving the optimum utilization of all available resources to maximize the benefits, and in solving the existing problems of groundwater system in the command area. The summery and salient conclusions of the study are as follows:

1. An extensive database for Tawa Command has been developed using geospatial tools, like remote sensing and GIS. The developed database facilitates in distributed parameter estimations for resources assessment, groundwater modelling and conjunctive use modelling. Use of loose coupling approach between database and different models reduces the computational complexity in the conjunctive use modelling. Thus, present study has demonstrated the effective use of geospatial techniques in water resources management studies.

2. A land use land cover change detection analysis has been carried out using temporal, multi-band remote sensing data and change detection layer generated using NIR band for two months (November and January) in Rabi season during 1995 and 2005. Supervised

classification technique has been applied to generate the land use map. Comparison between land use in Rabi season of years 1995 and 2005 reveals that the cropping intensity of major crop has increased during this decade. Also crop identification (change in cropping pattern) analysis has been carried out for the year 2013-14 and 2015-16.

3. The analysis of trend in groundwater using observation well data indicates that there are problems of rising groundwater levels in head reach (Hoshangabad and Itarsi block) and water table depletion in tail reach (Harda, Khirkiya and Timirani block) of Left Bank Main Canal system. This trend indicates the deficit surface water supply in tail reach and excess water uses in head reach of the canal.

4. Distributed groundwater model developed using observed aquifer parameters and water table data has been calibrated for the study area through inverse problem approach. The resulting hydraulic conductivity (K) ranges between 5.79E-05 to 5.90E-04 m/s. During model calibration stage, the Normalized RMS (NRMS) varies between 3.27% to 5.25% and, in validation stage, the NRMS is around 3.72% to 4.5%. The calibrated model has been found to be more sensitive to the values of recharge and hydraulic conductivity (K) than the specific yield (S_y).
5. Groundwater cost functions have been developed to estimate the unit cost of groundwater pumping for different well capacities in the study area. Optimum well capacity for the alluvium aquifer of the command area has been found to be 0.015 m^3/s.
6. Crop Production Response Functions for all the thirteen crops grown in the command area have been developed using generalized data on crop yield reduction in response to water deficit, published by FAO (Doorenbos et al., 1979). The month wise values of yield reduction factors (K_y) have been estimated for all the crops.
7. The cost coefficients of all resources and the Crop Production Response Functions have been internally integrated in the objective function of the conjunctive use model. However, the groundwater model has been externally coupled to the conjunctive use model to reduce the complexity of problem. The external coupling between conjunctive use model and groundwater pumping cost functions reduces the computational complexity of the conjunctive use model by successive linearization. The Crop Production Response Functions integrated in objective function of conjunctive use model adds the capability of managing the water deficit scenario to the developed model.

8. Designed cropping pattern and irrigation intensity scenario with total benefits of around 9223.56 Million Rupees, does not utilize all available resources (land and water) as the water utilization level for surface water and groundwater has been around 84.37% and 83.33% respectively.
9. Existing cropping pattern scenario in the command area is economically inferior to the design cropping pattern scenario, as the total benefits are decreased by 3.5% (323.76 Million Rupees). The benefits per unit cultivated area are also decreased by 1307 Rs/ha. However, the benefits per unit water utilized are increased by 3389 Rs/ha-m due to the decrease in groundwater utilization by 18.9%. The effect of existing cropping pattern on groundwater system indicates that the groundwater in head reach will continuously rise and trend of depletion in water table will aggravate further in tail reach if the same resources allocation scenario continues.
10. Two approaches; i) surface water supply reduction (20% to 100%) in Zone-3, ii) surface water diversion (20% to 100%) from Zone-3 to Zone-1, have been evaluated over existing cropping pattern scenario. The surface water reduction approach has been found unsuitable both on economic or technical aspects. The strategy of diverting 80% of surface water supply from Zone-3 to Zone-1 has been found optimal in second approach. The water utilization levels in this strategy are around 82.32% and 67.49% for surface water and groundwater respectively. The benefits from this strategy are less as compared to benefits from designed cropping pattern scenario and the resources are underutilized.
11. To maximize the utilization of available resources, the increase in irrigation intensity has been proposed for Rabi season (80%). The resources allocation results of this scenario indicate that the total benefits have increased by 5% (455.34 Million Rupees) over designed cropping pattern scenario and by 8.75% over the existing cropping pattern scenario. The surface water utilization level has also increased to 90% in this scenario. The increased irrigation intensity scenario has been found to be economically superior to the designed cropping pattern and existing cropping pattern scenarios.
12. Different surface water diversion strategies have been evaluated for increased irrigation intensity scenario. It has been found that benefits are higher in strategy of 80% surface water diversion from Zone-3 to Zone-1, but the surface water utilization level has decreased. The under-utilization of diverted surface water is due to temporal disparity

between irrigation water demand and supply. The irrigation water demand is high in the months of March and October. However, surface water supply is less than the demand in these months.

13. The spatio-temporal conjunctive use approach has been suggested with 100% diversion of surface water from Zone-3 and changed surface water supply schedule in Zone-1. Total benefits achieved in spatio-temporal conjunctive use scenario are around 9747.53 Million Rupees, 847.74 Million Rupees (10%) higher than the total benefits in existing cropping pattern scenario and 523.98 Million Rupees (6%) higher than the designed cropping pattern scenario. Benefits per unit water utilized are also highest in this strategy (25399 Rs/ha-m). The surface water utilization level is increased to 91.32% (119581.7 ha-m). The groundwater pumping/ utilization from Zone-1 have been reduced by 15500 ha-m and the groundwater pumping in Zone-3 is increased by 90% (26557.9 ha-m). The effect of changed irrigation intensity and spatio-temporal conjunctive use approach on groundwater system indicates that the groundwater depletion trend in Zone-1 will reverse and the rising groundwater levels in Zone-3 will be stabilized if this approach is implemented. The spatio-temporal conjunctive use approach not only increases the benefits of the command area but also makes the canal command system sustainable.
14. To demonstrate the capability of developed conjunctive use model to optimally manage the deficit water supply system, the groundwater availability has been reduced to 80000 ha-m for existing cropping pattern scenario. Total benefits from water deficit scenario are marginally less (61.13 Million Rupees) than that of normal water supply scenario. The benefits per unit water utilized are increased by 2112 Rs/ha-m as compared to normal water supply scenario. The groundwater pumping/utilization is reduced by 10% to 17% in different zones, due to deficit in availability. The analysis of deficit water supply on monthly basis indicates that the model reduces the groundwater supply in the time period when the deficit irrigation will have minimum impact on yield of a particular crop. The groundwater utilization level in particular time period has also been considered by the model to decide the time and amount of deficit water supply for irrigation.
15. With spatio-temporal conjunctive use approach, the utilization levels of resources would become optimal in the canal command system and Tawa project would become sustainable. The generalized conclusions drawn from present study are:

16. The mismanagement of surface water in command area of irrigation projects leads to the problems of reduction in benefits along with environmental degradation of the command area.
17. The approach of loose coupling between geospatial database and water resource management models improves the performance of models and reduces the uncertainty in results by providing spatially as well as temporally distributed input parameters.
18. The external coupling between groundwater model and conjunctive use model reduces the complexity, introduced by dynamic response of groundwater system. This approach enhances the applicability of distributed conjunctive use model for larger area with more number of decision variables.
19. The integration of Crop Production Response Functions in the conjunctive use model broadens the applicability of conjunctive use model in planning and managing the existing irrigation projects optimally in both normal supply scenario as well as water deficit scenario.
20. Judicious application of spatio-temporal conjunctive use approach could escalate the performance of irrigation system on all fronts including economic and environmental.
21. Major crops in the Tawa Command Area (TCA) are wheat in the Rabi season having acreage of 275, 324 ha and minor crops having an acreage of 71093 ha in the TCA. Kharif Acreage from 01-October-2000 has been delineated is 142,106 ha and 59,905 ha of land under minor crops.
22. Total ground water resources in the Tawa command area is 2712 MCM obtained from GWFM for the year 2003.Ground water pumping in the command area is 328 MCM. Because there is no significant pumping as compared to total ground water resources in the command area. Waterlogging conditions are observed at few places. Further being a flat area and varying conductivity zones further enhanced the shallow water table condition in these areas.
23. NDVI based crop identification and discrimination in large areas is helping planners in multiple of ways. In the preset study, two LISS III (24m x 24m) images and nine AWiFS (60m x 60m) images (23rd October 2011, 11th November 2011, 21st November 2011, 10th December 2011, 24th December 2011, 12th January 2012, 05th February 2012, 20th February 2012 and 10th March 2012) have been utilized for identifying and discriminating

different crops during Rabi season in the Tawa command. Based on the NDVI profile and sample GPS points taken during field visits, five principal crops viz., wheat (74.68%), chick-pea (14.52%), sugarcane (2.42%), linseeds (2.32%) and others mainly vegetables and orchards (6.06%) were identified in the command.

24. The study demonstrated how distributed crop evapotranspiration (ETc map) can be prepared based on the relationship between crop coefficient (Kc) values and NDVI values. This helps in estimating the distributed demand scenario in the canal command for better crop management. The NDVI based demand estimated for the months of October, November, December, January, February, and March are 724.63 ha-m, 18786.85 ha-m, 18587.72 ha-m, 18121.88 ha-m, 12737.38 ha-m, and 537.08 ha-m respectively.
25. Further, assessment was carried out on water availability and utilization scenario in the study based on the projected minimum and maximum temperature and rainfall from downscaled GCM HadCM3 A2 scenario.
26. In the study optimization models were formulated for the design cropping pattern, existing cropping pattern as reported from field, and existing cropping pattern as estimated based on identified crops using remote sensing satellites for the Rabi season in five zones of the Tawa canal command. Further, in the existing cropping pattern as estimated based on the RS technique, estimated crop water requirement from HadCM3 A2 scenario have been replaced and solved for optimization for the period 2020s, 2050s, and 2080s. The results from the optimization for different scenarios are as given below:
27. The total benefits from designed scenario (67% irrigation intensity) was to the tune of 3831.12 Million Rupees. The total benefits are converted in terms of benefit per unit of land cultivated (Rs./ha) and benefits per unit of water utilized (Rs./ ha-m). Accordingly, the benefits per unit of cultivated area are found to be 21851 Rs./ha and benefits per unit of water utilized are around 33618 Rs/ha-m. The surface water is under-utilized in all zones during Rabi season. The groundwater utilization/pumping was higher in March and May months to satisfy irrigation demand during harvesting and land preparation stage. Among all zones the groundwater utilization was highest in zone-1 (7781.11 ha-m).
28. The total benefits from existing scenario (74% irrigation intensity) was to the tune of 4310.12 Million Rupees. The benefits per unit land cultivated and per unit of water utilized are 24582 Rs./ha and 32792 Rs/ha-m respectively.

29. It has been seen that the existing cropping pattern in the command has considerably changed from the design cropping pattern. It has been captured while identifying the Rabi crops for the Tawa command using remote sensing imageries and GPS sampling. The existing irrigation intensity at present is about 81%. The results obtained the existing scenario (81%) indicated a total benefits of 5096.31 Million Rupees. The benefits per unit of cultivated area are found to be 29066 Rs./ha and benefits per unit of water utilized are around 32055 Rs/ha-m.
30. Keeping the irrigation intensity as 81%, the optimization models run separately for the periods 2020s, 2050s, and 2080s utilizing the estimated crop water requirement from the HadCM3 A scenario. The water availability has also been accounted based on the projected rainfall. It has been seen that the net benefits in the future is to the tune of 5228.63 Million Rupees, 5220.99 Million Rupees, and 5211.66 Million Rupees. This may be attributed to the higher cost on water utilization due to the increased demand of the crop water requirement in future. The increased rainfall as projected by the HadCM3 A2 scenario will have lesser impact in the Rabi season since the crops are mainly irrigated through canal supply. The increased rainfall in the command will have considerable effect for the crops during Kharif season.

10.2 RECOMMENDATIONS FOR FUTURE RESEARCH

The modelling concept developed in the present research has extended the application of spatial technologies and system engineering to resources management problems in Tawa Command Area. Following are some of the aspects worthy for consideration in future research:

1. Research on climate change is gaining momentum in wide spectrum of fields. The vagaries of climate change and its very threatening nature to the human existence is forcing world community to undertake research on its mitigation and adaptation since controlling climate is beyond our reach. The long term climate change pattern assessment and its feasibility of considering an option for adaptation to climate change ensuring food security in future needs to be investigated.
2. Recent reports indicate that nitrate concentration in some observation wells in the Tawa Command Area exceeded the permissible limits possibly due to pollutants from agricultural/municipal water use. The present model can be extended to include the water

quality aspects from various sources and water quality requirement of different crops into the decision process. However, it requires detailed data on water quality.

3. The cost functions for groundwater are developed considering uniform values of aquifer parameters from the entire command area. Though the specific yield for unconfined aquifers does not have any significant effect on the unit cost of groundwater but lower transmissivity may affect the unit cost. These aspects can be investigated in future work.
4. In the present study, optimization and groundwater simulation model is coupled externally through an iterative process to obtain the dynamic response of groundwater system in response to various management scenarios. Other approaches like, embedding and response coefficient approach can be explored further. Present modelling concept considers the nonlinearity of groundwater pumping, however, it can be extended to include the other hydraulic management objectives, like water table depth restriction.
5. Optimization for resources allocation in the Tawa command has been done for the *Rabi* season only. This is due to two reasons: (i) The crop identification based on NDVI profiling is difficult if cloud-free satellite images are not available. Due to non-availability of cloud-free imageries, *Kharif* crop identifications has not been attempted in the study; (ii) Canal supply is only practiced in the *Rabi* season. The optimization for resources allocation can be considered for both *Kharif* and *Rabi* seasons, possibly including the water quality requirement of different crops into the decision process. However, it requires detailed data on water quality.

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Appendix- I

CONJUNCTIVE USE MODEL RESULTS

Allocations of different resources and benefits for the existing cropping pattern (Strategy-3)

						TOTAL BENEFITS (Million Rs)= 8899.79
AREA UNDER DIFFERENT CROPS (ha)						
	ZONE-1	ZONE-2	ZONE-3	ZONE-4	ZONE-5	TOTAL
PADDY	4761.7	3566.8	1579.9	2372.0	778.9	13059.3
COTTON	4761.7	3566.8	1579.9	2372.0	778.9	13059.3
JAWAR	6666.3	4993.5	2211.9	3320.8	1090.4	18282.9
GROUNDNUT	4761.7	3566.8	1579.9	2372.0	778.9	13059.3
MAIZE	7618.7	5706.9	2527.9	3795.2	1246.2	20894.9
PULSES	4761.7	3566.8	1579.9	2372.0	778.9	13059.3
SOYABEAN	30474.6	22827.6	10111.7	15180.7	4984.7	83579.3
PERENNIAL	3809.3	2853.5	1264.0	1897.6	623.1	10447.5
WHEAT	52378.2	39235.0	17379.4	26091.8	8567.5	143651.9
GRAM	6666.3	4993.5	2211.9	3320.8	1090.4	18282.9
PEAS	1904.7	1426.7	632.0	948.8	311.5	5223.7
VEGETABLE	952.3	713.4	316.0	474.4	155.8	2611.9
LINSEED	1904.7	1426.7	632.0	948.8	311.5	5223.7
KHARIF CROPS	63806.4	47795.2	21171.1	31784.7	10436.9	174994.3
RABI CROPS	63806.2	47795.3	21171.3	31784.6	10436.7	174994.1
OPTIMAL ALLOCATION OF SURFACE WATER (ha-m)						
JANUARY	7148.2	5354.5	2371.8	3371.8	1169.2	19415.6
FEBRUARY	8239.3	8218.7	2508.5	3371.8	1794.7	24132.9
MARCH	3570.3	4213.8	1087.0	1461.1	821.4	11153.6
OCTOBER	4394.3	5186.2	1337.8	1798.3	1010.9	13727.5
NOVEMBER	8239.3	7312.0	2508.5	3371.8	1596.7	23028.2
DECEMBER	6906.3	5173.3	2291.6	3371.8	1129.7	18872.7
TOTAL	38497.7	35458.5	12105.2	16746.7	7522.5	**110330.5**
OPTIMAL ALLOCATION OF GROUNDWATER (ha-m)						
JANUARY	0.0	0.0	0.0	189.0	0.0	189.0
FEBRUARY	2732.5	0.0	1132.0	2093.7	0.0	5958.3
MARCH	5074.0	2261.4	1781.3	2845.0	592.5	12554.2
APRIL	826.6	619.2	274.3	411.8	135.2	2267.1
MAY	2175.1	1629.3	721.7	1083.5	355.8	5965.5
JUNE	1934.2	1448.8	641.8	963.5	316.4	5304.7
JULY	2002.8	1500.2	664.5	997.7	327.6	5492.7

AUGUST	1829.4	1370.4	607.0	911.3	299.3	5017.4
SEPTEMBER	6655.9	4985.7	2208.4	3315.6	1088.7	18254.3
OCTOBER	10706.8	6125.6	3672.8	5724.2	1459.2	27688.6
NOVEMBER	1522.1	0.0	730.4	1490.7	0.0	3743.3
DECEMBER	0.0	0.0	0.0	68.5	0.0	68.5
TOTAL	35459.5	19940.6	12434.2	20094.6	4574.7	**92503.6**

Allocations of different resources and benefits for the existing cropping pattern (Strategy-4)

TOTAL BENEFITS (Million Rs)=8900.917						
AREA UNDER DIFFERENT CROPS (ha)						
	ZONE-1	ZONE-2	ZONE-3	ZONE-4	ZONE-5	TOTAL
PADDY	4761.7	3566.8	1579.9	2372.0	778.9	13059.3
COTTON	4761.7	3566.8	1579.9	2372.0	778.9	13059.3
JAWAR	6666.3	4993.5	2211.9	3320.8	1090.4	18282.9
GROUNDNUT	4761.7	3566.8	1579.9	2372.0	778.9	13059.3
MAIZE	7618.7	5706.9	2527.9	3795.2	1246.2	20894.9
PULSES	4761.7	3566.8	1579.9	2372.0	778.9	13059.3
SOYABEAN	30474.6	22827.6	10111.7	15180.7	4984.7	83579.3
PERENNIAL	3809.3	2853.5	1264.0	1897.6	623.1	10447.5
WHEAT	52378.2	39235.0	17379.4	26091.8	8567.5	143651.9
GRAM	6666.3	4993.5	2211.9	3320.8	1090.4	18282.9
PEAS	1904.7	1426.7	632.0	948.8	311.5	5223.7
VEGETABLE	952.3	713.4	316.0	474.4	155.8	2611.9
LINSEED	1904.7	1426.7	632.0	948.8	311.5	5223.7
KHARIF CROPS	63806.4	47795.2	21171.1	31784.7	10436.9	174994.3
RABI CROPS	63806.2	47795.3	21171.3	31784.6	10436.7	174994.1
OPTIMAL ALLOCATION OF SURFACE WATER (ha-m)						
JANUARY	7148.2	5354.5	2371.8	3371.8	1169.2	19415.6
FEBRUARY	8866.4	8218.7	2508.5	3371.8	1794.7	24760.0
MARCH	3842.0	4213.8	1087.0	1461.1	821.4	11425.3
OCTOBER	4728.8	5186.2	1337.8	1798.3	1010.9	14062.0
NOVEMBER	8866.4	7312.0	2508.5	3371.8	1596.7	23655.4
DECEMBER	6906.3	5173.3	2291.6	3371.8	1129.7	18872.7
TOTAL	40358.1	35458.5	12105.2	16746.7	7522.5	**112191.0**
OPTIMAL ALLOCATION OF GROUNDWATER (ha-m)						
JANUARY	0.0	0.0	0.0	189.0	0.0	189.0
FEBRUARY	2105.4	0.0	1132.0	2093.7	0.0	5331.2
MARCH	4802.3	2261.4	1781.3	2845.0	592.5	12282.5
APRIL	826.6	619.2	274.3	411.8	135.2	2267.1

MAY	2175.1	1629.3	721.7	1083.5	355.8	5965.5
JUNE	1934.2	1448.8	641.8	963.5	316.4	5304.7
JULY	2002.8	1500.2	664.5	997.7	327.6	5492.7
AUGUST	1829.4	1370.4	607.0	911.3	299.3	5017.4
SEPTEMBER	6655.9	4985.7	2208.4	3315.6	1088.7	18254.3
OCTOBER	10372.4	6125.6	3672.8	5724.2	1459.2	27354.2
NOVEMBER	895.0	0.0	730.4	1490.7	0.0	3116.2
DECEMBER	0.0	0.0	0.0	68.5	0.0	68.5
TOTAL	33599.1	19940.6	12434.2	20094.6	4574.7	**90643.2**

Allocations of different resources and benefits for the existing cropping pattern (Strategy-5)

TOTAL BENEFITS (Million Rs)=8899.785						
AREA UNDER DIFFERENT CROPS (ha)						
	ZONE-1	ZONE-2	ZONE-3	ZONE-4	ZONE-5	TOTAL
PADDY	4761.7	3566.8	1579.9	2372.0	778.9	13059.3
COTTON	4761.7	3566.8	1579.9	2372.0	778.9	13059.3
JAWAR	6666.3	4993.5	2211.9	3320.8	1090.4	18282.9
GROUNDNUT	4761.7	3566.8	1579.9	2372.0	778.9	13059.3
MAIZE	7618.7	5706.9	2527.9	3795.2	1246.2	20894.9
PULSES	4761.7	3566.8	1579.9	2372.0	778.9	13059.3
SOYABEAN	30474.6	22827.6	10111.7	15180.7	4984.7	83579.3
PERENNIAL	3809.3	2853.5	1264.0	1897.6	623.1	10447.5
WHEAT	52378.2	39235.0	17379.4	26091.8	8567.5	143651.9
GRAM	6666.3	4993.5	2211.9	3320.8	1090.4	18282.9
PEAS	1904.7	1426.7	632.0	948.8	311.5	5223.7
VEGETABLE	952.3	713.4	316.0	474.4	155.8	2611.9
LINSEED	1904.7	1426.7	632.0	948.8	311.5	5223.7
KHARIF CROPS	63806.4	47795.2	21171.1	31784.7	10436.9	174994.3
RABI CROPS	63806.2	47795.3	21171.3	31784.6	10436.7	174994.1
OPTIMAL ALLOCATION OF SURFACE WATER (ha-m)						
JANUARY	7148.2	5354.5	1881.4	3371.8	1169.2	18925.1
FEBRUARY	8239.3	8218.7	1881.4	3371.8	1794.7	23505.8
MARCH	3570.3	4213.8	815.2	1461.1	821.4	10881.8
OCTOBER	4394.3	5186.2	1003.4	1798.3	1010.9	13393.1
NOVEMBER	8239.3	7312.0	1881.4	3371.8	1596.7	22401.1
DECEMBER	6906.3	5173.3	1881.4	3371.8	1129.7	18462.5
TOTAL	38497.7	35458.5	9344.1	16746.7	7522.5	**107569.4**

OPTIMAL ALLOCATION OF GROUNDWATER (ha-m)						
JANUARY	0.0	0.0	490.5	189.0	0.0	679.5
FEBRUARY	2732.5	0.0	1759.2	2093.7	0.0	6585.4
MARCH	5074.0	2261.4	2053.0	2845.0	592.5	12826.0
APRIL	826.6	619.2	274.3	411.8	135.2	2267.1
MAY	2175.1	1629.3	721.7	1083.5	355.8	5965.5
JUNE	1934.2	1448.8	641.8	963.5	316.4	5304.7
JULY	2002.8	1500.2	664.5	997.7	327.6	5492.7
AUGUST	1829.4	1370.4	607.0	911.3	299.3	5017.4
SEPTEMBER	6655.9	4985.7	2208.4	3315.6	1088.7	18254.3
OCTOBER	10706.8	6125.6	4007.2	5724.2	1459.2	28023.1
NOVEMBER	1522.1	0.0	1357.5	1490.7	0.0	4370.4
DECEMBER	0.0	0.0	410.2	68.5	0.0	478.7
TOTAL	35459.5	19940.6	15195.4	20094.6	4574.7	**95264.7**

Allocations of different resources and benefits for the existing cropping pattern (Strategy-6)

TOTAL BENEFITS (Million Rs)=8902.041						
AREA UNDER DIFFERENT CROPS (ha)						
	ZONE-1	ZONE-2	ZONE-3	ZONE-4	ZONE-5	TOTAL
PADDY	4761.7	3566.8	1579.9	2372.0	778.9	13059.3
COTTON	4761.7	3566.8	1579.9	2372.0	778.9	13059.3
JAWAR	6666.3	4993.5	2211.9	3320.8	1090.4	18282.9
GROUNDNUT	4761.7	3566.8	1579.9	2372.0	778.9	13059.3
MAIZE	7618.7	5706.9	2527.9	3795.2	1246.2	20894.9
PULSES	4761.7	3566.8	1579.9	2372.0	778.9	13059.3
SOYABEAN	30474.6	22827.6	10111.7	15180.7	4984.7	83579.3
PERENNIAL	3809.3	2853.5	1264.0	1897.6	623.1	10447.5
WHEAT	52378.2	39235.0	17379.4	26091.8	8567.5	143651.9
GRAM	6666.3	4993.5	2211.9	3320.8	1090.4	18282.9
PEAS	1904.7	1426.7	632.0	948.8	311.5	5223.7
VEGETABLE	952.3	713.4	316.0	474.4	155.8	2611.9
LINSEED	1904.7	1426.7	632.0	948.8	311.5	5223.7
KHARIF CROPS	63806.4	47795.2	21171.1	31784.7	10436.9	
RABI CROPS	63806.2	47795.3	21171.3	31784.6	10436.7	
OPTIMAL ALLOCATION OF SURFACE WATER (ha-m)						
JANUARY	7148.2	5354.5	1881.4	3371.8	1169.2	18925.1

FEBRUARY	9493.5	8218.7	1881.4	3371.8	1794.7	24760.0
MARCH	4113.8	4213.8	815.2	1461.1	821.4	11425.3
OCTOBER	5063.2	5186.2	1003.4	1798.3	1010.9	14062.0
NOVEMBER	9493.4	7312.0	1881.4	3371.8	1596.7	23655.3
DECEMBER	6906.3	5173.3	1881.4	3371.8	1129.7	18462.5
TOTAL	42218.4	35458.5	9344.1	16746.7	7522.5	**111290.2**
OPTIMAL ALLOCATION OF GROUNDWATER (ha-m)						
JANUARY	0.0	0.0	490.5	189.0	0.0	679.5
FEBRUARY	1478.3	0.0	1759.2	2093.7	0.0	5331.2
MARCH	4530.5	2261.4	2053.0	2845.0	592.5	12282.5
APRIL	826.6	619.2	274.3	411.8	135.2	2267.1
MAY	2175.1	1629.3	721.7	1083.5	355.8	5965.5
JUNE	1934.2	1448.8	641.8	963.5	316.4	5304.7
JULY	2002.8	1500.2	664.5	997.7	327.6	5492.7
AUGUST	1829.4	1370.4	607.0	911.3	299.3	5017.4
SEPTEMBER	6655.9	4985.7	2208.4	3315.6	1088.7	18254.3
OCTOBER	10037.9	6125.6	4007.2	5724.2	1459.2	27354.2
NOVEMBER	267.9	0.0	1357.5	1490.7	0.0	3116.2
DECEMBER	0.0	0.0	410.2	68.5	0.0	478.7
TOTAL	31738.7	19940.6	15195.4	20094.6	4574.7	**91543.9**

Allocations of different resources and benefits for the existing cropping pattern (Strategy-7)

TOTAL BENEFITS (Million Rs)=8899.78						
AREA UNDER DIFFERENT CROPS (ha)						
	ZONE-1	ZONE-2	ZONE-3	ZONE-4	ZONE-5	TOTAL
PADDY	4761.7	3566.8	1579.9	2372.0	778.9	13059.3
COTTON	4761.7	3566.8	1579.9	2372.0	778.9	13059.3
JAWAR	6666.3	4993.5	2211.9	3320.8	1090.4	18282.9
GROUNDNUT	4761.7	3566.8	1579.9	2372.0	778.9	13059.3
MAIZE	7618.7	5706.9	2527.9	3795.2	1246.2	20894.9
PULSES	4761.7	3566.8	1579.9	2372.0	778.9	13059.3
SOYABEAN	30474.6	22827.6	10111.7	15180.7	4984.7	83579.3
PERENNIAL	3809.3	2853.5	1264.0	1897.6	623.1	10447.5
WHEAT	52378.2	39235.0	17379.4	26091.8	8567.5	143651.9
GRAM	6666.3	4993.5	2211.9	3320.8	1090.4	18282.9
PEAS	1904.7	1426.7	632.0	948.8	311.5	5223.7
VEGETABLE	952.3	713.4	316.0	474.4	155.8	2611.9

LINSEED	1904.7	1426.7	632.0	948.8	311.5	5223.7
KHARIF CROPS	63806.4	47795.2	21171.1	31784.7	10436.9	
RABI CROPS	63806.2	47795.3	21171.3	31784.6	10436.7	
OPTIMAL ALLOCATION OF SURFACE WATER (ha-m)						
JANUARY	7148.2	5354.5	1254.2	3371.8	1169.2	18298.0
FEBRUARY	8239.3	8218.7	1254.2	3371.8	1794.7	22878.7
MARCH	3570.3	4213.8	543.5	1461.1	821.4	10610.1
OCTOBER	4394.3	5186.2	668.9	1798.3	1010.9	13058.6
NOVEMBER	8239.3	7312.0	1254.2	3371.8	1596.7	21774.0
DECEMBER	6906.3	5173.3	1254.2	3371.8	1129.7	17835.4
TOTAL	38497.7	35458.5	6229.4	16746.7	7522.5	**104454.7**
OPTIMAL ALLOCATION OF GROUNDWATER (ha-m)						
JANUARY	0.0	0.0	1117.6	189.0	0.0	1306.6
FEBRUARY	2732.5	0.0	2386.3	2093.7	0.0	7212.5
MARCH	5074.0	2261.4	2324.8	2845.0	592.5	13097.7
APRIL	826.6	619.2	274.3	411.8	135.2	2267.1
MAY	2175.1	1629.3	721.7	1083.5	355.8	5965.5
JUNE	1934.2	1448.8	641.8	963.5	316.4	5304.7
JULY	2002.8	1500.2	664.5	997.7	327.6	5492.7
AUGUST	1829.4	1370.4	607.0	911.3	299.3	5017.4
SEPTEMBER	6655.9	4985.7	2208.4	3315.6	1088.7	18254.3
OCTOBER	10706.8	6125.6	4341.7	5724.2	1459.2	28357.6
NOVEMBER	1522.1	0.0	1984.7	1490.7	0.0	4997.5
DECEMBER	0.0	0.0	1037.3	68.5	0.0	1105.8
TOTAL	35459.5	19940.6	18310.0	20094.6	4574.7	**98379.4**

Allocations of different resources and benefits for the existing cropping pattern (Strategy-8)

TOTAL BENEFITS (Million Rs)=8902.946						
AREA UNDER DIFFERENT CROPS (ha)						
	ZONE-1	ZONE-2	ZONE-3	ZONE-4	ZONE-5	TOTAL
PADDY	4761.7	3566.8	1579.9	2372.0	778.9	13059.3
COTTON	4761.7	3566.8	1579.9	2372.0	778.9	13059.3
JAWAR	6666.3	4993.5	2211.9	3320.8	1090.4	18282.9
GROUNDNUT	4761.7	3566.8	1579.9	2372.0	778.9	13059.3
MAIZE	7618.7	5706.9	2527.9	3795.2	1246.2	20894.9
PULSES	4761.7	3566.8	1579.9	2372.0	778.9	13059.3
SOYABEAN	30474.6	22827.6	10111.7	15180.7	4984.7	83579.3

PERENNIAL	3809.3	2853.5	1264.0	1897.6	623.1	10447.5
WHEAT	52378.2	39235.0	17379.4	26091.8	8567.5	143651.9
GRAM	6666.3	4993.5	2211.9	3320.8	1090.4	18282.9
PEAS	1904.7	1426.7	632.0	948.8	311.5	5223.7
VEGETABLE	952.3	713.4	316.0	474.4	155.8	2611.9
LINSEED	1904.7	1426.7	632.0	948.8	311.5	5223.7
KHARIF CROPS	63806.4	47795.2	21171.1	31784.7	10436.9	
RABI CROPS	63806.2	47795.3	21171.3	31784.6	10436.7	
OPTIMAL ALLOCATION OF SURFACE WATER (ha-m)						
JANUARY	7148.2	5354.5	1254.2	3371.8	1169.2	18298.0
FEBRUARY	10120.6	8218.7	1254.2	3371.8	1794.7	24760.0
MARCH	4385.5	4213.8	543.5	1461.1	821.4	11425.3
OCTOBER	5397.7	5186.2	668.9	1798.3	1010.9	14062.0
NOVEMBER	9761.4	7312.0	1254.2	3371.8	1596.7	23296.1
DECEMBER	6906.3	5173.3	1254.2	3371.8	1129.7	17835.4
TOTAL	43719.7	35458.5	6229.4	16746.7	7522.5	**109676.8**
OPTIMAL ALLOCATION OF GROUNDWATER (ha-m)						
JANUARY	0.0	0.0	1117.6	189.0	0.0	1306.6
FEBRUARY	851.2	0.0	2386.3	2093.7	0.0	5331.2
MARCH	4258.8	2261.4	2324.8	2845.0	592.5	12282.5
APRIL	826.6	619.2	274.3	411.8	135.2	2267.1
MAY	2175.1	1629.3	721.7	1083.5	355.8	5965.5
JUNE	1934.2	1448.8	641.8	963.5	316.4	5304.7
JULY	2002.8	1500.2	664.5	997.7	327.6	5492.7
AUGUST	1829.4	1370.4	607.0	911.3	299.3	5017.4
SEPTEMBER	6655.9	4985.7	2208.4	3315.6	1088.7	18254.3
OCTOBER	9703.5	6125.6	4341.7	5724.2	1459.2	27354.2
NOVEMBER	0.0	0.0	1984.7	1490.7	0.0	3475.4
DECEMBER	0.0	0.0	1037.3	68.5	0.0	1105.8
TOTAL	30237.4	19940.6	18310.0	20094.6	4574.7	**93157.3**

Allocations of different resources and benefits for the existing cropping pattern (Strategy-9)

TOTAL BENEFITS (Million Rs)=8899.056						
AREA UNDER DIFFERENT CROPS (ha)						
	ZONE-1	ZONE-2	ZONE-3	ZONE-4	ZONE-5	TOTAL
PADDY	4761.7	3566.8	1579.9	2372.0	778.9	13059.3
COTTON	4761.7	3566.8	1579.9	2372.0	778.9	13059.3

JAWAR	6666.3	4993.5	2211.9	3320.8	1090.4	18282.9
GROUNDNUT	4761.7	3566.8	1579.9	2372.0	778.9	13059.3
MAIZE	7618.7	5706.9	2527.9	3795.2	1246.2	20894.9
PULSES	4761.7	3566.8	1579.9	2372.0	778.9	13059.3
SOYABEAN	30474.6	22827.6	10111.7	15180.7	4984.7	83579.3
PERENNIAL	3809.3	2853.5	1264.0	1897.6	623.1	10447.5
WHEAT	52378.2	39235.0	17379.4	26091.8	8567.5	143651.9
GRAM	6666.3	4993.5	2211.9	3320.8	1090.4	18282.9
PEAS	1904.7	1426.7	632.0	948.8	311.5	5223.7
VEGETABLE	952.3	713.4	316.0	474.4	155.8	2611.9
LINSEED	1904.7	1426.7	632.0	948.8	311.5	5223.7
KHARIF CROPS	63806.4	47795.2	21171.1	31784.7	10436.9	
RABI CROPS	63806.2	47795.3	21171.3	31784.6	10436.7	
OPTIMAL ALLOCATION OF SURFACE WATER (ha-m)						
JANUARY	7148.2	5354.5	627.1	3371.8	1169.2	17670.9
FEBRUARY	8239.3	8218.7	627.1	3371.8	1794.7	22251.6
MARCH	3570.3	4213.8	217.1	1461.1	821.4	10283.7
OCTOBER	4394.3	5186.2	334.5	1798.3	1010.9	12724.2
NOVEMBER	8239.3	7312.0	627.1	3371.8	1596.7	21146.9
DECEMBER	6906.3	5173.3	627.1	3371.8	1129.7	17208.2
TOTAL	38497.7	35458.5	3060.1	16746.7	7522.5	**101285.5**
OPTIMAL ALLOCATION OF GROUNDWATER (ha-m)						
JANUARY	0.0	0.0	1744.7	189.0	0.0	1933.7
FEBRUARY	2732.5	0.0	3013.4	2093.7	0.0	7839.6
MARCH	5074.0	2261.4	2651.1	2845.0	592.5	13424.1
APRIL	826.6	619.2	274.3	411.8	135.2	2267.1
MAY	2175.1	1629.3	721.7	1083.5	355.8	5965.5
JUNE	1934.2	1448.8	641.8	963.5	316.4	5304.7
JULY	2002.8	1500.2	664.5	997.7	327.6	5492.7
AUGUST	1829.4	1370.4	607.0	911.3	299.3	5017.4
SEPTEMBER	6655.9	4985.7	2208.4	3315.6	1088.7	18254.3
OCTOBER	10706.8	6125.6	4676.2	5724.2	1459.2	28692.0
NOVEMBER	1522.1	0.0	2611.8	1490.7	0.0	5624.6
DECEMBER	0.0	0.0	1664.4	68.5	0.0	1732.9
TOTAL	35459.5	19940.6	21479.3	20094.6	4574.7	**101548.7**

Allocations of different resources and benefits for the existing cropping pattern (Strategy-10)

						TOTAL BENEFITS (Million Rs)=8902.969
AREA UNDER DIFFERENT CROPS (ha)						
	ZONE-1	ZONE-2	ZONE-3	ZONE-4	ZONE-5	TOTAL
PADDY	4761.7	3566.8	1579.9	2372.0	778.9	13059.3
COTTON	4761.7	3566.8	1579.9	2372.0	778.9	13059.3
JAWAR	6666.3	4993.5	2211.9	3320.8	1090.4	18282.9
GROUNDNUT	4761.7	3566.8	1579.9	2372.0	778.9	13059.3
MAIZE	7618.7	5706.9	2527.9	3795.2	1246.2	20894.9
PULSES	4761.7	3566.8	1579.9	2372.0	778.9	13059.3
SOYABEAN	30474.6	22827.6	10111.7	15180.7	4984.7	83579.3
PERENNIAL	3809.3	2853.5	1264.0	1897.6	623.1	10447.5
WHEAT	52378.2	39235.0	17379.4	26091.8	8567.5	143651.9
GRAM	6666.3	4993.5	2211.9	3320.8	1090.4	18282.9
PEAS	1904.7	1426.7	632.0	948.8	311.5	5223.7
VEGETABLE	952.3	713.4	316.0	474.4	155.8	2611.9
LINSEED	1904.7	1426.7	632.0	948.8	311.5	5223.7
KHARIF CROPS	63806.4	47795.2	21171.1	31784.7	10436.9	
RABI CROPS	63806.2	47795.3	21171.3	31784.6	10436.7	
OPTIMAL ALLOCATION OF SURFACE WATER (ha-m)						
JANUARY	7148.2	5354.5	627.1	3371.8	1169.2	17670.9
FEBRUARY	10747.8	8218.7	627.1	3371.8	1794.7	24760.0
MARCH	4657.3	4213.8	271.7	1461.1	821.4	11425.3
OCTOBER	5732.1	5186.2	334.5	1798.3	1010.9	14062.0
NOVEMBER	9761.4	7312.0	627.1	3371.8	1596.7	22669.0
DECEMBER	6906.3	5173.3	627.1	3371.8	1129.7	17208.2
TOTAL	44953.0	35458.5	3114.7	16746.7	7522.5	**107795.4**
OPTIMAL ALLOCATION OF GROUNDWATER (ha-m)						
JANUARY	0.0	0.0	1744.7	189.0	0.0	1933.7
FEBRUARY	224.0	0.0	3013.4	2093.7	0.0	5331.2
MARCH	3987.0	2261.4	2596.5	2845.0	592.5	12282.5
APRIL	826.6	619.2	274.3	411.8	135.2	2267.1
MAY	2175.1	1629.3	721.7	1083.5	355.8	5965.5
JUNE	1934.2	1448.8	641.8	963.5	316.4	5304.7
JULY	2002.8	1500.2	664.5	997.7	327.6	5492.7
AUGUST	1829.4	1370.4	607.0	911.3	299.3	5017.4
SEPTEMBER	6655.9	4985.7	2208.4	3315.6	1088.7	18254.3
OCTOBER	9369.0	6125.6	4676.2	5724.2	1459.2	27354.2

NOVEMBER	0.0	0.0	2611.8	1490.7	0.0	4102.5
DECEMBER	0.0	0.0	1664.4	68.5	0.0	1732.9
TOTAL	29004.1	19940.6	21424.7	20094.6	4574.7	**95038.7**

Allocations of different resources and benefits for the existing cropping pattern (Strategy-11)

						TOTAL BENEFITS (Million Rs)=8896.842
AREA UNDER DIFFERENT CROPS (ha)						
	ZONE-1	ZONE-2	ZONE-3	ZONE-4	ZONE-5	TOTAL
PADDY	4761.7	3566.8	1579.9	2372.0	778.9	13059.3
COTTON	4761.7	3566.8	1579.9	2372.0	778.9	13059.3
JAWAR	6666.3	4993.5	2211.9	3320.8	1090.4	18282.9
GROUNDNUT	4761.7	3566.8	1579.9	2372.0	778.9	13059.3
MAIZE	7618.7	5706.9	2527.9	3795.2	1246.2	20894.9
PULSES	4761.7	3566.8	1579.9	2372.0	778.9	13059.3
SOYABEAN	30474.6	22827.6	10111.7	15180.7	4984.7	83579.3
PERENNIAL	3809.3	2853.5	1264.0	1897.6	623.1	10447.5
WHEAT	52378.2	39235.0	17379.4	26091.8	8567.5	143651.9
GRAM	6666.3	4993.5	2211.9	3320.8	1090.4	18282.9
PEAS	1904.7	1426.7	632.0	948.8	311.5	5223.7
VEGETABLE	952.3	713.4	316.0	474.4	155.8	2611.9
LINSEED	1904.7	1426.7	632.0	948.8	311.5	5223.7
KHARIF CROPS	63806.4	47795.2	21171.1	31784.7	10436.9	
RABI CROPS	63806.2	47795.3	21171.3	31784.6	10436.7	
OPTIMAL ALLOCATION OF SURFACE WATER (ha-m)						
JANUARY	7148.2	5354.5	0.0	3371.8	1169.2	17043.8
FEBRUARY	8239.3	8218.7	0.0	3371.8	1794.7	21624.4
MARCH	3570.3	4213.8	0.0	1461.1	821.4	10066.6
OCTOBER	4394.3	5186.2	0.0	1798.3	1010.9	12389.7
NOVEMBER	8239.3	7312.0	0.0	3371.8	1596.7	20519.8
DECEMBER	6906.3	5173.3	0.0	3371.8	1129.7	16581.1
TOTAL	38497.7	35458.5	0.0	16746.7	7522.5	**98225.4**
OPTIMAL ALLOCATION OF GROUNDWATER (ha-m)						
JANUARY	0.0	0.0	2371.8	189.0	0.0	2560.8
FEBRUARY	2732.5	0.0	3640.5	2093.7	0.0	8466.7
MARCH	5074.0	2261.4	2868.2	2845.0	592.5	13641.2
APRIL	826.6	619.2	274.3	411.8	135.2	2267.1
MAY	2175.1	1629.3	721.7	1083.5	355.8	5965.5
JUNE	1934.2	1448.8	641.8	963.5	316.4	5304.7
JULY	2002.8	1500.2	664.5	997.7	327.6	5492.7

AUGUST	1829.4	1370.4	607.0	911.3	299.3	5017.4
SEPTEMBER	6655.9	4985.7	2208.4	3315.6	1088.7	18254.3
OCTOBER	10706.8	6125.6	5010.6	5724.2	1459.2	29026.5
NOVEMBER	1522.1	0.0	3238.9	1490.7	0.0	6251.8
DECEMBER	0.0	0.0	2291.6	68.5	0.0	2360.1
TOTAL	35459.5	19940.6	24539.4	20094.6	4574.7	**104608.8**

Allocations of different resources and benefits for the existing cropping pattern (Strategy-12)

TOTAL BENEFITS (Million Rs)=8901.258						
AREA UNDER DIFFERENT CROPS (ha)						
	ZONE-1	ZONE-2	ZONE-3	ZONE-4	ZONE-5	TOTAL
PADDY	4761.7	3566.8	1579.9	2372.0	778.9	13059.3
COTTON	4761.7	3566.8	1579.9	2372.0	778.9	13059.3
JAWAR	6666.3	4993.5	2211.9	3320.8	1090.4	18282.9
GROUNDNUT	4761.7	3566.8	1579.9	2372.0	778.9	13059.3
MAIZE	7618.7	5706.9	2527.9	3795.2	1246.2	20894.9
PULSES	4761.7	3566.8	1579.9	2372.0	778.9	13059.3
SOYABEAN	30474.6	22827.6	10111.7	15180.7	4984.7	83579.3
PERENNIAL	3809.3	2853.5	1264.0	1897.6	623.1	10447.5
WHEAT	52378.2	39235.0	17379.4	26091.8	8567.5	143651.9
GRAM	6666.3	4993.5	2211.9	3320.8	1090.4	18282.9
PEAS	1904.7	1426.7	632.0	948.8	311.5	5223.7
VEGETABLE	952.3	713.4	316.0	474.4	155.8	2611.9
LINSEED	1904.7	1426.7	632.0	948.8	311.5	5223.7
KHARIF CROPS	63806.4	47795.2	21171.1	31784.7	10436.9	174994.3
RABI CROPS	63806.2	47795.3	21171.3	31784.6	10436.7	174994.1
OPTIMAL ALLOCATION OF SURFACE WATER (ha-m)						
JANUARY	7148.2	5354.5	0.0	3371.8	1169.2	17043.8
FEBRUARY	10971.8	8218.7	0.0	3371.8	1794.7	24357.0
MARCH	4929.0	4213.8	0.0	1461.1	821.4	11425.3
OCTOBER	6066.6	5186.2	0.0	1798.3	1010.9	14062.0
NOVEMBER	9761.4	7312.0	0.0	3371.8	1596.7	22041.9
DECEMBER	6906.3	5173.3	0.0	3371.8	1129.7	16581.1
TOTAL	45783.3	35458.5	0.0	16746.7	7522.5	**105511.0**
OPTIMAL ALLOCATION OF GROUNDWATER (ha-m)						
JANUARY	0.0	0.0	2371.8	189.0	0.0	2560.8
FEBRUARY	0.0	0.0	3640.5	2093.7	0.0	5734.2

MARCH	3715.3	2261.4	2868.2	2845.0	592.5	12282.5
APRIL	826.6	619.2	274.3	411.8	135.2	2267.1
MAY	2175.1	1629.3	721.7	1083.5	355.8	5965.5
JUNE	1934.2	1448.8	641.8	963.5	316.4	5304.7
JULY	2002.8	1500.2	664.5	997.7	327.6	5492.7
AUGUST	1829.4	1370.4	607.0	911.3	299.3	5017.4
SEPTEMBER	6655.9	4985.7	2208.4	3315.6	1088.7	18254.3
OCTOBER	9034.5	6125.6	5010.6	5724.2	1459.2	27354.2
NOVEMBER	0.0	0.0	3238.9	1490.7	0.0	4729.6
DECEMBER	0.0	0.0	2291.6	68.5	0.0	2360.1
TOTAL	28173.9	19940.6	24539.4	20094.6	4574.7	**97323.1**

Allocations of different resources and benefits for the existing cropping pattern (Strategy-14)

						TOTAL BENEFITS (Million Rs)=9742.168
AREA UNDER DIFFERENT CROPS (ha)						
	ZONE-1	ZONE-2	ZONE-3	ZONE-4	ZONE-5	TOTAL
PADDY	4761.7	3566.8	1579.9	2372.0	778.9	13059.3
COTTON	4761.7	3566.8	1579.9	2372.0	778.9	13059.3
JAWAR	6666.3	4993.5	2211.9	3320.8	1090.4	18282.9
GROUNDNUT	4761.7	3566.8	1579.9	2372.0	778.9	13059.3
MAIZE	7618.7	5706.9	2527.9	3795.2	1246.2	20894.9
PULSES	4761.7	3566.8	1579.9	2372.0	778.9	13059.3
SOYABEAN	30474.6	22827.6	10111.7	15180.7	4984.7	83579.3
PERENNIAL	3809.3	2853.5	1264.0	1897.6	623.1	10447.5
WHEAT	60949.2	45655.3	20223.3	30361.3	8567.5	165756.5
GRAM	6666.3	4993.5	2211.9	3320.8	1090.4	18282.9
PEAS	1904.7	1426.7	632.0	948.8	311.5	5223.7
VEGETABLE	952.3	713.4	316.0	474.4	1557.8	4013.9
LINSEED	1904.7	1426.7	632.0	948.8	311.5	5223.7
KHARIF CROPS	63806.4	47795.2	21171.1	31784.7	10436.9	174994.3
RABI CROPS	72377.2	54215.6	24015.2	36054.1	11838.7	198500.7
OPTIMAL ALLOCATION OF SURFACE WATER (ha-m)						
JANUARY	8005.3	5996.5	2508.5	3371.8	1449.6	21331.8
FEBRUARY	8866.4	9419.3	2508.5	3371.8	1895.6	26061.5
MARCH	3842.0	4213.8	1087.0	1461.1	821.4	11425.3
OCTOBER	4728.8	5186.2	1337.8	1798.3	1010.9	14062.0
NOVEMBER	8866.4	7954.0	2508.5	3371.8	1877.1	24577.8

DECEMBER	7763.4	5815.3	2508.5	3371.8	1410.1	20869.1
TOTAL	42072.3	38585.2	12458.7	16746.7	8464.6	**118327.5**
OPTIMAL ALLOCATION OF GROUNDWATER (ha-m)						
JANUARY	0.00	0.00	147.74	615.95	0.00	763.7
FEBRUARY	3708.18	0.00	1663.85	2892.09	179.51	8443.6
MARCH	6096.48	3230.88	2210.71	3489.69	732.74	15760.5
APRIL	826.62	619.21	274.29	411.78	135.21	2267.1
MAY	2175.13	1629.33	721.72	1083.53	355.80	5965.5
JUNE	1934.19	1448.84	641.77	963.50	316.38	5304.7
JULY	2002.77	1500.20	664.51	997.66	327.60	5492.7
AUGUST	1829.44	1370.37	607.00	911.32	299.25	5017.4
SEPTEMBER	6655.87	4985.69	2208.43	3315.57	1088.71	18254.3
OCTOBER	11229.48	6767.62	3957.17	6151.17	1599.40	29704.8
NOVEMBER	1752.10	0.00	1014.80	1917.69	0.00	4684.6
DECEMBER	0.00	0.00	67.47	495.44	0.00	562.9
TOTAL	38210.3	21552.1	14179.5	23245.4	5034.6	**102221.9**

Allocations of different resources and benefits for the existing cropping pattern (Strategy-15)

TOTAL BENEFITS (Million Rs)=9743.291						
AREA UNDER DIFFERENT CROPS (ha)						
	ZONE-1	ZONE-2	ZONE-3	ZONE-4	ZONE-5	TOTAL
PADDY	4761.7	3566.8	1579.9	2372.0	778.9	13059.3
COTTON	4761.7	3566.8	1579.9	2372.0	778.9	13059.3
JAWAR	6666.3	4993.5	2211.9	3320.8	1090.4	18282.9
GROUNDNUT	4761.7	3566.8	1579.9	2372.0	778.9	13059.3
MAIZE	7618.7	5706.9	2527.9	3795.2	1246.2	20894.9
PULSES	4761.7	3566.8	1579.9	2372.0	778.9	13059.3
SOYABEAN	30474.6	22827.6	10111.7	15180.7	4984.7	83579.3
PERENNIAL	3809.3	2853.5	1264.0	1897.6	623.1	10447.5
WHEAT	60949.2	45655.3	20223.3	30361.3	8567.5	165756.5
GRAM	6666.3	4993.5	2211.9	3320.8	1090.4	18282.9
PEAS	1904.7	1426.7	632.0	948.8	311.5	5223.7
VEGETABLE	952.3	713.4	316.0	474.4	1557.8	4013.9
LINSEED	1904.7	1426.7	632.0	948.8	311.5	5223.7
KHARIF CROPS	63806.4	47795.2	21171.1	31784.7	10436.9	
RABI CROPS	72377.2	54215.6	24015.2	36054.1	11838.7	

OPTIMAL ALLOCATION OF SURFACE WATER (ha-m)						
JANUARY	8005.3	5996.5	1881.4	3371.8	1449.6	20704.6
FEBRUARY	9493.5	9419.3	1881.4	3371.8	1895.6	26061.5
MARCH	4113.8	4213.8	815.2	1461.1	821.4	11425.3
OCTOBER	5063.2	5186.2	1003.4	1798.3	1010.9	14062.0
NOVEMBER	9493.5	7954.0	1881.4	3371.8	1877.1	24577.8
DECEMBER	7763.4	5815.3	1881.4	3371.8	1410.1	20242.0
TOTAL	43932.7	38585.2	9344.0	16746.7	8464.6	**117073.2**
OPTIMAL ALLOCATION OF GROUNDWATER (ha-m)						
JANUARY	0.0	0.0	774.9	616.0	0.0	1390.8
FEBRUARY	3081.1	0.0	2291.0	2892.1	179.5	8443.6
MARCH	5824.7	3230.9	2482.4	3489.7	732.7	15760.5
APRIL	826.6	619.2	274.3	411.8	135.2	2267.1
MAY	2175.1	1629.3	721.7	1083.5	355.8	5965.5
JUNE	1934.2	1448.8	641.8	963.5	316.4	5304.7
JULY	2002.8	1500.2	664.5	997.7	327.6	5492.7
AUGUST	1829.4	1370.4	607.0	911.3	299.3	5017.4
SEPTEMBER	6655.9	4985.7	2208.4	3315.6	1088.7	18254.3
OCTOBER	10895.0	6767.6	4291.6	6151.2	1599.4	29704.8
NOVEMBER	1125.0	0.0	1641.9	1917.7	0.0	4684.6
DECEMBER	0.0	0.0	694.6	495.4	0.0	1190.0
TOTAL	36349.8	21552.1	17294.1	23245.4	5034.6	**103476.1**

Allocations of different resources and benefits for the existing cropping pattern (Strategy-16)

TOTAL BENEFITS (Million Rs)=9744.414						
AREA UNDER DIFFERENT CROPS (ha)						
	ZONE-1	ZONE-2	ZONE-3	ZONE-4	ZONE-5	TOTAL
PADDY	4761.7	3566.8	1579.9	2372.0	778.9	13059.3
COTTON	4761.7	3566.8	1579.9	2372.0	778.9	13059.3
JAWAR	6666.3	4993.5	2211.9	3320.8	1090.4	18282.9
GROUNDNUT	4761.7	3566.8	1579.9	2372.0	778.9	13059.3
MAIZE	7618.7	5706.9	2527.9	3795.2	1246.2	20894.9
PULSES	4761.7	3566.8	1579.9	2372.0	778.9	13059.3
SOYABEAN	30474.6	22827.6	10111.7	15180.7	4984.7	83579.3
PERENNIAL	3809.3	2853.5	1264.0	1897.6	623.1	10447.5
WHEAT	60949.2	45655.3	20223.3	30361.3	8567.5	165756.5

GRAM	6666.3	4993.5	2211.9	3320.8	1090.4	18282.9
PEAS	1904.7	1426.7	632.0	948.8	311.5	5223.7
VEGETABLE	952.3	713.4	316.0	474.4	1557.8	4013.9
LINSEED	1904.7	1426.7	632.0	948.8	311.5	5223.7
KHARIF CROPS	63806.4	47795.2	21171.1	31784.7	10436.9	
RABI CROPS	72377.2	54215.6	24015.2	36054.1	11838.7	
OPTIMAL ALLOCATION OF SURFACE WATER (ha-m)						
JANUARY	8005.3	5996.5	1254.2	3371.8	1449.6	20077.5
FEBRUARY	10120.6	9419.3	1254.2	3371.8	1895.6	26061.5
MARCH	4385.5	4213.8	543.5	1461.1	821.4	11425.3
OCTOBER	5397.7	5186.2	668.9	1798.3	1010.9	14062.0
NOVEMBER	10120.6	7954.0	1254.2	3371.8	1877.1	24577.7
DECEMBER	7763.4	5815.3	1254.2	3371.8	1410.1	19614.9
TOTAL	45793.1	38585.2	6229.4	16746.7	8464.6	**115818.9**
OPTIMAL ALLOCATION OF GROUNDWATER (ha-m)						
JANUARY	0.0	0.0	1402.0	616.0	0.0	2017.9
FEBRUARY	2453.9	0.0	2918.1	2892.1	179.5	8443.6
MARCH	5553.0	3230.9	2754.2	3489.7	732.7	15760.5
APRIL	826.6	619.2	274.3	411.8	135.2	2267.1
MAY	2175.1	1629.3	721.7	1083.5	355.8	5965.5
JUNE	1934.2	1448.8	641.8	963.5	316.4	5304.7
JULY	2002.8	1500.2	664.5	997.7	327.6	5492.7
AUGUST	1829.4	1370.4	607.0	911.3	299.3	5017.4
SEPTEMBER	6655.9	4985.7	2208.4	3315.6	1088.7	18254.3
OCTOBER	10560.6	6767.6	4626.1	6151.2	1599.4	29704.8
NOVEMBER	497.9	0.0	2269.0	1917.7	0.0	4684.7
DECEMBER	0.0	0.0	1321.7	495.4	0.0	1817.2
TOTAL	34489.4	21552.1	20408.8	23245.4	5034.6	**104730.4**

Allocations of different resources and benefits for the existing cropping pattern (Strategy-17)

						TOTAL BENEFITS (Million Rs)=9744.739
AREA UNDER DIFFERENT CROPS (ha)						
	ZONE-1	ZONE-2	ZONE-3	ZONE-4	ZONE-5	TOTAL
PADDY	4761.7	3566.8	1579.9	2372.0	778.9	13059.3
COTTON	4761.7	3566.8	1579.9	2372.0	778.9	13059.3
JAWAR	6666.3	4993.5	2211.9	3320.8	1090.4	18282.9
GROUNDNUT	4761.7	3566.8	1579.9	2372.0	778.9	13059.3
MAIZE	7618.7	5706.9	2527.9	3795.2	1246.2	20894.9

PULSES	4761.7	3566.8	1579.9	2372.0	778.9	13059.3
SOYABEAN	30474.6	22827.6	10111.7	15180.7	4984.7	83579.3
PERENNIAL	3809.3	2853.5	1264.0	1897.6	623.1	10447.5
WHEAT	60949.2	45655.3	20223.3	30361.3	8567.5	165756.5
GRAM	6666.3	4993.5	2211.9	3320.8	1090.4	18282.9
PEAS	1904.7	1426.7	632.0	948.8	311.5	5223.7
VEGETABLE	952.3	713.4	316.0	474.4	1557.8	4013.9
LINSEED	1904.7	1426.7	632.0	948.8	311.5	5223.7
KHARIF CROPS	63806.4	47795.2	21171.1	31784.7	10436.9	
RABI CROPS	72377.2	54215.6	24015.2	36054.1	11838.7	
OPTIMAL ALLOCATION OF SURFACE WATER (ha-m)						
JANUARY	8005.3	5996.5	627.1	3371.8	1449.6	19450.4
FEBRUARY	10747.7	9419.3	627.1	3371.8	1895.6	26061.5
MARCH	4657.3	4213.8	271.7	1461.1	821.4	11425.3
OCTOBER	5732.1	5186.2	334.5	1798.3	1010.9	14062.0
NOVEMBER	10618.5	7954.0	627.1	3371.8	1877.1	24448.5
DECEMBER	7763.4	5815.3	627.1	3371.8	1410.1	18987.8
TOTAL	47524.3	38585.2	3114.7	16746.7	8464.6	**114435.5**
OPTIMAL ALLOCATION OF GROUNDWATER (ha-m)						
JANUARY	0.0	0.0	2029.1	616.0	0.0	2645.0
FEBRUARY	1826.8	0.0	3545.2	2892.1	179.5	8443.6
MARCH	5281.3	3230.9	3025.9	3489.7	732.7	15760.5
APRIL	826.6	619.2	274.3	411.8	135.2	2267.1
MAY	2175.1	1629.3	721.7	1083.5	355.8	5965.5
JUNE	1934.2	1448.8	641.8	963.5	316.4	5304.7
JULY	2002.8	1500.2	664.5	997.7	327.6	5492.7
AUGUST	1829.4	1370.4	607.0	911.3	299.3	5017.4
SEPTEMBER	6655.9	4985.7	2208.4	3315.6	1088.7	18254.3
OCTOBER	10226.1	6767.6	4960.6	6151.2	1599.4	29704.8
NOVEMBER	0.0	0.0	2896.2	1917.7	0.0	4813.9
DECEMBER	0.0	0.0	1948.8	495.4	0.0	2444.3
TOTAL	32758.2	21552.1	23523.5	23245.4	5034.6	**106113.8**

Allocations of different resources and benefits for the existing cropping pattern (Strategy-18)

TOTAL BENEFITS (Million Rs)= 9743.272						
AREA UNDER DIFFERENT CROPS (ha)						
	ZONE-1	ZONE-2	ZONE-3	ZONE-4	ZONE-5	TOTAL
PADDY	4761.7	3566.8	1579.9	2372.0	778.9	13059.3
COTTON	4761.7	3566.8	1579.9	2372.0	778.9	13059.3
JAWAR	6666.3	4993.5	2211.9	3320.8	1090.4	18282.9
GROUNDNUT	4761.7	3566.8	1579.9	2372.0	778.9	13059.3

MAIZE	7618.7	5706.9	2527.9	3795.2	1246.2	20894.9
PULSES	4761.7	3566.8	1579.9	2372.0	778.9	13059.3
SOYABEAN	30474.6	22827.6	10111.7	15180.7	4984.7	83579.3
PERENNIAL	3809.3	2853.5	1264.0	1897.6	623.1	10447.5
WHEAT	60949.2	45655.3	20223.3	30361.3	8567.5	165756.5
GRAM	6666.3	4993.5	2211.9	3320.8	1090.4	18282.9
PEAS	1904.7	1426.7	632.0	948.8	311.5	5223.7
VEGETABLE	952.3	713.4	316.0	474.4	1557.8	4013.9
LINSEED	1904.7	1426.7	632.0	948.8	311.5	5223.7
KHARIF CROPS	63806.4	47795.2	21171.1	31784.7	10436.9	
RABI CROPS	72377.2	54215.6	24015.2	36054.1	11838.7	
OPTIMAL ALLOCATION OF SURFACE WATER (ha-m)						
JANUARY	8005.3	5996.5	0.0	3371.8	1449.6	18823.3
FEBRUARY	11374.9	9419.3	0.0	3371.8	1895.6	26061.5
MARCH	4929.0	4213.8	0.0	1461.1	821.4	11425.3
OCTOBER	6066.6	5186.2	0.0	1798.3	1010.9	14062.0
NOVEMBER	10618.5	7954.0	0.0	3371.8	1877.1	23821.4
DECEMBER	7763.4	5815.3	0.0	3371.8	1410.1	18360.6
TOTAL	48757.7	38585.2	0.0	16746.7	8464.6	**112554.1**
OPTIMAL ALLOCATION OF GROUNDWATER (ha-m)						
JANUARY	1199.7	0.0	4172.3	2892.1	179.5	8443.6
FEBRUARY	5009.5	3230.9	3297.7	3489.7	732.7	15760.5
MARCH	826.6	619.2	274.3	411.8	135.2	2267.1
APRIL	2175.1	1629.3	721.7	1083.5	355.8	5965.5
MAY	1934.2	1448.8	641.8	963.5	316.4	5304.7
JUNE	2002.8	1500.2	664.5	997.7	327.6	5492.7
JULY	1829.4	1370.4	607.0	911.3	299.3	5017.4
AUGUST	6655.9	4985.7	2208.4	3315.6	1088.7	18254.3
SEPTEMBER	9891.6	6767.6	5295.0	6151.2	1599.4	29704.8
OCTOBER	0.0	0.0	3523.3	1917.7	0.0	5441.0
NOVEMBER	0.0	0.0	2576.0	495.4	0.0	3071.4
DECEMBER	0.0	0.0	2576.0	495.4	0.0	3071.4
TOTAL	31524.9	21552.1	26557.9	23124.9	5034.6	**107794.4**

Appendix - II

GPS SAMPLE POINTS COLLECTED DURING FIELD VISIT OF THE TAWA CANAL COMMAND ON 25TH NOVEMBER 2011

No. of sample	Latitude	Longitude	Crop	No. of sample	Latitude	Longitude	Crop
1	22.6051	77.8116	Wheat	36	22.5995	77.8007	Wheat
2	22.6051	77.8116	Wheat	37	22.5973	77.7977	Wheat
3	22.6052	77.8116	Wheat	38	22.5973	77.7977	Wheat
4	22.6051	77.8112	Wheat	39	22.5973	77.7977	Wheat
5	22.6051	77.8112	Wheat	40	22.5974	77.5915	Wheat
6	22.6051	77.8112	Wheat	41	22.5974	77.5915	Wheat
7	22.6036	77.8063	Wheat	42	22.5974	77.5915	Wheat
8	22.6036	77.8063	Wheat	43	22.5915	77.7917	Wheat
9	22.6036	77.8063	Wheat	44	22.5915	77.7917	Wheat
10	22.6037	77.8064	Wheat	45	22.5915	77.7917	Wheat
11	22.6037	77.8064	Wheat	46	22.5915	77.7969	Wheat
12	22.6037	77.8064	Wheat	47	22.5915	77.7969	Wheat
13	22.6022	77.8042	Wheat	48	22.5915	77.7969	Wheat
14	22.6022	77.8042	Wheat	49	22.5826	77.7769	Wheat
15	22.6022	77.8042	Wheat	50	22.5826	77.7769	Wheat
16	22.6022	77.8043	Wheat	51	22.5827	77.7769	Wheat
17	22.6022	77.8043	Wheat	52	22.5825	77.7762	Wheat
18	22.6022	77.8043	Wheat	53	22.5826	77.7762	Wheat
19	22.6017	77.8009	Wheat	54	22.5826	77.7762	Wheat
20	22.6017	77.8009	Wheat	55	22.5802	77.7745	Wheat
21	22.6017	77.8009	Wheat	56	22.5802	77.7745	Wheat
22	22.6018	77.8009	Wheat	57	22.5802	77.7745	Wheat
23	22.6018	77.8009	Wheat	58	22.58	77.7744	Wheat
24	22.6018	77.8009	Wheat	59	22.58	77.7744	Wheat
25	22.6021	77.7966	Wheat	60	22.58	77.7744	Wheat
26	22.6021	77.7966	Wheat	61	22.5756	77.7678	Wheat
27	22.6021	22.602	Wheat	62	22.5756	77.7678	Wheat
28	22.6021	77.7666	Wheat	63	22.5756	77.7678	Wheat

No. of sample	Latitude	Longitude	Crop	No. of sample	Latitude	Longitude	Crop
29	22.6022	77.7667	Wheat	64	22.5756	77.7677	Wheat
30	22.6022	77.7667	Wheat	65	22.5756	77.7677	Wheat
31	22.5996	77.8009	Wheat	66	22.5756	77.7677	Wheat
32	22.5996	77.8009	Wheat	67	22.5788	77.7646	Sugarcane
33	22.5996	77.8009	Wheat	68	22.5788	77.7646	Orchard
34	22.5995	77.8007	Wheat	69	22.5788	77.7646	Orchard
35	22.5995	77.8007	Wheat	70	22.5788	77.7646	Orchard
71	22.5788	77.7646	Orchard	110	22.5449	77.7366	Wheat
72	22.5788	77.7649	Orchard	111	22.5449	77.7366	Wheat
73	22.5801	77.7633	Orchard	112	22.5427	77.7232	Wheat
74	22.5801	77.7633	Orchard	113	22.5427	77.7232	Wheat
75	22.5801	77.7633	Orchard	114	22.5427	77.7232	Wheat
76	22.5801	77.7633	Vegetable	115	22.5428	77.7233	Wheat
77	22.5801	77.7633	Vegetable	116	22.5428	77.7233	Wheat
78	22.5801	77.7633	Vegetable	117	22.5429	77.7233	Wheat
79	22.5816	77.7582	Wheat	118	22.5378	77.7053	Wheat
80	22.5816	77.7582	Wheat	119	22.5378	77.7053	Wheat
81	22.5816	77.7582	Wheat	120	22.5378	77.7053	Wheat
82	22.5803	77.7508	Wheat	121	22.5379	77.7054	Wheat
83	22.5803	77.7508	Wheat	122	22.5379	77.7054	Wheat
84	22.5803	77.7509	Wheat	123	22.5379	77.7054	Wheat
85	22.5802	77.7508	Wheat	124	22.6672	77.7758	Wheat
86	22.5802	77.7508	Wheat	125	22.6672	77.7758	Wheat
87	22.5802	77.7508	Wheat	126	22.6672	77.7759	Wheat
88	22.575	77.7575	Wheat	127	22.6672	77.7758	Wheat
89	22.575	77.7575	Wheat	128	22.6672	77.7758	Wheat
90	22.575	77.7576	Wheat	129	22.6672	77.7758	Wheat
91	22.5749	77.7475	Wheat	130	22.6673	77.7765	Wheat
92	22.575	77.7475	Wheat	131	22.6673	77.7765	Wheat
93	22.575	77.7475	Wheat	132	22.6673	77.7765	Wheat
94	22.567	77.7484	Wheat	133	22.6673	77.7767	Wheat
95	22.567	77.7484	Wheat	134	22.6673	77.7767	Wheat

No. of sample	Latitude	Longitude	Crop	No. of sample	Latitude	Longitude	Crop
96	22.567	77.7484	Wheat	135	22.6674	77.7767	Wheat
97	22.5667	77.7483	Wheat	136	22.6675	77.7771	Linseed
98	22.5667	77.7483	Wheat	137	22.6675	77.7771	Linseed
99	22.5667	77.7483	Wheat	138	22.6675	77.7771	Linseed
100	22.5512	77.7432	Wheat	139	22.6675	77.777	Linseed
101	22.5512	77.7432	Wheat	140	22.6675	77.777	Linseed
102	22.5512	77.7432	Wheat	141	22.6675	77.777	Wheat
103	22.5521	77.7432	Wheat	142	22.6641	77.7776	Wheat
104	22.5521	77.7432	Wheat	143	22.6641	77.7777	Wheat
105	22.5521	77.7432	Wheat	144	22.6641	77.7777	Wheat
106	22.5448	77.7336	Wheat	145	22.6641	77.7777	Wheat
107	22.5448	77.7336	Wheat	146	22.6641	77.7777	Wheat
108	22.5448	77.7336	Wheat	147	22.6641	77.7777	Wheat
109	22.5449	77.7366	Wheat	148	22.6641	77.7779	Wheat
149	22.6641	77.7779	Wheat	188	22.6863	77.769	Chick-pea
150	22.6641	77.7779	Wheat	189	22.6863	77.769	Chick-pea
151	22.6641	77.778	Wheat	190	22.6863	77.769	Chick-pea
152	22.6641	77.778	Wheat	191	22.6863	77.7691	Wheat
153	22.6641	77.778	Wheat	192	22.6863	77.7691	Wheat
154	22.6629	77.7788	Wheat	193	22.6863	77.7691	Wheat
155	22.6629	77.7788	Wheat	194	22.6852	77.7647	Wheat
156	22.6629	77.7788	Wheat	195	22.6852	77.7647	Wheat
157	22.6625	77.7782	Wheat	196	22.6852	77.7647	Wheat
158	22.6625	77.7782	Wheat	197	22.685	77.7648	Wheat
159	22.6625	77.7782	Wheat	198	22.685	77.7648	Wheat
160	22.6628	77.7831	Wheat	199	22.685	77.7649	Chick-pea
161	22.6628	77.7831	Wheat	200	22.6839	77.7587	Chick-pea
162	22.6628	77.7832	Wheat	201	22.6839	77.7587	Chick-pea
163	22.6672	77.7631	Wheat	202	22.684	77.7587	Chick-pea
164	22.6672	77.7631	Wheat	203	22.6837	77.7587	Wheat
165	22.6672	77.7632	Wheat	204	22.6838	77.7587	Wheat
166	22.687	77.7811	Wheat	205	22.6838	77.7587	Wheat

No. of sample	Latitude	Longitude	Crop	No. of sample	Latitude	Longitude	Crop
167	22.6871	77.7811	Wheat	206	22.6838	77.7588	Wheat
168	22.6871	77.7811	Wheat	207	22.6838	77.7588	Wheat
169	22.687	77.7871	Wheat	208	22.6838	77.7588	Wheat
170	22.687	77.7871	Wheat	209	22.6827	77.7549	Vegetable
171	22.687	77.7871	Wheat	210	22.6827	77.7549	Vegetable
172	22.6869	77.7816	Wheat	211	22.6827	77.7549	Vegetable
173	22.6869	77.7816	Wheat	212	22.6828	77.7549	Wheat
174	22.6869	77.7816	Wheat	213	22.6828	77.7549	Wheat
175	22.6869	77.782	Wheat	214	22.6828	77.7549	Wheat
176	22.6869	77.782	Wheat	215	22.6826	77.7541	Wheat
177	22.6869	77.782	Wheat	216	22.6826	77.7541	Wheat
178	22.6868	77.7763	Wheat	217	22.6827	77.7541	Wheat
179	22.6868	77.7763	Wheat	218	22.6872	77.827	Wheat
180	22.6868	77.7763	Wheat	219	22.6872	77.827	Wheat
181	22.6869	77.7763	Wheat	220	22.6872	77.827	Wheat
182	22.6868	77.7714	Wheat	221	22.6871	77.8257	Wheat
183	22.6868	77.7714	Wheat	222	22.6871	77.8257	Wheat
184	22.6868	77.7714	Wheat	223	22.6871	77.8257	Wheat
185	22.687	77.7774	Wheat	224	22.6882	77.8235	Wheat
186	22.687	77.7774	Wheat	225	22.6882	77.8235	Wheat
187	22.687	77.7774	Wheat	226	22.6882	77.8235	Wheat
227	22.6984	77.8277	Wheat	266	22.7146	77.8084	Wheat
228	22.6384	77.8278	Wheat	267	22.7146	77.8084	Wheat
229	22.6384	77.8278	Wheat	268	22.7146	77.8084	Wheat
230	22.6984	77.8278	Wheat	269	22.7146	77.8084	Wheat
231	22.6984	77.8278	Wheat	270	22.718	77.8079	Wheat
232	22.6984	77.8278	Wheat	271	22.718	77.8079	Wheat
233	22.7014	77.83	Wheat	272	22.718	77.8079	Wheat
234	22.7014	77.83	Wheat	273	22.7182	77.8079	Vegetable
235	22.7014	77.83	Wheat	274	22.7182	77.8079	Vegetable
236	22.7014	77.83	Wheat	275	22.7182	77.8079	Vegetable
237	22.7014	77.83	Wheat	276	22.7201	77.802	Wheat

No. of sample	Latitude	Longitude	Crop	No. of sample	Latitude	Longitude	Crop
238	22.7014	77.83	Wheat	277	22.7201	77.802	Wheat
239	22.7059	77.8314	Orchard	278	22.7201	77.802	Wheat
240	22.709	77.8251	Wheat	279	22.7136	77.8029	Wheat
241	22.709	77.8251	Wheat	280	22.7136	77.8148	Wheat
242	22.709	77.8251	Wheat	281	22.7136	77.8148	Wheat
243	22.7091	77.825	Vegetable	282	22.7136	77.8029	Wheat
244	22.7092	77.8209	Vegetable	283	22.7136	77.8029	Wheat
245	22.7092	77.8209	Vegetable	284	22.7136	77.8029	Wheat
246	22.7121	77.8208	Vegetable	285	22.7136	77.8229	Wheat
247	22.7121	77.8208	Vegetable	286	22.7136	77.8229	Wheat
248	22.7121	77.8208	Vegetable	287	22.7136	77.8229	Wheat
249	22.7122	77.8209	Linseed	288	22.7161	77.8014	Wheat
250	22.7122	77.8209	Linseed	289	22.7131	77.8014	Wheat
251	22.7122	77.8209	Linseed	290	22.7131	77.8014	Wheat
252	22.7151	77.8155	Linseed	291	22.719	77.8008	Wheat
253	22.7151	77.8155	Linseed	292	22.719	77.8008	Wheat
254	22.7151	77.8155	Linseed	293	22.719	22.8008	Wheat
255	22.7153	77.8148	Vegetable	294	22.7161	77.8013	Wheat
256	22.7154	77.8149	Vegetable	295	22.7161	77.8013	Wheat
257	22.7154	77.8149	Vegetable	296	22.7161	77.8013	Wheat
258	22.7146	77.8084	Vegetable	297	22.719	77.8009	Wheat
259	22.7146	77.8084	Vegetable	298	22.719	77.8009	Wheat
260	22.7146	77.8084	Vegetable	299	22.719	77.8009	Wheat
261	22.7146	77.8084	Wheat	300	22.7211	77.7959	Wheat
262	22.7146	77.8084	Wheat	301	22.7211	77.7959	Wheat
263	22.7146	77.8084	Wheat	302	22.7211	77.7959	Wheat
264	22.7146	77.8083	Wheat	303	22.7248	77.7892	Wheat
265	22.7145	77.8084	Wheat	304	22.7248	77.7892	Wheat
305	22.7248	77.7892	Wheat	318	22.7339	77.7729	Wheat
306	22.725	77.7892	Wheat	319	22.7333	77.7729	Wheat
307	22.725	77.7892	Wheat	320	22.7323	77.7729	Wheat
308	22.725	77.7892	Wheat	321	22.7386	77.7638	Vegetable

No. of sample	Latitude	Longitude	Crop	No. of sample	Latitude	Longitude	Crop
309	22.7302	77.7804	Wheat	322	22.7386	7.8E+07	Vegetable
310	22.7302	77.7804	Wheat	323	22.7386	77.7638	Vegetable
311	22.7302	77.7805	Wheat	324	22.7402	77.7402	Vegetable
312	22.7338	77.7638	Wheat	325	22.7402	77.7608	Vegetable
313	22.7338	77.7638	Wheat	326	22.7402	77.7608	Vegetable
314	22.7338	77.7638	Wheat	327	22.7408	77.7608	Vegetable
315	22.7386	77.7638	Vegetable	328	22.7402	77.7605	Vegetable
316	22.7386	77.7638	Vegetable	329	22.7402	77.7605	Vegetable
317	22.7386	77.7638	Vegetable	330	22.7402	77.7605	Vegetable

Appendix - III

Short Code Used in GPS During Survey

Class	Code
Wheat	G
Rice	C
Mung Dal	M
kala Chana	K
Mater	R
Empty	E
Settlement	S
Tuar-Harhar	H
Talab-kamal	TK
Rice cut field	CE
Barren Land	BR
Natural Veg	NR
Canal Point	CN
Scrub	SR
Sugarcane	GA
Makka	MK
Makka Kata hua	MKE
Soyabean	SB
Direct soil	DR
Road	RD
Flower Genda	FG
Water Body	WT
Natural and Scrub mixed	NS
Rice kata hua and Natural Veg	CENR
Road and Natural Veg	RDNR
Settlement and Natural Veg	SNR
Stone	ST
Mustered/ Sarso	SRS
Kala channa/ Black Pea	K

Appendix – IV (A)

GPS Points and Data code collected during 2016

Sr.No	*Short Code**	*Elevation*	*Lat*	*long*
1	C	319.94	22.7119	77.9478
2	C	320.29	22.7118	77.9481
3	C	321.03	22.7123	77.9475
4	C	324.38	22.7117	77.9479
5	C	322.89	22.7116	77.9478
6	S	328.06	22.7166	77.9514
7	S	331.28	22.7169	77.9525
8	H	335.82	22.7252	77.9626
9	H	333.85	22.7261	77.9634
10	G	334.84	22.7306	77.9675
11	G	332.86	22.7307	77.9676
12	G	331.27	22.7310	77.9677
13	H	324.77	22.7357	77.9716
14	CE	337.64	22.7360	77.9845
15	CE	338.46	22.7350	77.9852
16	CE	337.89	22.7344	77.9854
17	CE	338.07	22.7283	77.9833
18	CE	335.85	22.7281	77.9836
19	M	337.69	22.7277	77.9835
20	M	334.65	22.7277	77.9836
21	G	335.15	22.7230	77.9853
22	TK	333.63	22.7197	77.9841
23	CE	324.59	22.7177	77.9789
24	M	324.94	22.7162	77.9737
25	M	326.18	22.7154	77.9707
26	M	327.59	22.7144	77.9673
27	M	324.49	22.7128	77.9622
28	CE	334.18	22.6992	77.9768
29	CE	333.65	22.6991	77.9766
30	M	333.03	22.6991	77.9765
31	M	333.93	22.6991	77.9765
32	M	331.66	22.6991	77.9765
33	CE	326.97	22.6990	78.0002
34	CE	326.73	22.6990	78.0004
35	CE	326.73	22.6991	78.0005
36	CE	326.96	22.6991	78.0006
37	CE	326.90	22.6992	78.0007

Sr.No	*Short Code**	*Elevation*	*Lat*	*long*
38	CE	326.27	22.6992	78.0008
39	CE	326.73	22.6991	78.0007
40	CE	327.49	22.6990	78.0007
41	CE	328.57	22.6989	78.0007
42	CE	328.72	22.6988	78.0007
43	CE	327.85	22.6987	78.0007
44	CE	327.60	22.6987	78.0006
45	CE	328.12	22.6988	78.0005
46	CE	322.99	22.6990	78.0047
47	CE	335.04	22.6972	78.0185
48	CE	334.36	22.6975	78.0185
49	CE	332.89	22.6976	78.0186
50	CE	332.05	22.6977	78.0186
51	CE	331.73	22.6978	78.0187
52	CE	331.05	22.6978	78.0188
53	CE	330.23	22.6977	78.0189
54	CE	329.96	22.6976	78.0190
55	CE	330.27	22.6976	78.0190
56	CE	330.26	22.6976	78.0192
57	CE	330.38	22.6975	78.0193
58	CE	329.72	22.6975	78.0194
59	CE	329.44	22.6975	78.0195
60	CE	329.37	22.6974	78.0197
61	CE	330.61	22.6975	78.0198
62	CE	330.34	22.6974	78.0199
63	CE	330.49	22.6973	78.0199
64	CE	330.34	22.6972	78.0199
65	CE	330.87	22.6971	78.0197
66	CE	331.06	22.6972	78.0196
67	CE	331.36	22.6972	78.0195
68	CE	331.93	22.6972	78.0194
69	CE	324.76	22.6952	78.0351
70	CE	325.95	22.6954	78.0351
71	CE	324.47	22.6946	78.0387
72	BR	325.42	22.6939	78.0431
73	BR	325.02	22.6939	78.0430
74	CE	322.22	22.6941	78.0430
75	CE	322.58	22.6942	78.0430
76	CE	323.77	22.6942	78.0431

Sr.No	*Short Code**	*Elevation*	*Lat*	*long*
77	CE	323.85	22.6942	78.0431
78	S	332.51	22.6907	78.0842
79	S	330.11	22.6902	78.0883
80	S	333.27	22.6902	78.0900
81	C	333.01	22.6904	78.1020
82	C	335.21	22.6902	78.1021
83	M	345.38	22.6901	78.1090
84	C	346.14	22.6901	78.1119
85	C	344.02	22.6903	78.1150
86	C	342.11	22.6904	78.1169
87	C	342.27	22.6906	78.1204
88	CN	344.45	22.6908	78.1226
89	CN	345.80	22.6908	78.1228
90	C	344.66	22.6911	78.1228
91	CN	344.83	22.6934	78.1453
92	CN	344.35	22.6935	78.1454
93	NR	337.04	22.6975	78.1668
94	NR	337.16	22.6976	78.1666
95	CN	331.72	22.6980	78.1662
96	CN	333.35	22.6978	78.1663
97	NR	332.92	22.6975	78.1670
98	M	336.08	22.6980	78.1689
99	NR	343.51	22.6994	78.1768
100	S	320.58	22.6980	78.1928
101	S	330.70	22.6988	78.1939
102	S	334.72	22.6995	78.1947
103	S	334.44	22.6997	78.1957
104	S	333.52	22.7012	78.1983
105	S	333.46	22.7010	78.1993
106	S	333.93	22.7007	78.2000
107	S	334.04	22.7002	78.2006
108	S	341.73	22.7037	78.2011
109	NR	332.18	22.7082	78.1971
110	NR	337.92	22.7221	78.1892
111	CN	340.95	22.7299	78.1885
112	CN	342.24	22.7300	78.1885
113	CE	339.48	22.7300	78.1886
114	CE	336.60	22.7298	78.1883
115	CE	332.76	22.7299	78.1880

Sr.No	*Short Code**	*Elevation*	*Lat*	*long*
116	CE	333.95	22.7298	78.1878
117	CE	335.90	22.7298	78.1876
118	CE	334.20	22.7298	78.1876
119	S	335.23	22.7300	78.1875
120	S	336.20	22.7300	78.1877
121	S	335.56	22.7302	78.1877
122	NR	338.25	22.7303	78.1876
123	NR	337.58	22.7304	78.1875
124	CN	318.89	22.7132	77.7353
125	NR	317.26	22.7038	77.7408
126	CN	332.74	22.6352	77.7725
127	CN	332.57	22.6353	77.7724
128	S	333.41	22.6331	77.7734
129	S	335.87	22.6314	77.7741
130	S	334.58	22.6298	77.7747
131	S	333.73	22.6290	77.7751
132	S	332.19	22.6275	77.7756
133	S	332.28	22.6259	77.7761
134	S	330.89	22.6243	77.7761
135	S	330.63	22.6228	77.7761
136	S	331.33	22.6203	77.7760
137	S	337.53	22.6072	77.7767
138	S	332.46	22.6070	77.7768
139	S	328.53	22.6018	77.7792
140	TAWA	332.05	22.5884	77.7880
141	BR	337.58	22.5886	77.7880
142	BR	335.63	22.5888	77.7880
143	SR	333.92	22.5824	77.7771
144	SR	333.68	22.5815	77.7762
145	SR	332.56	22.5800	77.7746
146	SR	333.10	22.5786	77.7731
147	SR	334.07	22.5776	77.7720
148	SR	333.96	22.5762	77.7705
149	NR	333.65	22.5751	77.7693
150	NR	333.48	22.5746	77.7683
151	NR	334.29	22.5755	77.7678
152	NR	334.01	22.5759	77.7674
153	GA	328.87	22.5782	77.7653
154	SR	330.50	22.5785	77.7651

Sr.No	*Short Code**	*Elevation*	*Lat*	*long*
155	MK	330.50	22.5801	77.7632
156	MK	330.36	22.5800	77.7632
157	M	331.67	22.5800	77.7633
158	SB	332.79	22.5800	77.7631
159	NR	331.30	22.5801	77.7634
160	NR	330.86	22.5803	77.7633
161	NR	331.88	22.5805	77.7632
162	DR	331.47	22.5816	77.7629
163	DR	330.85	22.5816	77.7629
164	DR	333.60	22.5812	77.7630
165	DR	332.32	22.5811	77.7630
166	DR	332.18	22.5810	77.7630
167	DR	332.22	22.5809	77.7631
168	DR	332.18	22.5808	77.7631
169	S	331.14	22.5807	77.7632
170	NR	332.18	22.5809	77.7630
171	NR	333.22	22.5809	77.7630
172	CE	330.09	22.5815	77.7631
173	CE	330.36	22.5815	77.7631
174	CE	331.91	22.5816	77.7631
175	CE	330.89	22.5817	77.7631
176	S	330.09	22.5827	77.7623
177	S	330.93	22.5827	77.7621
178	S	332.36	22.5827	77.7620
179	S	333.42	22.5826	77.7619
180	S	333.34	22.5826	77.7617
181	S	333.60	22.5826	77.7615
182	S	334.50	22.5827	77.7614
183	S	335.34	22.5828	77.7613
184	S	330.50	22.5829	77.7621
185	S	335.06	22.5830	77.7621
186	S	335.74	22.5833	77.7620
187	S	333.73	22.5835	77.7620
188	NR	329.99	22.5826	77.7627
189	NR	328.75	22.5826	77.7628
190	DR	329.35	22.5824	77.7627
191	NR	322.68	22.5849	77.7588
192	DR	327.62	22.5847	77.7587
193	SR	329.28	22.5837	77.7585

Sr.No	*Short Code**	*Elevation*	*Lat*	*long*
194	SR	329.57	22.5837	77.7587
195	SR	331.11	22.5836	77.7588
196	CE	335.35	22.5708	77.7485
197	CE	334.06	22.5709	77.7486
198	CE	335.42	22.5710	77.7486
199	NR	337.90	22.5706	77.7484
200	NR	340.08	22.5706	77.7484
201	NR	338.82	22.5705	77.7485
202	SR	337.80	22.5634	77.7480
203	SR	335.04	22.5634	77.7480
204	SR	336.33	22.5635	77.7478
205	SR	336.52	22.5635	77.7477
206	SR	338.11	22.5637	77.7477
207	SR	338.27	22.5637	77.7479
208	S	338.39	22.5633	77.7482
209	S	343.01	22.5587	77.7458
210	NR	341.51	22.5430	77.7258
211	NR	341.75	22.5389	77.7104
212	DR	343.45	22.5426	77.7108
213	FG	338.35	22.5447	77.7105
214	FG	337.17	22.5446	77.7104
215	DR	336.00	22.5450	77.7105
216	SR	337.20	22.5452	77.7105
217	SR	334.96	22.5452	77.7106
218	DR	333.82	22.5503	77.7095
219	DR	334.54	22.5512	77.7090
220	DR	336.23	22.5534	77.7097
221	DR	336.69	22.5533	77.7094
222	DR	329.24	22.5588	77.7093
223	DR	331.44	22.5597	77.7097
224	DR	331.27	22.5604	77.7100
225	DR	331.20	22.5612	77.7103
226	DR	330.45	22.5617	77.7107
227	DR	330.62	22.5624	77.7113
228	WT	331.25	22.5645	77.7128
229	DR	328.69	22.5643	77.7129
230	S	328.42	22.5643	77.7130
231	S	328.34	22.5643	77.7130
232	MKE	326.79	22.5641	77.7129

Sr.No	*Short Code**	*Elevation*	*Lat*	*long*
233	DR	323.71	22.5680	77.7133
234	DR	326.43	22.5705	77.7131
235	DR	324.81	22.5725	77.7129
236	DR	324.55	22.5731	77.7129
237	RD	325.10	22.5743	77.7128
238	RD	326.02	22.5757	77.7136
239	RD	324.26	22.5760	77.7146
240	RD	323.91	22.5763	77.7155
241	NR	323.02	22.5762	77.7155
242	S	322.87	22.5764	77.7157
243	S	322.87	22.5769	77.7168
244	S	321.39	22.5771	77.7170
245	S	323.97	22.5775	77.7170
246	S	323.21	22.5777	77.7173
247	S	322.16	22.5784	77.7175
248	S	321.78	22.5787	77.7177
249	S	323.80	22.5788	77.7184
250	NR	322.66	22.5791	77.7186
251	NR	323.41	22.5791	77.7185
252	S	322.81	22.5791	77.7189
253	TK	320.94	22.5794	77.7192
254	DR	321.21	22.5697	77.7132
255	DR	331.64	22.5532	77.7066
256	DR	332.23	22.5531	77.7058
257	DR	331.08	22.5529	77.7047
258	DR	331.41	22.5527	77.7035
259	DR	331.19	22.5524	77.7025
260	DR	331.58	22.5522	77.7011
261	DR	332.96	22.5519	77.7000
262	DR	333.20	22.5517	77.6988
263	DR	333.69	22.5515	77.6978
264	DR	334.21	22.5512	77.6962
265	DR	335.04	22.5510	77.6952
266	DR	335.66	22.5506	77.6933
267	DR	336.04	22.5503	77.6922
268	DR	335.99	22.5501	77.6908
269	DR	336.13	22.5499	77.6899
270	NR	338.53	22.5480	77.6832
271	NR	338.82	22.5480	77.6832

Sr.No	*Short Code**	*Elevation*	*Lat*	*long*
272	DR	339.66	22.5479	77.6832
273	CE	338.74	22.5479	77.6828
274	SB	337.94	22.5479	77.6827
275	CE	336.61	22.5479	77.6826
276	CN	333.87	22.5479	77.6834
277	CN	333.47	22.5475	77.6836
278	NR	332.54	22.5414	77.6762
279	AQUDUT	331.55	22.5403	77.6751
280	NR	333.05	22.5319	77.6676
281	RD	323.72	22.5319	77.6545
282	RD	324.45	22.5324	77.6521
283	RD	323.49	22.5320	77.6503
284	RD	318.69	22.5308	77.6477
285	MK	330.48	22.5321	77.6464
286	M	326.16	22.5321	77.6466
287	NR	331.48	22.5322	77.6462
288	NR	323.78	22.5324	77.6459
289	CE	320.94	22.5321	77.6452
290	NR	324.57	22.5317	77.6447
291	NR	323.08	22.5317	77.6443
292	CE	324.25	22.5316	77.6441
293	CE	324.70	22.5316	77.6440
294	CE	325.43	22.5316	77.6439
295	CE	325.91	22.5315	77.6439
296	NR	332.93	22.5316	77.6446
297	RD	328.68	22.5316	77.6447
298	S	324.64	22.5325	77.6458
299	RD	335.38	22.5323	77.6461
300	RD	329.66	22.5309	77.6437
301	RD	329.39	22.5300	77.6411
302	CE	334.90	22.5293	77.6338
303	CE	329.88	22.5290	77.6337
304	RD	328.62	22.5269	77.6273
305	RD	329.38	22.5253	77.6248
306	S	333.60	22.5173	77.6019
307	RD	333.86	22.5181	77.5996
308	S	325.73	22.5156	77.5827
309	RLY	313.13	22.5120	77.5510
310	RD	316.98	22.5325	77.5551

Sr.No	*Short Code**	*Elevation*	*Lat*	*long*
311	S	320.77	22.5353	77.5536
312	NR	317.62	22.5348	77.5534
313	S	320.52	22.5356	77.5535
314	NR	305.38	22.5035	77.5398
315	NR	316.57	22.5035	77.5400
316	NR	315.21	22.5023	77.5378
317	NR	317.50	22.5007	77.5361
318	NR	314.40	22.4923	77.5236
319	S	312.84	22.4891	77.5146
320	DR	307.89	22.4892	77.5147
321	S	312.28	22.4890	77.5148
322	CE	313.42	22.4887	77.5151
323	CE	313.34	22.4887	77.5151
324	DR	316.14	22.4892	77.5140
325	S	313.21	22.4894	77.5140
326	DR	311.98	22.4890	77.5140
327	DR	313.14	22.4892	77.5139
328	DR	314.19	22.4892	77.5138
329	NR	314.79	22.4892	77.5137
330	NR	315.21	22.4893	77.5138
331	S	314.05	22.4893	77.5137
332	DR	311.76	22.4769	77.4983
333	DR	311.78	22.4769	77.4983
334	DR	311.58	22.4770	77.4983
335	SR	311.15	22.4771	77.4985
336	SR	311.11	22.4771	77.4986
337	SR	311.26	22.4771	77.4986
338	RD	309.67	22.4772	77.4982
339	S	311.15	22.4773	77.4982
340	S	312.21	22.4773	77.4982
341	S	312.42	22.4772	77.4982
342	S	312.68	22.4771	77.4981
343	S	312.58	22.4770	77.4981
344	S	312.68	22.4769	77.4980
345	S	312.60	22.4768	77.4980
346	S	312.88	22.4767	77.4979
347	CE	309.47	22.4765	77.4978
348	CE	310.97	22.4765	77.4977
349	NS	318.62	22.4664	77.4883

Sr.No	*Short Code**	*Elevation*	*Lat*	*long*
350	NS	321.32	22.4664	77.4884
351	NS	318.38	22.4665	77.4884
352	NS	317.96	22.4665	77.4884
353	RD	314.54	22.4609	77.4852
354	RD	321.17	22.4596	77.4843
355	RD	322.40	22.4585	77.4840
356	RD	323.39	22.4564	77.4836
357	RD	324.34	22.4551	77.4827
358	RD	323.60	22.4542	77.4822
359	RD	324.08	22.4534	77.4817
360	RD	325.36	22.4524	77.4812
361	SR	319.82	22.4499	77.4816
362	NR	319.25	22.4499	77.4817
363	S	320.74	22.4329	77.4943
364	S	320.90	22.4329	77.4944
365	NS	322.19	22.4330	77.4939
366	S	322.46	22.4329	77.4941
367	NR	322.99	22.4329	77.4943
368	S	323.81	22.4329	77.4943
369	S	318.62	22.4329	77.4943
370	S	323.66	22.4330	77.4943
371	S	324.05	22.4331	77.4943
372	NR	323.87	22.4333	77.4943
373	S	323.85	22.4333	77.4943
374	CE	320.89	22.4328	77.4972
375	CE	320.16	22.4328	77.4973
376	CENR	323.73	22.4328	77.4969
377	NR	323.71	22.4328	77.4969
378	CE	321.82	22.4327	77.4969
379	CE	321.05	22.4327	77.4969
380	CE	319.46	22.4325	77.4969
381	CE	319.20	22.4325	77.4969
382	CE	320.59	22.4326	77.4971
383	SR	321.16	22.4357	77.4888
384	SR	324.33	22.4356	77.4887
385	SR	324.27	22.4356	77.4887
386	SR	322.56	22.4354	77.4887
387	SR	321.40	22.4354	77.4887
388	SR	320.30	22.4353	77.4886

Sr.No	*Short Code**	*Elevation*	*Lat*	*long*
389	SR	319.02	22.4352	77.4886
390	SR	318.30	22.4360	77.4885
391	SR	319.17	22.4362	77.4883
392	SR	326.64	22.4393	77.4840
393	CN	328.07	22.4429	77.4494
394	CN	328.97	22.4429	77.4494
395	SR	327.53	22.4428	77.4495
396	SR	328.36	22.4429	77.4496
397	RD	318.96	22.4392	77.4391
398	RD	324.23	22.4383	77.4366
399	RD	328.57	22.4372	77.4339
400	RDNR	336.52	22.4349	77.4281
401	SNR	329.73	22.4295	77.4251
402	DR	329.38	22.4296	77.4252
403	S	329.59	22.4297	77.4252
404	S	326.47	22.4282	77.4253
405	S	324.84	22.4274	77.4256
406	CN	321.99	22.4263	77.4256
407	CN	322.40	22.4264	77.4256
408	NR	323.63	22.4262	77.4256
409	NR	326.10	22.4248	77.4247
410	DR	326.43	22.4247	77.4247
411	DR	326.97	22.4246	77.4245
412	CE	322.19	22.4243	77.4238
413	CE	322.41	22.4244	77.4238
414	CE	322.82	22.4244	77.4238
415	CE	318.59	22.4244	77.4237
416	CE	319.19	22.4244	77.4237
417	CE	320.32	22.4245	77.4236
418	CE	320.70	22.4246	77.4236
419	CE	319.97	22.4247	77.4235
420	CE	318.38	22.4248	77.4234
421	S	319.09	22.4512	77.4610
422	S	319.39	22.4512	77.4621
423	RD	319.48	22.4513	77.4634
424	NR	316.33	22.4517	77.4648
425	S	313.20	22.4516	77.4655
426	S	308.89	22.4516	77.4659
427	S	305.90	22.4517	77.4667

Sr.No	*Short Code**	*Elevation*	*Lat*	*long*
428	S	303.87	22.4517	77.4673
429	S	301.69	22.4517	77.4677
430	NR	305.61	22.4517	77.4683
431	S	307.21	22.4517	77.4688
432	NR	308.90	22.4526	77.4697
433	S	310.70	22.4532	77.4709
434	S	313.31	22.4543	77.4719
435	S	313.24	22.4551	77.4725
436	S	312.77	22.4561	77.4733
437	S	313.00	22.4572	77.4743
438	NR	313.89	22.4587	77.4760
439	S	314.96	22.4595	77.4768
440	S	315.78	22.4596	77.4779
441	S	315.60	22.4603	77.4787
442	RD	316.25	22.4620	77.4788
443	RD	316.52	22.4633	77.4788
444	RD	316.70	22.4647	77.4792
445	S	315.86	22.4660	77.4802
446	RD	315.50	22.4671	77.4810
447	S	314.89	22.4683	77.4818
448	RD	316.95	22.4686	77.4820
449	S	315.88	22.4691	77.4824
450	S	312.66	22.4700	77.4836
451	NR	309.38	22.4709	77.4849
452	RD	309.11	22.4717	77.4857
453	S	307.96	22.4727	77.4864
454	S	308.65	22.4728	77.4863
455	RAIL	314.60	22.4732	77.4857
456	S	317.62	22.4737	77.4853
457	NR	318.62	22.4741	77.4846
458	NR	313.04	22.4748	77.4829
459	SR	311.72	22.4759	77.4813
460	SR	310.69	22.4758	77.4812
461	NR	309.51	22.4768	77.4800
462	NR	312.18	22.4781	77.4783
463	NR	311.14	22.4837	77.4691
464	CE	316.99	22.4840	77.4690
465	CE	314.88	22.4842	77.4688
466	CE	315.21	22.4843	77.4685

Sr.No	*Short Code**	*Elevation*	*Lat*	*long*
467	CE	314.32	22.4843	77.4684
468	CE	314.87	22.4845	77.4684
469	CE	315.04	22.4846	77.4683
470	CE	314.74	22.4847	77.4683
471	CE	315.16	22.4848	77.4683
472	CE	315.42	22.4849	77.4684
473	CE	315.29	22.4848	77.4686
474	NR	315.99	22.4848	77.4689
475	NR	315.44	22.4847	77.4690
476	NR	314.24	22.4846	77.4690
477	CE	314.51	22.4846	77.4690
478	CE	315.42	22.4844	77.4690
479	NR	314.24	22.4843	77.4688
480	CE	312.37	22.4842	77.4690
481	S	313.47	22.4840	77.4694
482	NR	313.23	22.4841	77.4695
483	NR	312.58	22.4837	77.4688
484	NR	313.69	22.4837	77.4686
485	NR	314.30	22.4836	77.4686
486	CE	314.23	22.4836	77.4686
487	CE	314.64	22.4835	77.4686
488	CE	314.39	22.4835	77.4687
489	CE	313.73	22.4834	77.4689
490	CE	312.27	22.4836	77.4690
491	NR	312.15	22.4836	77.4691
492	NR	293.21	22.4783	77.4935
493	NR	299.51	22.4800	77.4961
494	NR	302.18	22.4838	77.5022
495	NR	311.79	22.4908	77.5191
496	GRAS	317.65	22.4936	77.5245
497	NR	304.05	22.4930	77.5229
498	NR	305.06	22.4931	77.5232
499	NR	314.68	22.4932	77.5236
500	S	300.31	22.7543	77.7336
501	NR	361.64	22.5553	77.8100
502	NR	367.28	22.5511	77.8127
503	RD	373.07	22.5478	77.8127
504	NR	412.75	22.5333	77.8251
505	RD	417.24	22.5305	77.8258

Sr.No	*Short Code**	*Elevation*	*Lat*	*long*
506	NR	425.47	22.5251	77.8241
507	NR	432.66	22.5232	77.8243
508	NR	447.92	22.5352	77.8553
509	NR	447.87	22.5372	77.8578
510	NR	449.29	22.5396	77.8629
511	NR	455.16	22.5423	77.8708
512	NR	461.49	22.5463	77.8785
513	NR	456.33	22.5512	77.8863
514	R	457.82	22.5558	77.8897
515	NR	443.67	22.5600	77.9022
516	S	438.90	22.5599	77.9066
517	NR	415.41	22.5618	77.9129
518	RD	423.80	22.5617	77.9163
519	RD	425.62	22.5635	77.9191
520	RD	423.60	22.5638	77.9212
521	GRAS	339.27	22.5633	77.9748
522	NR	336.41	22.5632	77.9752
523	TWA TOP	362.26	22.5623	77.9752
524	TWA TOP	362.55	22.5623	77.9754
525	ST	321.18	22.7280	77.7358
526	ST	314.25	22.7278	77.7356
527	NARMADA	296.85	22.7630	77.7160

Appendix - IV(B)

GPS Point with data code During 2017

Sr.No	*Code*	*LAT*	*LONG*	*Elevation*
1	RD	22.643	77.7689	321.2271
2	G	22.5841	77.7784	337.7569
3	G	22.584	77.7783	337.492
4	SRS	22.5769	77.7669	333.4966
5	SRS	22.5756	77.7677	337.3592
6	CNL	22.5683	77.7561	339.1271
7	G	22.5709	77.7484	333.2058
8	K	22.5582	77.7455	342.9545
9	G	22.5582	77.7454	343.3017
10	K	22.5582	77.7454	341.9738
11	SRS	22.5432	77.7281	339.5003
12	SRS	22.5432	77.7279	342.4388
13	SRS	22.5432	77.7279	343.4207
14	K	22.5431	77.7262	341.6609
15	K	22.5431	77.7263	345.6937
16	K	22.5431	77.7264	347.0339
17	K	22.5425	77.7252	342.55
18	SRS	22.5413	77.7173	344.0635
19	G	22.5413	77.7172	340.4487
20	K	22.5389	77.7113	340.2013
21	K	22.539	77.7113	341.3945
22	K	22.539	77.7115	341.4813
23	SNTRA	22.5315	77.6742	336.6194
24	K	22.5309	77.6587	333.7804
25	G	22.5291	77.6308	330.0623
26	G	22.5282	77.6292	327.179
27	K	22.5063	77.5643	320.3919
28	K	22.5065	77.5644	320.1644
29	SRS	22.5064	77.5643	318.9835
30	G	22.719	77.806	322.5393
31	BGN	22.719	77.8059	312.7519
32	G	22.7191	77.8053	307.0395
33	BGN	22.7186	77.8059	305.0037
34	G	22.7186	77.8059	306.1433
35	TUR BIG	22.7193	77.8057	304.5197
36	G	22.7009	77.9556	317.7178
37	G	22.753	77.7171	289.7519
38	G	22.753	77.717	289.0441
39	G	22.753	77.717	289.0212

Appendix - V

Photo Locations during Survey

Sr.No	Image	Lat	Long
1.		22.7087	77.8391
2.		22.7087	77.8391
3.		22.7103	77.8458
4.		22.7083	77.9203
5.		22.7082	77.9213
6.		22.7079	77.9224
7.		22.7082	77.9445
8.		22.7121	77.9473
9.		22.7123	77.9476
10.		22.7117	77.9478
11.		22.7113	77.9483
12.		22.7251	77.9624
13.		22.7251	77.9624
14.		22.7251	77.9624
15.		22.7251	77.9624
16.		22.7251	77.9624
17.		22.7251	77.9624
18.		22.7251	77.9624
19.		22.7373	77.9741
20.		22.7396	77.9774
21.		22.7396	77.9774

22.		22.7396	77.9774
23.		22.7396	77.9774
24.		22.737	77.9826
25.		22.737	77.9826
26.		22.7328	77.9858
27.		22.7328	77.9858
28.		22.7328	77.9858
29.		22.7199	77.9842
30.		22.7196	77.9843
31.		22.72	77.9843
32.		22.72	77.9843
33.		22.72	77.9843
34.		22.7051	77.9426
35.		22.6992	77.9767
36.		22.6992	77.9767
37.		22.6992	77.9767
38.		22.6992	77.9767
39.		22.6992	77.9767
40.		22.699	78.0002
41.		22.699	78.0002
42.		22.699	78.0002
43.		22.6977	78.0187
44.		22.6977	78.0187

45.		22.6977	78.0187
46.		22.6977	78.0187
47.		22.695	78.0348
48.		22.6908	78.1228
49.		22.6908	78.1228
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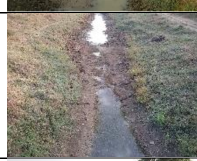
51.		22.6908	78.1228
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56.		22.6974	78.1667
57.		22.7297	78.1883
58.		22.7297	78.1883
59.		22.7297	78.1883
60.		22.7297	78.1883
61.		22.7297	78.1883
62.		22.7297	78.1883
63.		22.7297	78.1883
64.		22.7297	78.1883
65.		22.7302	78.1885
66.		22.7302	78.1885

67.		22.7302	78.1885
68.		22.7302	78.1885
69.		22.7302	78.1885
70.		22.7295	78.188
71.		22.7295	78.188
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73.		22.7295	78.188
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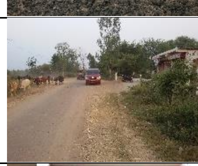
76.		22.7298	78.188
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81.		22.7428	77.7575
82.		22.7428	77.7575
83.		22.635	77.7724
84.		22.635	77.7724
85.		22.635	77.7724
86.		22.635	77.7724
87.		22.6353	77.7722
88.		22.6008	77.7795

89.		22.6008	77.7795
90.		22.6006	77.7799
91.		22.5884	77.7882
92.		22.5884	77.7882
93.		22.5884	77.7882
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96.		22.5884	77.7882
97.		22.5884	77.7882
98.		22.5884	77.7882
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107.		22.5799	77.7635
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117.		22.582	77.7632
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125.		22.5831	77.7618
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129.		22.5849	77.7595
130.		22.5849	77.7595
131.		22.5844	77.7589
132.		22.5845	77.7586

133.		22.5845	77.7586
134.		22.5709	77.7484
135.		22.5709	77.7484
136.		22.5707	77.7486
137.		22.5707	77.7486
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139.		22.5707	77.7486
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142.		22.5696	77.7481
143.		22.5696	77.7481

144.		22.5696	77.7481
145.		22.5389	77.71
146.		22.5389	77.71
147.		22.5446	77.7103
148.		22.5446	77.7103
149.		22.5446	77.7103
150.		22.5452	77.7107
151.		22.5452	77.7107
152.		22.5477	77.7103
153.		22.5477	77.7103
154.		22.5477	77.7103

155.		22.5477	77.7103
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165.		22.5531	77.7088

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167.		22.5531	77.7088
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173.		22.5578	77.709
174.		22.5642	77.7129
175.		22.5642	77.7129
176.		22.5642	77.7129
177.		22.5642	77.7129
178.		22.5763	77.7153
179.		22.5763	77.7153

180.		22.5763	77.7165
181.		22.5763	77.7165
182.		22.5762	77.7157
183.		22.5762	77.7157
184.		22.5762	77.7157
185.		22.5762	77.7157
186.		22.5762	77.7157
187.		22.5763	77.7157
188.		22.5787	77.7188
189.		22.5787	77.7188
190.		22.5791	77.7188

191.		22.5795	77.7189
192.		22.5497	77.687
193.		22.5497	77.687
194.		22.5497	77.687
195.		22.5497	77.687
196.		22.5497	77.687
197.		22.5479	77.6839
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201.		22.5479	77.6839

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206.		22.5941	77.6836
207.		22.5941	77.6836
208.		22.5941	77.6836
209.		22.5941	77.6836
210.		22.5417	77.7067
211.		22.5321	77.6462
212.		22.5321	77.6462

213.		22.5321	77.6465
214.		22.5321	77.6465
215.		22.5323	77.6455
216.		22.5323	77.6455
217.		22.5323	77.6455
218.		22.5323	77.6455
219.		22.5314	77.6438
220.		22.5314	77.6438
221.		22.5314	77.6438
222.		22.5314	77.6438
223.		22.529	77.6316

224.		22.529	77.6316
225.		22.529	77.6316
226.		22.529	77.6316
227.		22.5291	77.6306
228.		22.5291	77.6306
229.		22.5285	77.6297
230.		22.5285	77.6297
231.		22.5191	77.6195
232.		22.5191	77.6195
233.		22.5191	77.6195
234.		22.5183	77.6191

235.		22.5166	77.6181
236.		22.5149	77.6169
237.		22.5143	77.616
238.		22.5138	77.6151
239.		22.5136	77.6111
240.		22.5065	77.5536
241.		22.5065	77.5536
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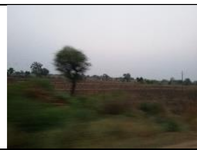
246.		22.5413	77.566
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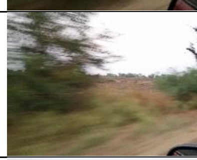
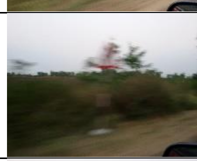
250.		22.5425	77.569
251.		22.543	77.5698
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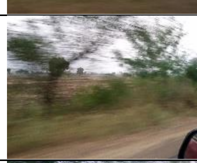
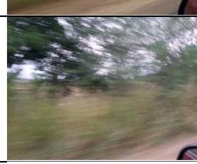
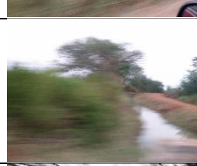
253.		22.5435	77.5706
254.		22.5446	77.5735
255.		22.5446	77.5735
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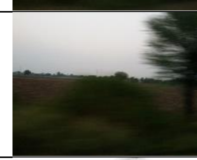
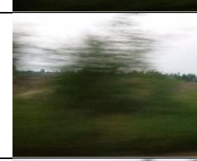
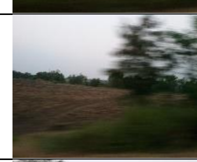
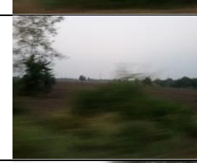
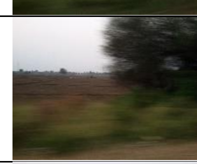
261.		22.5495	77.5837
262.		22.5495	77.5837
263.		22.5499	77.5846
264.		22.5508	77.5864
265.		22.5512	77.5874
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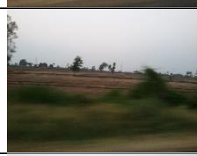
270.		22.5544	77.5937
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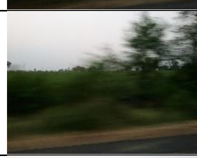
272.		22.555	77.5945
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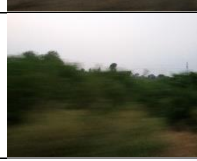
274.		22.56	77.5996
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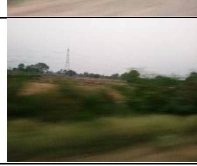
278.		22.5626	77.6028

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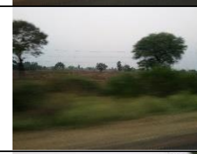
280.		22.5635	77.605
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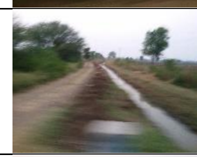
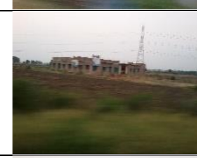
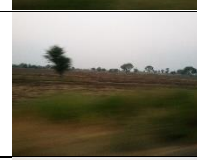
282.		22.5654	77.6087
283.		22.566	77.6095
284.		22.5687	77.6127
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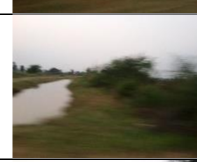
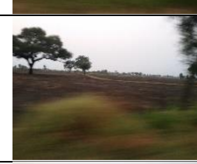
286.		22.5721	77.6166
287.		22.5721	77.6166
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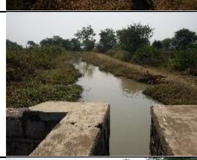
294.		22.5414	77.5663
295.		22.5414	77.5663
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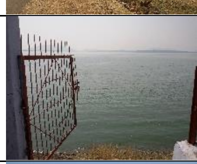
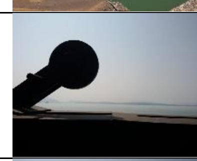
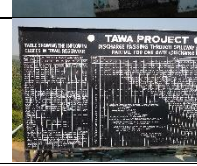
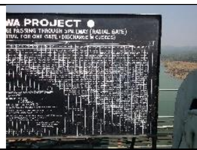
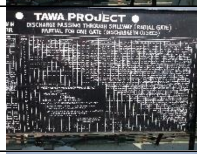
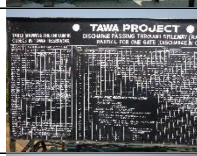
419.		22.5612	77.9672
420.		22.5612	77.9672
421.		22.5612	77.9672
422.		22.5612	77.9672

423.		22.5612	77.9672
424.		22.5612	77.9672
425.		22.5612	77.9672
426.		22.5612	77.9672
427.		22.5612	77.9672
428.		22.5612	77.9672
429.		22.5611	77.9669
430.		22.5631	77.9756
431.		22.5631	77.9756
432.		22.5623	77.9752
433.		22.5623	77.9752
434.		22.5623	77.9752

435.		22.5623	77.9752
436.		22.5623	77.9752
437.		22.5623	77.9752
438.		22.5623	77.9752
439.		22.5622	77.9633
440.		22.5624	77.9755
441.		22.5622	77.9762
442.		22.5622	77.9762
443.		22.5622	77.9762
444.		22.5622	77.9762
445.		22.5626	77.9768

446.		22.5626	77.9768
447.		22.5626	77.9768
448.		22.5626	77.9768
449.		22.5626	77.9768
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452.		22.5626	77.9768
453.		22.5623	77.976
454.		22.5623	77.976

455.		22.5623	77.976
456.		22.5623	77.976
457.		22.5623	77.976
458.		22.5623	77.976
459.		22.5623	77.976
460.		22.5623	77.9752
461.		22.5623	77.9752
462.		22.5623	77.9752
463.		22.5622	77.9633