GIS Based Efficient Distribution System for a Command

National Institute of Hydrology
Jalvigyan Bhawan
Roorkee – 247 667 (Uttaranchal)
March, 2003

CONTENTS

* * *

LIST OF TABLES & FIGURES

*** * ***

DIRECTOR	**-**	Dr. K. S. Ramasastri

STUDY GROUP

M. K. Goel	Scientist ‘E1’
Dr. S. K. Jain	Scientist ‘F’
P. K. Agarwal	Principal Research Assistant

PREFACE

Conjunctive water management in irrigation systems requires huge volume of data pertaining to hydrological, hydro-geological, hydro-meteorological, soil, agronomic, and cropping pattern parameters in command areas. For the operation of canal system in a command area, information on the existing cropping pattern, irrigation demands, groundwater conditions, canal system characteristics, and their spatial distribution is a prerequisite. These data need to be effectively analyzed, stored and retrieved whenever required. In addition, a simulation model is required which can integrate the available data to evaluate the system operation and provide an integrated picture of the total system.

To help in the judicious conjunctive management of water resources in a canal irrigation system, there was a need to develop a canal network simulation model that can utilize real-time data and geographic data of the irrigation system to help the operator in decision-making process. With this need in view, a GIS based model has been developed for the conjunctive operation simulation of a canal irrigation system. The model uses the real-time irrigation demands in the command area and calculates the total flow requirement in each minor, distributory, and branch in a canal system after accounting for the water application efficiency, field channel efficiency, seepage losses, and canal capacity and water availability constraints.

The model uses the groundwater depth information in the command to decide the allocation plan of canal water and groundwater use during a week. The model aims to utilize the available canal water to the maximum extent provided that groundwater conditions permit. The adopted approach also tries to ensure groundwater stabilization by curtailing canal water supply in the water logged area, pumping groundwater in the shallow water table area and using canal water in deeper groundwater area. The model computes a canal-run configuration that provides higher effective utilization of canal water, relatively higher canal seepage in the areas of deeper groundwater and in least energy requirement for pumping groundwater. Model application is cited for the Lakhaoti command area under the Madhya Ganga Canal system. The database of the Lakhaoti command has been developed and model computations have been presented in tabular and graphical form. The model can be used to design or alter the canal system configuration and different scenarios of canal capacities, canal system layout, and area actually irrigated by them can be evaluated.

The study has been carried out by Sh. M. K. Goel, Sc. “E1”, Dr. S. K. Jain, Sc. “F”, and Sh. P. K. Agarwal, PRA of the Water Resources Systems Division of this Institute.

(K. S. Ramasastri)
Director

ABSTRACT

Conjunctive management of water resources in irrigation systems requires multi-disciplinary data pertaining to hydrological, hydro-geological, hydro-meteorological, soil, agronomic, and cropping pattern parameters in command areas. Further, a model is required that can integrate all the available information to evaluate the system operation and provide an integrated picture of the total system. Computers now make possible the use of larger data sets, more sophisticated analytical techniques and a variety of graphical means for presenting analysis results.

While the demands for water by all the sectors (municipal, industrial, irrigation, hydropower etc.) are rising, investments for development of additional water resources are limited. This requires more efficient and rationale utilization of the available resources based on scientific principles. The realization of this objective in the irrigation sector requires a formal framework for water resources decision-making that enables spatial assessment of water supplies and demands in real-time and a balancing of the two to meet specified objectives. A GIS based procedure has been developed in the present study for conjunctive operation of the canal system. The model utilizes real-time data and multi-disciplinary spatial and attribute data in a canal irrigation system and can help the operator in decision-making process.

The model uses the real-time irrigation demands in the command area (calculated by another model) and calculates the total flow requirements at each minor, distributory, and branch in a canal system after accounting for the water application efficiency, field channel efficiency, seepage losses, and canal capacity and water availability constraints. In addition, the model uses the information of groundwater depth in the irrigation system for finding the optimum canal-run configuration during each week. The model aims at utilizing the available canal water to the maximum extent provided that groundwater conditions in the area permit. In case of shortage of surface water, the demands of a minor/distributory with least water table depth are met from groundwater. Through iterative simulation of canal operation, the model finds a canal-run configuration that provides higher effective utilization of canal water, relatively higher canal seepage in the areas of deeper groundwater and requires least energy for pumping groundwater. In the development of this procedure, it is inherently assumed that it is always economical to utilize the surface water as compared to the groundwater provided that surface water is available.

A computer program has been written for the allocation model and applied to the Lakhaoti command area under the Madhya Ganga Canal system. Data requirement of the model is quite high. Detailed database has been developed for the Lakhaoti command. Layout of canal system up to the minor level has been delineated using the PAN sensor data of IRS-1C satellite. Minor-wise command area has been digitized. The location of groundwater wells and the groundwater depths in various wells in the year 1998-99 have been collected from

field offices and groundwater surfaces have been generated in the GIS system (ILWIS). Characteristics of different canal segments have also been collected from the field offices of the Madhya Ganga Canal system. The operation of canal system is based on the irrigation demands (as worked out by another model), canal water availability and the groundwater depth in any week.

Major advantages of the model are that it operates the system for the actual cropping pattern and uses real-time information about spatially distributed irrigation demands and groundwater depths. It considers different characteristics of the canal segments and utilizes the information of different irrigation practices in different parts of the command area rather than assuming lumped values. Further, the model uses least number of assumptions in terms of canal seepage, recharge because of rainfall and irrigation, income and expenditure on various crops, and cost of providing surface and groundwater etc. The approach suggests the operation plan for each week. The aim is to satisfy the irrigation demands in the command area with least cost of pumping. To approach also tries to ensure groundwater stabilization by curtailing canal water supply in the water logged area, pumping groundwater in the shallow water table area and using canal water in deeper groundwater area.

One major limitation of the model is extensive database requirement. The model requires digitization of Sajra maps for the whole canal system. Further, the approach requires the determination of actual cropping pattern for the command area before the start of the season. The approach also requires a network of well-distributed groundwater observation wells and collection of groundwater level data from the observation wells at weekly/monthly time step.

However, once the database is developed, the model can show simulation analysis for different scenarios of canal water availability in the form of maps and tables. The model can be used to design or alter the system configuration and different scenarios of canal capacities and canal system layout, and area actually irrigated by them can be evaluated.

* * *

CHAPTER – 1
INTRODUCTION

Irrigation is required to obtain high crop yields through optimum scheduling of water application on farms. The objective is to deliver water to the farms in an equitable manner so that the soil moisture is kept in the optimum range and does not fall below the stress level. Maximum crop yield can result only if the crops receive right quantity and quality of water at the right time. Both, the quantity and timing, depend upon various meteorological factors and the soil water status for any given crop. For maximizing the crop yield, there is a need to carefully plan the regime of watering over the entire crop period.

Despite large investments made in the irrigation sector and the phenomenal growth of irrigation since independence, the performance of irrigation in many command areas in this country is not very satisfactory. Because of the indiscipline in the irrigation water distribution, excess water is used in the head reach of the command area in the belief that more the water supplied for the crop, the higher would be the yield. Excess irrigation causes waterlogging due to rise in the subsoil water table. Continued waterlogging results in salinity development and may render the land unproductive. Waterlogging is a serious problem and has been widely reported, especially in the head reaches of some canal irrigation projects. A survey in 1983 of the Tungabhadra Project (commissioned in 1953) in Karnataka, found 33,000 ha of land severely affected by waterlogging and salinity, increasing at the rate of 6,000 ha annually (Abrol, 1985). In parts of Haryana where the waters of the Bhakra canal were delivered in 1963, the rising water table created a problem of salinisation. Salinity has also developed in the command of the Mahi-Kadana project in Gujarat with groundwater rising at the rate of about one meter per year (WTC, 1983). In the Sarda Sahayak Project in Uttar Pradesh., there is loss of 1 lakh ha of land because of waterlogging and salinisation.

Further, due to irregularities in the irrigation water distribution, the tail end of a command area is deprived of irrigation facilities leading to complaints and discontent. Tail ends of main canals, branch canals, distributaries, minor and field watercourses all suffer. Deprivation takes many forms and is reflected in various indicators relating to water supply, irrigation intensity, crops grown, cultivation practices, yields and incomes. Higher valued and more water-intensive crops tend to be concentrated in the head reaches.

Different methods of water distribution are followed in canal irrigation systems in India. These are briefly described in Chapter – 2. The supply of water diverted into a main canal is distributed amongst different branches, distributaries and minors in accordance with demand on different channels. In the states of Punjab, Haryana and Rajasthan, the system of rotational scheduling is known as “Warabandi”. In Uttar Pradesh, it is called “Osrbandi” and in Maharashtra as “Shejpali”. Warabandi is a system of equitable distribution of water by turns according to a predetermined schedule, specifying the day, the exact time and the duration of supply of water to each irrigator. The total volume of water that each farmer receives is in proportion to his landholding in the outlet command. The basis of scheduling the system is thus a fixed quantity of water per unit of land. All the systems, as mentioned above, are basically rotational schedule systems but differ in details. The unit of rotation is the village in some cases and random group of farmers in others. Warabandi system is logically the best amongst these as in this system the individual farmer is provided with the rotational schedule. There are many canal systems in India where no schedule of any kind is adhered. It is the general policy of the Government of India to eventually promote the system of Warabandi on all canal systems. In those canal systems where scheduling system is not properly functioning, farmers in the lower reaches of the canal are always at the mercy of farmers in the upper reaches. Different water distribution systems of India are detailed in the following chapters.

The importance of conjunctive use management of water has long been felt in this country. The National Water Policy 1987 recommended for the planning for conjunctive use right from the formulation stage of a project. The concept recognizes the unified nature of surface and groundwater resources as a single natural resource. The main objective of conjunctive use is to have a system of water distribution spread over an extended time span to have better cropping pattern and achieve maximum production with minimum soil damage. The process takes advantage of the interactions between the surface and ground phases of the hydrologic cycle. There is a need to develop computerized procedures for conjunctive management of water in command areas that can simulate the system operation using available information database. An information system contains a huge volume of data pertaining to hydrological, hydro-geological, hydro-meteorological, soil, agronomical, and cropping pattern parameters and is operated to provide instantaneous information about the various activities under conjunction operation. A simulation model is mostly computational in nature and contains equations involved in various processes. Using a suitable combination of information system and simulation model, the system response can be evaluated and an integrated picture of the total system can be analyzed.

1.1 OBJECTIVES AND SCOPE OF THE STUDY

Enough attention is being paid now a day in India to evaluate and improve the present operational systems to keep pace with developments in the field of soil-crop-water-atmosphere relationships. The present systems do not provide for water in relation to the requirements of the crops. Except for the Warabandi system, other systems do not take into account the filling time and conveyance losses in the watercourses. Erratic delivery systems and irrational management of water and crops have further aggravated the situation in the command areas. Recent advances in computer hardware and software including increased speed and storage, advanced software debugging tools and GIS/spatial analysis software have made it possible to carry out large area simulations and evaluate the consequences of adopting a particular approach. It is, therefore, necessary to develop suitable criteria for the regulation of canal systems and make improvement in the existing water delivery system. The developed procedure must consider groundwater scenarios in a command along with surface water availability so as to treat overall water resources of a command in a unified manner.

Efforts to improve agricultural practice by making more efficient use of available water resources are common nowadays. Most such efforts require mathematical models to simulate the dynamics of water allocation in the root zone of a crop. The objective of the present study is to develop a GIS based model for conjunctive operation of a canal system at weekly time interval. Based on the water balance of root zone for each week, spatially distributed irrigation demands in the canal system are worked out. The model uses the real-time irrigation demands in the canal system and calculates the total flow requirement at each canal segment (minor, distributory, and branch) in the system after accounting for the water application efficiency, field channel efficiency, seepage losses in canals, and the conveyance capacity constraints. The canal system is represented in the model in terms of segments connected to each other at nodes. Canal system characteristics such as capacity, conveyance efficiency etc. are input to the model.

In addition to the surface water availability and capacity constraints, the procedure utilizes the information about the groundwater depth below each canal segment in the system for the week under consideration. The allocation model utilizes the surface water to the extent possible provided that groundwater table is below the maximum allowable limit. In case of shortage of surface water, the demands of a canal segment that has the highest groundwater table are met from the groundwater. This way, the model tries to find the allocation pattern for the least cost of pumping. The use of groundwater in the high water table zone and the use of canal water in the deeper groundwater zone also tend to stabilize the groundwater table in the region. The model recursively tries to find the canal-run configuration that requires least amount of energy for pumping groundwater. In this procedure, it is inherently assumed that it is always economical to utilize the surface water as compared to the groundwater provided the surface water is available and the groundwater conditions permit.

The model application is presented for the Lakhaoti command area under the Madhya Ganga Canal system. Accurate layout of the canal system of the Lakhaoti branch up to the minor level has been delineated using the PAN sensor data of IRS-1C satellite. Minor-wise command area has been digitized and linked to the corresponding minors through unique identifiers. The location of groundwater wells and the groundwater depths in various wells in the year 1998-99 have been collected from field offices and groundwater surfaces have been generated in the GIS system (ILWIS) using different methods of interpolation/kriging. Based on the groundwater surface and the DEM of the topography, the depth of pumping at each grid has been calculated. The operation of the canal system is based on the actual irrigation demands, actual surface water availability and the groundwater depth in any week.

* * *

CHAPTER – 2
IRRIGATION WATER DISTRIBUTION – A REVIEW

The supply of water diverted into a main canal is distributed amongst different branches, distributaries and minor canals in accordance with demand on different channels. This distribution is easy when the available supply equals or exceeds the demand. However, when the supply is insufficient to run the whole canal system simultaneously, some distributing channels are kept closed while others are operated. Proper regulation of canals and distribution of the required quantity of water are essential for efficient use of irrigation water. The paramount objective in the effective management of an irrigation system in any command area is to ensure that water is distributed in adequate quantities and at proper times throughout the command area to meet the requirements of the crops grown.

Different methods of water distribution are followed in canal irrigation systems in India. However, enough attention has not been paid to evaluate and improve on these methods to keep pace with developments in the field of soil-crop-water-atmosphere relationships. Erratic delivery systems and irrational management of water and crops have further aggravated the situation in the command area. It is, therefore, necessary to evaluate the performance of prevalent water distribution methods and to develop suitable criteria for regulation and water delivery schedules. The different water distribution practices that are being practiced in India are discussed in brief in the following paragraphs.

2.1 CANAL WATER DELIVERY SYSTEMS IN INDIA

Agro-climatic and socio-economic conditions in India vary widely, and the irrigation management systems and practices that have either been introduced or evolved reflect this diversity. Most surface irrigation schemes may be classified as either supply-based or demand-based. The former is generally confined to the warabandi system as practised in the Punjab, Haryana and parts of Rajasthan and Uttar Pradesh codified under the North India Act (1873). The Bengal Act (1876) covers water apportionment in Bihar, West Bengal and Orissa. The Bombay Act (1876), applicable to water apportionment in Gujarat, Maharashtra and part of Madhya Pradesh, defines the operation of schemes that are essentially ‘demand-based’. In parts of the southern states of Andhra Pradesh, Karnataka and Tamil Nadu, where rice is the preferred crop and irrigation is synonymous with paddy cultivation, a system known as ‘localization’ has evolved. In the paddy-intensive southern and eastern delta areas (e.g. Godavari, Krishna and Cauvery) a traditional ‘field-to-field’ system is practised.

a) Warabandi System

The Warabandi system of Haryana, Punjab and Rajasthan is a system of delivery of water in rotation amongst cultivators sharing water from a canal outlet. The system is designed to distribute available water as equitably and reliably as possible. It is known as Osrabandi in Uttar Pradesh. The share of water of an irrigator is in proportion to the area of his landholding in the command outlet. A predetermined quantity of water is provided to each irrigator once a week. Because the farmer is assured of a pre-determined amount of water, he arranges his cropping accordingly and is able to maximize the return of water and rainfall by careful irrigation. The duration of water supply allowed per unit area of the irrigated land under the command of the outlet is determined by dividing the number of minutes in a week by the area of land to be irrigated. Allowances are made for the watercourse filling time and the conveyance losses in the watercourse.

The warabandi system was originally developed for mono-cropped areas of cereals on the level, deep, homogeneous alluvial soils of the north-west Indo-Gangetic plains where the effective rainfall is too low (330-450 mm per year) to permit the rain fed cultivation of paddy and wheat. It was designed to spread available water over as large an area as possible from run-of-the-river diversions to take advantage of the seasonal snowmelt runoff prior to the onset of the monsoon, although natural variations in flow have since been augmented by storage structures. However, without conjunctive use of groundwater, the system cannot easily accommodate a diverse cropping pattern with differing water requirements. Further, the lack of an adequate drainage system and poorly managed water distribution has brought about a rising water table and widespread salinisation, particularly in Punjab, Haryana, and Uttar Pradesh.

Notwithstanding the more recently recognized drawbacks, the warabandi system is generally considered to have been a success in the northwestern states and there have been calls for the system to be introduced elsewhere in India. There are, however, a number of constraints to the system's wider adoption, particularly under conditions of a higher rainfall where a kharif crop based primarily on rainfall is possible. If rainfed cropping is viable in an average year, farmers plan on the expected rainfall and plant the greater part of their holding. If, however, rainfall is below normal or poorly distributed in a particular year the whole command area needs water simultaneously and farmers at the head have as much to gain from diverting water to save a standing crop as those at the tail-end have to lose. Widely varying demand results therefore in an unstable and uncertain system with endemic farmer intervention.

b) Shejpali System

The Shejpali and Block systems of western and central India is a demand based water distribution system operated in the States of Gujarat, Maharashtra, Karnataka and parts of Madhya Pradesh. Under this system, estimates of expected water availability are made and applications are invited from farmers seeking information on the crop to be grown and the area to be irrigated under each crop. Sanctions are provided to farmers by the State Irrigation Department to grow particular crops and the farmer is thus authorized to draw water to suit his perceived needs. Water is then sanctioned taking into account the total demand and the water availability. A schedule, called Shejpali, giving turns to different irrigators in the sanctioned crop area of the outlet is prepared for each rotation. In the block system, a long-term agreement for the supply of water for 6 to 12 years is made, especially in case of perennial crops. A system called "Rigid Shejpali" has been introduced recently. In this system, definite duration for the supply of water to a particular field area is recorded on the passbooks issued to farmers of the sanctioned area.

In principle, the Shejpali system is compatible with agro-ecological conditions and works for so long as the full area demanded by farmers is sanctioned and supplied. Canal procedures are therefore 'demand-driven'.

c) Zonal System

This system has been introduced in the Lower Bhavani Project in Tamil Nadu. In this system the command area is divided into two halves. Water is made available continuously to one half of the area for one season, which extends over a period of 4 months in a year. The other half gets irrigation water sufficient for wet crops in the next year. This way each half gets irrigation supplies for wet and dry crops in alternate years. This system of irrigation with dry and wet crop seasons is known as year to year rotation.

d) Localized System

This system is practised in most of the irrigation projects in southern and northeastern states as well as in the states of West Bengal, Orissa, Bihar and Jammu and Kashmir, where paddy is the main crop. Under this system, irrigation below the canal outlet proceeds from one field to another through surface flooding. The localized system of irrigation is presently followed in most of the command areas in India. There is no control over the quantity of water applied in this system. The fertility of the higher fields gets progressively reduced.

2.2 REVIEW OF LITERATURE

Maximum crop yield can result only if the crops receive water in optimum quantity and at the optimum time. Both the quantity and timing depend upon various meteorological factors and the soil water status for any given crop. The total yield from the irrigation system can be maximum only if each and every farmer has this total freedom of water availability as regards the quantity and time. "On Demand" irrigation involving total flexibility and freedom, is an inherently opposite idea to Warabandi system using a fixed schedule of frequency and period of availability of water to each farmer. While warabandi is employed on many canal systems in India, the "On Demand Delivery" system has recently been used in USA, France and in some African nations on a few canal systems. The "On Demand" system needs much greater automation, a higher level of sophistication and different types of structures as compared to the requirements of conventional upstream control and rotational schedules in India.

The variety and complexity of mathematical models used in planning for conjunctive use management have increased dramatically during the last thirty years. This increase has been possible by significant advances in digital computers and necessitated by environmental and economic concerns. A large number of different models and approaches is the result of various assumptions used to reduce a general model to some solvable form. Some useful studies which dealt with conjunctive use of surface water and groundwater by linear programming technique are: Yoganarasimhan and Chand (1979), Chandra et al. (1979), Louie et al. (1984), Kumar and Pathak (1990), and Chawla et al. (1991). A brief review of some the related studies reported in the literature are summarized in the following.

Bredehoeft and Young (1970) presented a simulation approach for determining temporal withdrawal policy for groundwater basin. Their procedure provided results that display the efficiency and the alternative ground water basin management policies. Later, they extended their work for conjunctive use, by incorporating hydrologic simulation model with an economic model that represents response of irrigation water users to variations in the water supply and cost (Young and Bredehoeft, 1972). The basin planning simulation model incorporated the temporal and spatial interrelationship of stream aquifer systems, the stochastic properties of surface flows, characteristic of such system and the response of individual water user to hydrologic, economic and institutional conditions. Their management model was the first conjunctive use model to treat the interaction phenomenon as an integral part of the modeling process. In continuation of their previous works, Bredehoeft and Young (1983) used the simulation model to investigate the extent of ground water to be developed as insurance against the period of low stream flow.

Laxminarayan and Rajagopalan (1977) applied Smith's model to Bari Doab system in Punjab, India for allocation of irrigated area to alternative crops and the amount of seasonal water releases from the canals and tube wells, during a one year-crop period of operation such that benefits from the system are maximized. Like the Smith's model, this was a deterministic model but the dynamic response of groundwater was not considered.

Noel et al. (1980) presented an optimal control approach to determine the socially optimal spatial and temporal allocation of surface water and ground water for agricultural and urban uses. The model was a linear quadratic control model comprising of hydrologic and economic components. The study demonstrated that optimal rates of ground water pumping over the planning horizon were highly sensitive to increasing energy costs. Later Noel and Howit (1982) applied the optimal control approach to analyze the economic effects of conjunctive management of surface water and ground water supplies for irrigation.

Kashyap (1982) developed mathematical model for arriving at an optimal conjunctive use policy incorporating spatially and temporally distributed ground water withdrawals for a predefined pattern of surface water availability and spatially distributed cropping pattern. The problem was solved within the framework of nonlinear programming.

O'Mara and Duloy (1984) used a simulation model to examine alternative policies for achieving more efficient conjunctive use in Indus basin. The model links the hydrology of stream aquifer system to an economic model of agricultural production together with a network model of flows in river reaches, link canals and irrigation canal. They also studied the joint effect of various canal water allocation and associated private tubewells tax or subsidy policies on overall system efficiency.

Illangasekare and Morel-Seytoux (1986) developed a "Discrete-Kernel" simulation model for the conjunctive use of a stream-aquifer system. Morel-Seytoux and Restrepo (1986) developed SAMSUN (Stream Aquifer Model by Simulation and Optimization) for conjunctive operation of water. The model consists of two parts, the physical model and the decision (allocation) model. The allocation model determines the magnitude of the excitation of the system (e.g., how much to divert at a given diversion point on the river, how much to pump from an aquifer, etc.) on the basis of legal (water rights), agronomic nature (consumptive use) and other aspects. The physical model provides the response of the system to these excitation.

Paudyal and Das Gupta (1987) developed a model to simulate the operation of a groundwater reservoir with surface water for Tinao river basin in southern Nepal. The objective function of minimizing the maximum relative shortage of irrigation water in any month was transformed into a linear programming model, which was then solved as a mixed integer programming problem. The model gave optimum combinations of surface and groundwater in each month for changes in volumetric recharge. The groundwater reservoir was treated as a renewable resource with a limited reserve. Preference was given to surface water use that was assumed to be cheaper than groundwater.

Rao et al. (1988) made a two level mathematical formulation for irrigation scheduling at weekly intervals for a single crop under limited water supply. The model is based on a dated water-production function and weekly soil water balance. At the first level, water-production function is maximized by dynamic programming to obtain optimal allocations for growth stages. At the second level, the water allocated to each growth stage is re-allocated to satisfy weekly water deficits within the stage in a sequential order. Water delivery and soil water storage constraints are included at both the levels. The model is applied to derive weekly irrigation programmes for cotton under various levels of seasonal water supply and initial soil moisture.

Wesseling et al. (1988) presented the application of a numerical model SWATRE for farm management and prediction of time of irrigation. Predictions simulate the soil water balance for the area assuming the meteorological conditions to remain constant for subsequent five days. At the end of 5–day forecasting period, the predicted results are adjusted with the actual meteorological data. The results indicate the usefulness of the model for better irrigation scheduling.

Wills et al. (1989) presented a nonlinear conjunctive use planning model. The model maximized the net revenue generated from the production of three crops over a one-year planning horizon. The cost of production included the distribution costs of river water, fertilizers and nonlinear ground water pumping cost. Agricultural production function developed from the past studies were used in the model. The ground water hydraulic response equations were developed using finite element method.

Paudyal and Das Gupta (1990) applied multi level optimization technique for solving complex problem of irrigation management in a large heterogeneous basin. They aimed at determining the optimal cropping pattern in various sub-areas of the basin, the optimal design capacities of irrigation facilities, and optimal allocation policies for conjunctive use.

Ranjha et al. (1990) presented methodology for computing, perennial ground water yield and conjunctive water use strategies. They have discussed an example of Arkansas Grand Prairie as a case study. This included development of an optimization model for computing sustainable groundwater pumping strategies and a post processor for allocating groundwater and surface water in space and time.

Sharma et al. (1990) analyzed the existing warabandi system used in Northwest India and Pakistan and the effect of conveyance losses on the water distribution. It is shown that the water distribution within a watercourse command is not equitable and landholdings situated at the tail receive less water. A variable time model is proposed within a watercourse command to achieve equity of water distribution by increasing irrigation time per unit area for the downstream landholdings in proportion to the seepage loss rate. Tow case studies of watercourse commands of India and Pakistan are presented.

Ahmad et al. (1990) carried out a simulation study of irrigation scheduling of a watercourse command and made a comparison between the fixed-rotation strategy and the demand–based strategy. It is concluded that under the fixed-rotation strategy, the net farm return was reduced by 28 – 43 % and required 17 – 39 % of extra water pumping as compared to demand strategy. It is suggested to change the fixed-rotation system by the demand system for improved water allocation, saving in pumping energy and effective utilisation of canal water in a watercourse command.

Ontor et al. (1991) presented a three step modeling approach for the design of an irrigation system. Long-term operation policies were first determined by a stochastic dynamic programming optimization model. Then, a lumped simulation model was used to evaluate the alternative plans and policies. Finally, a multiple criteria decision-making method was used to select the most satisfactory alternative plan for indicating the pumping and canal capacities and water allocation policies.

Latif and James (1991) presented a conjunctive use model to control the water logging and salinization. The water user's return was maximized under limited and dynamic water supply for long-term conditions. Salt distribution in the root zone was modeled and its effect on the crop yield was taken into account in the model.

Matsukawa et al. (1992) presented a model that incorporated the hydraulics of surface water and ground water system, cost of water supply, hydropower, and ground water and benefit resulting from surface water supply. Constraints of the planning model included hydropower production limits, water quality constraints to meet the municipal demand, and minimum in-stream flow needs downstream of the water supply abstraction point. The optimization model was solved using nonlinear programming. The model was applied to the Mad River basin in Northern California for which the optimal planning policies were determined for the water resource system.

Chavez-Morales et al. (1992) used a simulation model which considered alternative cropping pattern, profits for the farmers in the irrigation district, monthly reservoir and aquifer operating schedules for a one year planning horizon, and hydropower generation. Andrews et al. (1992) presented a network programming based model to simulate water allocation and distribution in the surface water system of Kern country, California.

Rao et al. (1992) developed a procedure for real-time irrigation scheduling under limited water supply. The goal was to develop a two-stage policy that maximizes the crop yields and is responsive to current season changes in weather and other variables. In the first stage, irrigations are planned for the entire season at weekly intervals using historical data. In the second stage, the decisions for the subsequent weeks are revised each week after updating the status of the system with real-time data up to that week and solving the irrigation optimization model once again for the new conditions. The procedure is illustrated by the case study.

Radhey Shyam et al. (1994) developed an improved method of water allocation to different canals in a canal system using a linear programming formulation. Three alternate operation policies are also analyzed in which the optimal allocation takes place at different stages of water distribution. It is concluded that for obtaining highest returns, the optimal allocation must start right at the branch canal. Since the main system is operated by the State Governments and the on-farm system is managed by the user farmers, it is suggested to have a close coordination between the main system and the on-farm system to ensure desirable performance of an irrigation system.

Kalu et al. (1995) suggested a water distribution policy in irrigation projects considering the objectives of equity and efficiency. First, the policies are generated through an optimization model by varying the level of irrigation and the proportion of area of each field plot to be irrigated. Then a simulation model is employed to evaluate the consequences with respect to efficiency and equity measures. Application of the method for irrigating winter wheat in a case study shows that the policy emphasizing system efficiency is not optimal with respect to equity and vice versa. Therefore, a multi-objective analysis is suggested to select a compromise solution.

Cabelguenne et al. (1997) tested the real-time EPIC-PHASE model on a maize crop to evaluate its potential for real-time tactical irrigation management based on model predictions every 5 days. The details of the model have been presented by Cabelguenne and Debaeke (1995). Using the model, it is possible to simulate different irrigation tactics with weather forecasts. Mainuddin et al. (1997) formulated a monthly planning model to determine the optimal cropping pattern and the groundwater abstraction in an existing groundwater development project. Two objectives, maximization of net economic benefit and maximization of irrigated area were considered. Uncertainty in water availability was accounted by solving the model for three levels of reliability of rainfall and groundwater resources. Best alternative plan is selected using multi-objective analysis considering the preferences of decision-makers.

Garg et al. (1998) developed a model to schedule the sowing dates of crops in such a manner that the peak water requirements of different crops are more uniformly distributed over different months and thus more area can be irrigated for a given canal and groundwater capacities. A two-level optimization model is developed for this purpose. In the first level, the model gives optimal cropping pattern and monthly water withdrawals from canal and tube well for a given set of sowing dates to maximize the net economic returns. At second level, the sowing dates are varied within the allowable limits and the optimized sowing dates are obtained using an integer programming model. The sowing dates at the first level are then taken as those obtained from the second level and the process is repeated till it converges. The model application is shown for the Dadu canal command in lower Indus basin.

Wardlaw (1999) suggested an easy-to-use approach for real-time water allocation. The approach is aimed at improving the availability of water for sustainable food production in irrigation systems with complex distribution networks, in which there is water stress and competition for scarce water resources. The objective is to ensure optimal and equitable distribution of irrigation water to farmers in times of drought. Crop yield based objective function is developed in which the objective is to maximize the relative crop yield in an equitable manner. Soil moisture balance modeling is carried out to determine the actual irrigation demands which is linked with the optimization model.

Garg et al. (2000) developed an optimum policy for pumping out the optimized volume of groundwater for Dadu canal command in lower Indus basin. The groundwater hydraulics simulation model shows the development of serious waterlogging problem in the lower reaches of the command. The policy suggests to operate the existing tube wells at their maximum capacity and to suitably increase the tube wells along with their placing for tackling the waterlogging problem.

From the discussed literature, it is seen that various programming tools have been used by the researchers to develop conjunctive operation policies for different systems. The major objective of different studies has been to maximize the benefits from the system within the constraints of sustainability. Either the demand pattern is assumed to be constant and the operation plan is worked out or the cropping pattern is optimized under given conditions. The spatial variation of irrigation demand and availability of surface and groundwater is not considered in most of the studies. The use of dynamic programming is observed to restrict the specification of the groundwater and surface water systems to low-dimensioned representations of the system. Linear programming, though numerically very elegant, is rather restrictive in the sense that it requires objective function and associated constraints to be linear function of decision variables.

In the development of an optimal plan for the operation of an irrigation system, it is necessary to make appropriate estimates of the likely supplies and demands. Present day knowledge of soil-water-plant-atmosphere relationships provides a scientific basis for determining the optimum irrigation requirement for a given cropping pattern. Records of rainfall and canal flow provide the basis for estimating the available supplies. With the availability of remote sensing technology and GIS tools, it is now possible to gather instant observations over large areas and to integrate and manage different observations to find the optimum irrigation schedule under given conditions. With the availability of fast speed computers, it is now possible to simulate the integrated picture of the total system and correspondingly take a decision for the operation of the canal system.

In the present study, a model is developed to simulate the short-term operation of a canal system. The procedure considers the actual irrigation demands and the prevailing groundwater conditions in the command and suggests the possible operation of the canals. The objective of model is to satisfy the irrigation demands in the system with least cost of pumping groundwater. Various system constraints include surface water availability, conveyance capacity and groundwater depth. One major feature of the developed procedure is the consideration of spatial variations in the demands, surface water supply and groundwater conditions in the area.

* * *

CHAPTER - 3
MODELLING OF CANAL SYSTEM OPERATION

3.1 PROBLEMS OF IRRIGATION WATER MANAGEMENT

Water management is a vital factor for healthy environment and sustenance of eco-system of any irrigation project. The objective of effective management in an irrigation system is to ensure water distribution in adequate quantities and at proper times throughout the command area to meet the requirements of the crops grown. Proper regulation of canals and distribution of required quantity of water are essential for efficient use of irrigation water. Different methods of water distribution are followed in canal irrigation systems in India. However, enough attention has not been paid to evaluate and improve on these methods to keep pace with developments in the field of soil-crop-water-atmosphere relationships. Erratic delivery systems and irrational management of water and crops have aggravated the situation in the command areas.

Because of indiscipline in irrigation water distribution, head reaches of a command are over-irrigated while the tail ends are deprived of even basic irrigation requirements. Time and space both favour head reaches. Historically, the head reaches are constructed first when water is abundant and head reach farmers usually establish preemptive rights before middle and tail farmers begin to receive water. They adopt cropping patterns that consume much water. Seasonally too, head reach farmers have enough or excess water early on. Tail-enders get their first irrigation late, and get none towards the end of the season if water is short. The important problems of irrigation water management are summarized in the following:

1. Non-observance of designed cropping pattern, and scientifically realistic water doses for the crops.
2. Excessive depth of irrigation is applied to crops. In the absence of field channels, irrigation water is distributed from one field to another.
3. Uncertainty in the time and amount of canal water supply leads to application of higher irrigation depth than actually needed.
4. Since the command area is not developed along with the creation of irrigation potential, the head reach farmers continue to use more water as they did in the earlier years depriving the tail-enders.
5. Conjunctive use of canal water and groundwater is limited.
6. Canal capacities are inadequate to meet the required demands.
7. Siltation, weed growth, and scour of slopes in canals also reduce conveyance capacities.
8. Absence of network of watercourses and field channels leading to each field. Fragmented and small land holdings discourage farmers to adopt scientific water management. They are highly skeptical and refuse to part with even very small land area for preparing field irrigation and drainage channels.
9. Absence or inadequacy of measuring devices such as Parshal flumes, gauge runs, notches etc. at control and off-taking points.
10. Lands not leveled and properly graded to suit the type of irrigation.

11. Poor upkeep of watercourses and field channels, causing inadequate withdrawal capacity and wastage of water.
12. The farmers have received no formal training in irrigation management They can not appreciate the importance of improved water management technologies.

The constraints in efficient irrigation management, as mentioned above, are multi-disciplinary in nature. In the present study, it is envisaged to develop a computer model for providing assistance to the decision-maker in the operation of the canal system. Before explaining the allocation model, a brief account of conjunctive use approach and a generalized model is presented.

3.2 CONJUNCTIVE USE APPROACH OF IRRIGATION MANAGEMENT

The available water resources, both surface and ground, are not adequate enough to cover the entire cultivated area in the country. It is estimated (INCID, 1995) that even on full exploitation, the available water resources could cover only half the cultivated area for irrigation. The practice of planning surface irrigation without much consideration of groundwater status has often resulted in waterlogging and salinity problems in command areas due to gradual rise of groundwater caused by irrigation. It is therefore important that both, the surface and groundwater resources have to be used in an integrated manner by planning the conjunctive use, as recommended by the National Water Policy 1987.

The concept of conjunctive use recognizes the unified nature of water resources as a single natural resource. The process takes advantage of the interactions between the surface and groundwater phases of the hydrological cycle in planning the use of water from the two phases. Integration of the use of water from two sources on land may involve different levels of time and space integration. The conjunctive use of surface and groundwater sources may be practised in order to attain one or more of the following objectives:

a) A higher total amount of supply.
b) Better regulation of the combined system, using the storage volume of the aquifer.
c) Savings in evaporation losses from surface reservoirs.
d) Higher flexibility in supply according to the demand curve, by evening out peaks in stream flow and pumping groundwater as and when needed.
e) Mixing of different quality water, either in supply system or in aquifer, to reduce salinity.
f) Reduction of capital and operational expenditures by shortening route for surface water.
g) Inducing groundwater replenishment from streams by extending the duration of flows in the streams by means of dams, or retarding the flow by means of groynes or levees.
h) Arresting depletion of groundwater table in areas where no surface irrigation exists and excessive groundwater extraction is done, by introducing surface irrigation from small rivers which will also help the groundwater regime through recharge.

While conjunctive use can effectively take care of the extra recharge caused by the surface irrigation, it is not considered as a solution to remedy the bad management practices for surface irrigation such as over-irrigation and inequitable distribution. General strategies available for conjunctive operation in an irrigation system are as follows:

a) Strategy – 1: ***Allocating Parcels of Land Permanently to a Particular Use***

Under this strategy, separate locations of the command are permanently allocated for the surface water or groundwater use. It is envisaged that recharge from the surface water application will supplement the groundwater and this will be utilized as groundwater withdrawal in the adjacent area marked for groundwater use. Individual distribution networks are likely to be small under this strategy as compared to higher order surface networks. This strategy is the most cost-effective, if it can be implemented. However, this form of conjunctive use is effective in those conditions where distance of the wells from the major recharge area (surface irrigation) is so small that the groundwater flow is sustained by the available gradient. Application of such strategy is feasible in alluvial areas because of the appreciable movement of groundwater. In hard rock areas and in clay soils, this strategy may not be feasible.

b) Strategy – 2: ***Integrating Surface Water and Groundwater in Time***

Under this strategy, surface and groundwater resources are allocated in time such that in a particular season only surface water is used and in other season only groundwater is used. Since the same area is irrigated with surface water at one point of time and groundwater at another point of time, groundwater is allowed to use the same field channels that carry the surface water. If private sources of groundwater extraction are not available in the command, then augmentation tubewells are planned and operated in such a way that groundwater carriage over long distances is avoided. Augmentation tubewells may feed either minors or may be located near the outlets.

When the groundwater is saline and unfit for direct use as a single source, then either the two water are physically mixed to have resultant water of acceptable quality or rotations are distributed amongst the two sources.

c) Combination of Strategy 1 and 2: ***Space & Time Integration***

Under this strategy, some parcels of land are permanently allocated for surface water irrigation, some parcels are permanently allocated for groundwater use, and some parcels are supplied with surface water in one season and groundwater in another. For parcels of land in which both groundwater and surface water are used, the intra annual regime of the uses can vary from year to year in order to take advantage of the stabler regime of groundwater. This could involve the groundwater partly for carryover purposes. Also, it may require larger use of surface water in years of surplus surface flows.

3.3 GENERAL FORM OF CONJUNCTIVE USE MODEL

Available surface and groundwater resources are managed such that one supplements the other to compensate for the inadequacies (in terms of quantity and quality in time and space) for getting the increased productivity while mitigating the environmental hazards like high water table, soil salinity, and aquifer mining. The conjunctive management tries to maximize the benefits from the system while satisfying various technical, administrative, and socio-economic constraints.

The conjunctive use management models have been formulated in the past in different context, such as optimum scale of development for dam and groundwater recharge facilities, evaluation of alternative plans for surface and groundwater use, operation of reservoir and groundwater pumping facilities, temporal and spatial relationship of stream-aquifer system, water quality management, and so forth. In the present study, the objective is optimum utilization of available surface and groundwater in space at weekly time step.

Based on some administrative, technical, or feasibility considerations, the command area is divided into a number of units, each unit is called as agricultural zone. The generalized form of conjunctive use model related to allocation of resources consists of a number of decision variables such as surface water and groundwater supplies in each time period to each agricultural area and optimal irrigated area in different agricultural areas. The model requires a number of parameters such as irrigation efficiencies, unit costs of development and operation of surface and groundwater resources, recharge etc. Different variables and parameters used in a conjunctive allocation model for i (agricultural area), j (crop type), and t (time period) are as follows:

Z	-	Net benefit from irrigated crops
BI	-	Annual net return from total irrigated area excluding farm cost
BR	-	Annual net return from unirrigated area
CSW	-	Annual equivalent cost of surface water development
CGW	-	Annual equivalent cost of groundwater development
SWC_i	-	Annual canal capacity in i^{th} area
GWC_i	-	Annual available pumping capacity in i^{th} area
OCS	-	Annual operation and maintenance cost of surface water
OCG	-	Annual operation and maintenance cost of groundwater
Y_j	-	Yield of j^{th} crop at full irrigation level per unit area
P_j	-	Selling price of j^{th} crop
C_j	-	Cost of cultivation of j^{th} crop excluding cost of irrigation per unit area
CC_i	-	Equivalent unit annual cost of canal, drainage and leveling works for i^{th} agricultural area per unit volume of water used
CG_i	-	Equivalent unit annual cost of groundwater pumping system in i^{th} area per unit volume of water used
CO_i	-	Annual operation and maintenance cost of canal works in i^{th} area per unit volume of water used
CP_i	-	Annual operation and maintenance cost of GW pumping system in i^{th} area per unit volume of water used
SW_{it}	-	Surface water allocation to i^{th} area during t^{th} period
GW_{it}	-	Groundwater to be pumped in i^{th} area during t^{th} period
H_i	-	Average depth to water table in i^{th} area

DD_{it}	-	Drawdown due to pumping in i^{th} area during t^{th} period
DDL_{it}	-	Permissible drawdown in i^{th} area during t^{th} period
A_i	-	Irrigated area in i^{th} agricultural area
AM_i	-	Available area for irrigation in i^{th} agricultural area
a_{ij}	-	Area of j^{th} crop in i^{th} agricultural area as fraction of total cultivated area
b_j	-	Irrigation level expressed as fraction, b_j is 1 when jth crop is fully irrigated
q_{bj}	-	Yield of j^{th} crop per unit area when irrigated at b_j irrigation level
s	-	Fraction of irrigation water delivered that becomes surface runoff
r	-	Fraction of irrigation water delivered that becomes recharge to aquifer
n	-	Total number of agricultural areas
k	-	Total number of crops
T	-	Total number of time periods
P_t	-	Total precipitation averaged over the area during t^{th} period
ψ_t	-	Average deep percolation loss from rice fields during t^{th} period
β_{ip}	-	Drawdown at i^{th} area due to unit pumpage at p^{th} area
δ_{ijt}	-	Crop water requirement per unit area of j^{th} crop in i^{th} area during t^{th} period
θ_{1i}	-	Conveyance efficiency above outlet in i^{th} area
θ_{2i}	-	Field channel efficiency in i^{th} area
θ_{3i}	-	Water application efficiency in i^{th} area

The conjunctive use model maximizes the net annual economic return from irrigation water use in an year of average water supply. It considers the benefits from growing given crops and development and operation costs of surface and groundwater facilities subject to a variety of constraints. The objective function is described as:

$$\text{Max. } Z = (BI + BR) - (CSW + OCS + CGW + OCG) \qquad \ldots(3.1)$$

where,

BI	=	f_1 {A_i, a_{ij}, q_{bj}, b_j, P_j, s, Y_j, P_j, C_j, land capability }
BR	=	f_2 { A_i, a_{ij}, P_t, C_j, land capability }
CSW	=	f_3 {life of system, discount rate, development cost of SWC_i }
OCS	=	f_4 (operation year, component life, discount rate, SW_{it} }
CGW	=	f_5 {life of system, discount rate, development cost of GWC_i }
OCG	=	f_6 { GW_{it}, H_i (GW_{it}, β_{ip}), CP_i (H_i) }

All the above terms are expressed either as present worth value or in terms of annual equivalent cost over the assumed planning period. The optimization of the objective function is subject to the following constraints:

i) Crop Water Balance Constraint

Crop water balance depends on the crop water requirement, desired level of irrigation for j^{th} crop during the t^{th} period, irrigation efficiencies, and surface and groundwater allocations as follows:

$$\sum [SW_{it} + GW_{it}] = f_7 \{\delta_{ijt}, a_{ij}, A_i, b_j, \theta_{1i}, \theta_{2i}, \theta_{3i} \} \qquad \ldots(3.2)$$

ii) Recharge Balance Constraint

Recharge balance depends on the groundwater pumpage, canal seepage, field application losses, rainfall, evapo-transpiration, subsurface inflow and outflow etc. It is required to be maintained through proper surface and groundwater supplies for attaining stabilization of the groundwater system.

iii) Drawdown Constraint

Drawdown (DD_{it}) depends on the influence coefficient (β) and the groundwater pumpage. It may be considered to be linear or non-linear. Using this constraint, drawdown is restricted in a particular area as represented below:

$$DD_{it} = f_8 \{GW_{it}, \beta_{ip}\} \quad \ldots(3.3)$$

$$DD_{it} \leq DDL_{it} \quad \ldots(3.4)$$

iv) Capacity Constraints

Conveyance capacity constraints for existing facilities are to be imposed. Canal water supply to each agricultural area is limited by the existing conveyance capacity. Similarly, groundwater pumpage from the tubewells in each area is limited by the existing pumping capacity. These are represented as below:

$$SW_{it} \leq SWC_{it} \quad \ldots(3.5)$$

$$GW_{it} \leq GWC_{it} \quad \ldots(3.6)$$

v) Land Constraint

Area irrigated in each agricultural area is limited by the available land under cultivation as follows:

$$A_i \leq AM_I \quad \ldots(3.7)$$

vi) Other Constraints

Miscellaneous other constraints representing policy decisions based on socio-economic considerations may include:

a) Irrigation levels for some crops so as to have equitable distribution of water.
b) Cropping pattern restrictions based on socio-economic requirements.
c) Limits on groundwater pumpage in some time periods.
d) Limits on surface water supply in some time periods.

The conjunctive use model, described above, is a non-linear representation of the physical phenomenon. The groundwater dynamics is incorporated in the form of influence coefficients that need to be derived separately for each agricultural area by calibrating a groundwater model for the study area.

In the present study, a GIS based model is prepared for simulating the operation of a canal system. The model integrates the information about the actual irrigation demands in the command area, available surface water, canal capacity constraints, and the groundwater scenario in the command area and suggests a possible plan of operation of the canal system at weekly time step. Actual irrigation demands are computed by another model (*DEMAND*). This model is developed and presented in detail in a NIH report entitled "Optimum Water Management in a Command Area". This is briefly described in the following section:

3.4 MODEL TO FIND IRRIGATION DEMANDS (*DEMAND*)

The irrigation requirements of a farm, an outlet command area, a minor etc. are determined by adding the irrigation needs of individual crops and water losses taking place in fields, conveyance, and distribution systems. Knowledge of water requirement of crops is one of the basic needs for irrigation management. The dynamics of water within the unsaturated zone of soil is a complex phenomenon dependent on the atmosphere, soil and vegetation. Hillel (1972) compared the plant's water supply in the root zone with a bank account that is "robbed and embezzled almost daily".

A *DEMAND* model has been developed for determining the spatially distributed real-time irrigation water demands in a command area so that allocation of available water resources can be made with reference to the prevailing demands and water distribution criteria. The method allows the planner to compute a continuous record of soil moisture, actual evapo-transpiration, and groundwater recharge in field from meteorological, soil and vegetation records. The model, including its structure, database generation, and application has been described in detail in a NIH report entitled "Optimum Water Management in a Command Area". The irrigation demand, as determined by the model, is used in the *ALLOCATION* model for the operation of the canal system.

The program performs grid-wise computations and uses raster as well as attribute data of different variables. Input data to the program include three files of distributed raster data, namely, crop type, soil type, and the Thiessen polygon of rainfall stations. Different crops, soils and Thiessen polygons are given different identification numbers. Based on the identification number at a particular location, the program identifies the crop type, soil type and the associated rain gauge station and uses the corresponding attribute data for water balance computation. Input attribute data include properties of different crops, soils, daily/weekly rainfall at various rain gauge stations, and daily/weekly reference crop evapo-transpiration in the command. Various crop parameters used by the program include crop coefficients at different growth stages, maximum root depth, time to reach maximum root depth, starting time (calendar day/week) of crop, duration of crop in the field, fraction of available water below which crop yield is affected, and the standing water requirement, if any. Various soil parameters used by the program include porosity, field capacity, permanent wilting point, and apparent specific gravity.

Four output files are generated: a) supplementary water requirement (irrigation demands), b) final water depth, c) stress condition, and d) groundwater recharge. The result files are generated in a format that can be converted into maps and displayed in any GIS system for easy interpretation and decision making.

3.5 MODEL FOR OPERATION OF CANAL SYSTEM (*ALLOCATION*)

A water distribution network comprises of the main canal, branch canals, major and minor distributaries, canal outlet, watercourses and field channels. The ultimate objective of the management of such a system is to maximize the production or net returns per unit of water per unit of land and per unit time on a sustained basis and without adverse effects on environment. The supply of water diverted into a main canal is distributed amongst different branches, distributaries and minor canals in accordance with demand on different channels. This distribution is easy when the available supply equals or exceeds the demand. However, when the supply is insufficient to run whole canal system simultaneously, some distributing channels are kept closed while others are operated. In the development of an optimal plan for the operation of irrigation system, it is necessary to make appropriate estimates of the likely supplies and demands. Knowledge of soil-water-plant-atmosphere relationships provides a scientific basis for determining the optimum irrigation schedule for a given cropping pattern. Records of rainfall and canal flow provide the basis for estimating the available supplies.

With the availability of high speed computers, storage media for keeping vast amount of information, and software for processing, analyzing, and utilizing available information, it has become possible to simulate the operation of a canal system in real-time considering actual cropping pattern in the area, available surface water in the system, and prevailing groundwater scenario in the area. The present study aims to utilize the recently developed capabilities of data collection, handling, and analysis for rational operation of a canal system.

Before we discuss the objectives of the model and the approach adopted, a few terms related to the canal network are first described. Irrigation water distribution network comprises of the main canal, branch canals, distributaries, minors, canal outlets, watercourses and field channels. In this study, canal system up to minor level is considered. Various terms used in the model are explained with an illustrative example as shown in Figure – 3.1.

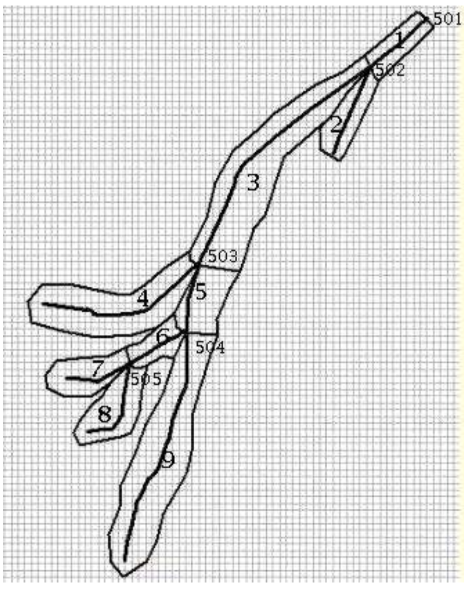

Figure – 3.1: Illustrative example of a canal network *a) Canal segment*

A canal segment represents a link in the canal network. For the intermediate part of network, a segment is the portion of canal in-between two diversion links. For the tail-end of a canal, it represents the portion of canal after the last diversion up to canal end. Each canal segment is allocated unique numerical identity as shown in Figure – 3.1. Though the segment numbers 1, 3, 5, and 9 represent same distributary, yet they are considered as different canal segments. Canal characteristics, such as discharge, cross section, conveyance efficiency, application and field channel efficiency, seepage rate etc. are assumed uniform in a segment. In the model, the number range 1 to 500 is reserved for the specification of canal segments.

b) System node identification

Various canal segments are connected to each other at junctions called “Nodes”. These are also allocated unique numeric identities starting from 501. Range 501 – 1000 is reserved in the model for specifying junction nodes. In Figure – 3.1, the canal system head is represented by node number 501. Other junction nodes in the network are 502, 503, 504, and 505. Tail-end of a canal segment with no downstream network is given an identity of 1000.

c) Irrigable command of segment

A canal segment is considered to have a number of outlets through which canal water is distributed in its command area. Irrigable area under the direct command of a canal segment is termed as the irrigable command of segment. It does not include the irrigable area of the network lying downstream of the segment. In Figure – 3.1, periphery of the irrigable command areas of different canal segments is shown. For the area lying outside of the periphery, it is not possible to supply canal water.

d) Grid identification number

Based on the association of a grid to a canal segment, each grid is given a numeric identity, which is the same as that of the canal segment. This identity is used to transfer the irrigation demands from individual grids to the canal system. Grids lying outside of the irrigable command of all canal segments are represented with identity “0”. Such grids are solely dependent on the groundwater for irrigation supply.

e) Free and intermediate segments

The last segment of a canal that does not have any downstream network is considered as a free segment while a segment with canals bifurcating from its lower node is taken as the intermediate segment. In Figure – 3.1, segments 2, 4, 7, 8, and 9 are free segments while 1, 3, 5, and 6 are intermediate segments. A free segment is operated to meet its own demands only while an intermediate segment is required to supply water for meeting its own demands (of local irrigable area) and the demands of the downstream network.

f) Fill-time/Run-time of a segment

Fill-time of a canal segment is the time required for the water to travel from the nearest running canal segment (at the end of previous week) to the current segment and fill it.

Run-time is the maximum time required to operate a canal segment for meeting irrigation demands in its irrigable command (including losses in canal segment, field channels, and water application). Maximum possible run-time available to a canal segment is computed by subtracting its fill-time (in hours) from 168 (duration of a week in hours). In Figure – 3.1, assume that segment 1 and 3 are running at the end of previous week. Let the fill-time of segment 7 (time required for the water to travel from node 502 to tail end of segment 7) be 24 hours. Then, the maximum possible run-time for segment 7 will be 144 hours.

g) Groundwater depth in a segment

Groundwater depth in a segment refers to the average of the depths of groundwater in all the irrigable grids under a canal segment. If average groundwater depth in a segment is less than specified critical depth (that define waterlogging conditions), then the segment is not supplied canal water and groundwater is pumped for meeting irrigation demands in its irrigable command. Further, in cases of canal water deficit in the command, groundwater depth data becomes a useful deciding factor for the allocation of canal water.

h) Groundwater availability in a segment

Groundwater availability refers to the maximum amount of water that can be pumped from the groundwater reservoir in the irrigable command area of canal segment in one week. This amount depends on the number of wells in the area, their pumping capacity, number of hours of power supply, and the average groundwater depth. Groundwater availability varies spatially as well as temporally.

3.5.1 Objectives of the model

The objective of the developed approach is to suggest the weekly operation schedule of a canal system for satisfying the water requirements of all crops under the direct command of the system by using either the canal water or the groundwater. In addition to the irrigation demands in the command, the operation of a canal system is also governed by the availability of water at the canal system head and the prevailing groundwater conditions in the command. Taking advantage of the GIS capabilities, spatial variation of irrigation demands and groundwater depths have been accounted for.

Another objective of the approach is to use the surface water in the area to the extent possible provided that groundwater conditions permit. The groundwater is utilized only at those locations where surface water is not available (because of insufficiency or canal capacity constraint) or where groundwater has risen above the permissible limits (waterlogging conditions). During the monsoon season, if the available surface water is used to the maximum extent and the groundwater reservoir is allowed to recharge, then the same can be utilized during the lean season when the surface water availability reduces appreciably. This is one of the many forms of conjunctive utilization of water. Further, the higher water table will allow the groundwater extraction with lower amount of energy required per unit of water.

3.5.2 Assumptions of the model

a) It is assumed that maximum benefits from the system can be obtained if proper soil moisture is kept in the root zone of crops during each week.
   Justification: The approach considers the actual cropping pattern in the command area in contrast to many optimization models, which maximize the benefits from the system by suggesting optimum cropping pattern for the prevailing conditions. The farmers in real practice may or may not adopt the optimum pattern derived from the operation studies. So, efforts are made to maximize the benefits under existing cropping pattern in the field by maintaining optimum moisture in the root zone.

b) Another important assumption is that surface water is cheaper than groundwater.
   Justification: For the surface water development, major part of the expenditure is incurred towards the construction of reservoir/barrage and the canal water distribution system. Though the operation and maintenance cost constitute the recurrent expenditure for the operation of canals, yet it is quite marginal and maximum benefits from the system can be drawn only when it is utilized in the optimal manner. For the case of groundwater, in addition to the development of the resource, the operation and maintenance cost contributes substantially towards the overall cost of utilization of groundwater. Cost calculations have not been carried out in the present approach and surface water has been used to the maximum possible extent. The present approach utilizes groundwater in the following conditions:

- It is waterlogging condition and groundwater depth is above/near the specified threshold (maximum permissible limit).
- Surface water is not available.
- Surface water is available quantitatively by can not be utilized because of canal conveyance capacity constraint.

3.5.3 Input data requirement

Various types of spatial and attribute information are integrated by the model to simulate the operation of canal network. Spatial information include crop type, layout of irrigable command areas of different canal segments, irrigation demands, and the depth of water table from the land surface. Attribute information relates to the characteristics of different canal segments and their irrigable command area. Information about the canal segments running at the end of previous week is used to calculate the fill-time of different segments. Details of various data input to the model are as follows:

a) Crop map

The crop map is used to define the critical depth of water table (waterlogging condition) for a canal segment. By knowing crop types in the irrigable command of a segment, the critical water table depth for the segment is found out. If the average water table depth in the irrigable command is within the specified critical depth, then the segment is treated as waterlogged and is not considered for canal water supply.

b) Layout map of irrigable command areas

Layout of irrigable command areas of different canal segments is required to transfer the spatial irrigation demands to the canal segments. The layout of irrigable area of each canal segment is obtained from the field records. This information is digitized in GIS and rasterized with same identity as that of corresponding canal segment.

c) Irrigation demand map

Irrigation demand at a grid is worked out by the DEMAND model. This demand is estimated for each week with due consideration to the reference crop evapo-transpiration, rainfall, and soil and crop characteristics. The primary objective of canal operation model is to satisfy these irrigation demands to the extent possible. Irrigation demand data are used by the model to decide the quantity of water to be supplied in a canal segment in any week.

d) Groundwater depth map

The data regarding groundwater depth are extensively used by the allocation model to simulate the operation of canal network. It is also used to find groundwater potential in a canal segment during a week. By knowing the location of observation wells and their groundwater levels, a groundwater surface is generated in a GIS by kriging/interpolation. Subtracting groundwater surface from DEM gives the water table depth at each grid.

e) Canal system characteristics

Canal characteristics vary from one part of a canal network to another. To account for such variations, a canal network is divided into a number of segments (links) joined together at nodes. Various characteristics that are specified for each canal segment include: numeric identity, discharge capacity (CAP) in cumec, length (ALEN) in m, bed width (BEDW) in m, water depth (WDEPT) in m, side slope (V:H::1:z), irrigable area in ha, conveyance efficiency (CEFF) in percent, application efficiency (AEFF) in the irrigable command, field channel efficiency (FCEFF) in the irrigable command, seepage rate (SEEPR) in cumec/million sq. m of wetted area, code (ISCOD) for specifying the method for canal seepage estimation (1 – conveyance efficiency, 2 – empirical formula, 3 – seepage rate), number of tube wells (NOP) operating in the irrigable command, average power of pumping plants (PPP) in horse power, number of hours for which power supply (POWS) is available in the irrigable command, and the source of power commonly used in the irrigable command (1–power supply, 2–generator sets). Canal cross-sections are assumed to be trapezoidal. Data that define the linkage of various segments in the network include: upstream and downstream node numbers of each segment, total number of nodes located downstream to each segment, total number of segments bifurcating from the downstream node of each segment, and their identity.

f) Canals running at the end of previous week

Information regarding the identity of canals running at the end of previous week is used to find the time required for the water to reach and fill those canal segments that were not running at the end of the previous week. Knowing the fill-time of all the segments in the network, maximum available run-time of different segments in the current week is calculated.

3.5.4 Approach adopted in the model

The developed approach takes into account actual irrigation demands, probable canal water supply during the week, and prevailing groundwater conditions in the command area for deriving operation plan of a canal network. System constraints that have been considered in the model include canal water availability, conveyance capacity of canal segments, and groundwater availability. Two alternate operation policies have been developed for allocation of surface water and groundwater and an optimum policy (third policy) has been derived using the results of two policies. The adopted approach is briefly described in the following.

3.5.4.1 Transfer of spatial demands to canal network

Grid-wise irrigation demands, as worked out by the DEMAND model, are transferred to the canal segments using the information of irrigable areas, field channel efficiency, and water application efficiency under each canal segment. To meet these demands, the run-time of canal segment is calculated using conveyance capacity and assuming (initially) no canal seepage loss. Based on the run-time, canal seepage is calculated. Seepage loss is added to the irrigation demands and run-time and seepage is calculated again. This procedure is iterated till the run-time value stabilizes. The water requirements in different canal segments are accumulated upstream through the network up to the canal head after giving due consideration to the conveyance capacity of each segment and its maximum available run-time during a week. If the conveyance capacity is a constraint at some segment, then groundwater requirement at that segment is worked out.

3.5.4.2 Capacity constraint satisfaction

After accumulating the water demands up to the canal head, groundwater demands at various intermediate segments (due to capacity constraint) are first settled by curtailing the canal water demands of one or more downstream segments. Different authors have specified different methods to satisfy capacity constraint. Krogt (1993) has reported that in case of limited supply, water supply to unauthorized crops is curtailed first followed by proportionate reduction. Malano et al. (1993) have reported that in the IMSOP package, either the capacity constraint is not considered or the flow is reduced proportionately. In the present model, the curtailment of canal water is based on the depth of groundwater. In this method, canal water d emands of free segments lying downstream of the capacity-constrained intermediate canal segment and having least groundwater depth are curtailed. The curtailment is continued till the capacity constraint in all the intermediate canal segments is satisfied.

3.5.4.3 Distribution/Allocation policy

After the capacity constraint in all segments is satisfied and the canal water demand and run-time in various canal segments become known, the canal water demand at head of canal network is compared with the available water. If canal water availability exceeds the required demand, then the system is operated according to the calculated run-time and discharge. However, if the water availability falls short of the demands, then some water distribution policy needs to be adopted to rationally allocate the available canal water in the irrigation command. Researchers have reported different allocation policies in existing models. While Krogt (1993) and Malano (1993) have specified the policy of proportionate supply, Mateos et al. (2002) have reported adoption of three policies for water allocation in the SIMIS package: fixed rotation, arranged rotation, and proportionate supply. Burton (1994) has reported nine different allocation policies for the CAMSIS model (given in Chapter-2). Kipkorir et al. (2001) have adopted four different strategies: maximum benefits, equitable benefit, equitable yield, and system equity. In the present model, three distribution/ allocation policies have been included. These are described below:

a) Policy 1 - Head-reach priority

Under this policy, the segments in head reach of the canal network are given priority and their demands are met in full. The canal water is utilized as far as and as long as it is available. In this policy, canal seepage losses are least as the water is utilized in the immediate vicinity of its distribution network. This also results in maximum utilization of canal water for satisfying irrigation demands. In this sense, this policy provides maximum efficiency of canal water use. However, this policy does not take into account the groundwater conditions in the command. Using this policy, the manager can visualize the extent of canal system that can be satisfied with the available canal water.

b) Policy 2 – Conjunctive utilization of water

Under this policy, water deficit at the head of canal system is compensated by curtailing the canal water demands of some downstream canal segments (provided they have sufficient groundwater potential). The identification of affected segments is governed by the average groundwater depth under each segment. Of all the canal segments with possible canal water supply (after satisfying capacity constraint), free segment of least depth of groundwater is selected and its canal water demands are curtailed. Calculations are repeated for the revised scenario of canal water demands in the system and the revised demands at head are found and compared with the availability. The process is iterated till the deficit at the system head reduces to zero.

In this policy, groundwater is used only when it is required and in the area of least depth of pumping. This policy tries to balance groundwater conditions in the command by pumping groundwater in the area of shallow depth and recharging (through canal seepage) in the area of deeper water table. Further, pumping of water from shallow depth areas results in overall reduction of energy consumption for pumping groundwater. However, this policy results in higher canal seepage and greater amount of groundwater pumping as the areas of deeper water table are generally located in tail portion of a command.

c) Policy 3 – Conjunctive use with minimum energy demand

In policy of conjunctive use, lots of water is wasted through seepage in taking the canal water to areas with deeper water table resulting in increased use of groundwater. At the same time, since groundwater is extracted in shallow water table areas, energy required for pumping groundwater can be conserved. But since the groundwater utilization increases, it is quite possible that the total amount of energy required for pumping groundwater exceeds the corresponding amount under policy – 2. So, an optimization is performed through successive iterations to find canal-run configuration for least energy demand for pumping groundwater.

For finding the optimum canal-run configuration corresponding to minimum energy requirement, first the Policy-2 is applied and the canal operation configuration corresponding to conjunctive use is found out. Corresponding energy requirement in the irrigation system for pumping groundwater is also calculated. Now, the canal water demands of the segment having maximum distance from the head are curtailed and the canal water demands of one upstream segment having least depth of pumping (among the curtailed upstream segments during the allocation under Policy-2) are restored. Energy demand for the new configuration is computed and stored along with the canal operation configuration. This way, the most distant segment demands are curtailed and upstream segment demands are restored and the process is iterated till the canal head is reached. The configuration that requires least energy for pumping groundwater becomes the recommendation of Policy-3.

3.5.5 Computational steps of model

Various steps of model calculation are presented below:

a) Reading of input data & analysis options

Model reads the spatial, attribute, and dynamic data of the command. In addition, some analysis options need to be specified at the time of simulation run. These include: available discharge at system head and the water allocation policy (1-head-reach priority, 2-conjunctive use, 3- conjunctive use with minimum energy demand).

b) Transfer of irrigation demands from grids to canal segments

Water demands from individual grids under the irrigable area of a canal segment are accumulated up to the segment. At a grid (i,j) where ‘i’ represents the row and ‘j’ represents the column, the supplementary water requirement, SWR(i,j), is specified in terms of depth of water in mm. This is converted to volume (WR_{ij}) in cubic meter by multiplying the depth by the area of a grid (24 m x 24 m) and then divided by the application efficiency ($AEFF_{id}$) and field channel efficiency ($FCEFF_{id}$) under the canal segment (id) to get water demand $(WDG_{ij})_{id}$ at canal segment.

$$WR_{ij} = SWR(i, j) * 24 * 24 / 1000 \qquad \ldots(3.8)$$

$$(WDG_{ij})_{id} = \frac{WR_{ij}}{AEFF_{id} * FCEFF_{id}} \qquad \ldots(3.9)$$

Water demands of all grids that lie under the local command of a canal segment are added to get the total irrigation demands WD_{id} at the canal segment. Initially, it is assumed that all demands are met from canal water. Therefore, canal water demand ($TWRCN_{id}$) in a segment is taken as:

$$WD_{id} = \sum (WDG_{ij})_{id} \qquad \ldots(3.10)$$

$$TWRCN_{id} = WD_{id} \qquad \ldots(3.11)$$

c) Calculation of average groundwater depth and groundwater potential

Groundwater depth at a grid [IGWD(i,j)] varies spatially. Average groundwater depth in a canal segment (AGW_{id}) is found by accumulating the groundwater depths in all the grids (TGW_{id}) in the local command of the segment and dividing by the number of grids ($NGCA_{id}$) in the local command.

$$AGW_{id} = TGW_{id} / NGCA_{id} \quad \ldots(3.12)$$

Groundwater potential in a canal segment depends on the average groundwater depth (AGW_{id}), pump capacity (PPP_{id}), pump efficiency (EFF), number of pumps (NOP_{id}), and power supply in hours ($POWS_{id}$) under canal segment 'id'. If generator sets are used in a segment, then power supply is not limited. Groundwater pumping capacity in command of segment 'id' (after suitable conversion of units and assuming 1 horse power = 75 kg m/sec and unit weight of water = 1000 kg/m^3) is given by:

$$GCAP_{id} = \frac{2.7 * PPP_{id} * NOP_{id} * POWS_{id} * EFF}{AGW_{id}} \quad \ldots(3.13)$$

d) Identification of waterlogging and revision of demand

Based on the type of crop present in canal segment and its root depth, critical waterlogging depth is defined for each segment. If a segment is waterlogged, all its local irrigation demands are met from groundwater. Groundwater utilization ($TWGCN_{id}$) in waterlogged segment is given by:

$$TWRCN_{id} = 0 \quad \ldots(3.14)$$

$$TWGCN_{id} = \text{Minimum of } [WD_{id}, GCAP_{id}] \quad \ldots(3.15)$$

If available groundwater potential is less than the demand, the number of additional pumps required ($NOPR_{id}$) is calculated as:

$$NOPR_{id} = \frac{[WD_{id} - TWGCN_{id}] * AGW_{id}}{2.7 * PPP_{id} * POWS_{id} * EFF} \quad \ldots(3.16)$$

The model uses an indicator (IR_{id}) for all segments that indicate whether the demand of a segment is satisfied with canal water or not. If the canal water could not be supplied, then the cause of the same is specified by the indicator. For waterlogged segments, IR_{id} is taken equal to 1.

e) Calculation of system connectivity and linkages

Before accumulating demands in different segments, it is necessary to know the system connectivity and linkages. Based on the upstream and downstream node numbers and the identity of canal segments bifurcating from the downstream node, the total number of segments lying downstream of each segment ($ITDCN_{id}$) and their identity ($IDDCN_{id,k}$ where k varies from 1 to $ITDCN_{id}$) is found out. Similarly, number of free segments (NFS_{id}) below each segment are calculated. The identity of immediately upstream segment ($IUPS_{id}$) above each segment is also found out. To find the relative position of segments (from head to tail) in the network, model calculates the distance ($DIST_{id}$) of each segment head from system head.

f) Calculation of filling-time

Depending on the distance of a segment from the nearest upstream running segment of the last week and the velocity of flow in intermediate segments, the time required for the water to reach and fill each canal segment ($FILTIM_{id}$) is evaluated. Velocity of flow (VEL_{id}) and time of travel (FIL_{id}) in each segment is calculated as:

$$VEL_{id} = \frac{CAP_{id}}{\left[(BEDW_{id} + SL_{id} * WDEPT_{id}) * WDEPT_{id}\right]} \qquad \ldots(3.17)$$

$$FIL_{id} = {ALEN_{id}}/{VEL_{id}} \qquad \ldots(3.18)$$

FIL_{id} of all intermediate segments through which water flows from the upstream running segment to the segment 'id' is added to give the total time of travel of water ($FILTIM_{id}$) to the segment end.

g) Calculation of Demand Distribution Index (DDI)

Demand distribution index (DDI) is related to the spatial distribution of irrigation demands in the command area. DDI is calculated as the ratio of total length of those canal segments that have local canal water demands to the total length of the canal network over which water has to be conveyed (from the canal head) to satisfy these demands. In Figure – 3.1, let irrigation demands exist only in segment 8 having a length of 2803 m. To meet its demands, a canal length of 17142 m (Segment 1+3+5+6+8) needs to be run. So the DDI becomes 2803/17142 = 0.1635.

In a particular week, it may so happen that due to the occurrence of rainfall, irrigation demands exist only in some localized segments of the command area and water has to be conveyed over a large length of canal network to supply water to these segments, which may not be economical. To account for such situation, DDI is computed by the model. If DDI falls short of some specified minimum, the canal system is not operated. The allocation model is invoked only when the DDI exceeds a specified minimum. If 'AL' is the length of all segments having local canal water demands and 'BL' is the length of network required to be run to satisfy the canal water demands, then DDI is given by:

$$DDI = AL/BL \qquad \ldots(3.19)$$

h) Calculation of run-time, discharge, and canal seepage

After finding the system linkages and irrigation demands (corresponding to spatial irrigation demands) in all canal segments, the run-time, discharge, and seepage loss in each segment are calculated in a subroutine (COPR). The calculations are started from the tail segments of the system in upstream direction towards the system head. For a segment, the calculations are made as follows:

i) Initially assume canal seepage (CANSEP) equal to 0.

ii) Required run-time for segment 'id' is calculated as:

$$RUNTIM_{id} = \frac{(TWRCN_{id} + CANSEP + WRSN(IDS)_{id})}{CAP_{id}} \qquad \ldots(3.20)$$

where WRSN(IDS_{id}) is the water demand at downstream node (IDS) of segment 'id'. Maximum value of $RUNTIM_{id}$ is restricted to (TIM–$FILTIM_{id}$) where TIM is the time of week. Further, $RUNTIM_{id}$ cannot be less than run-time of its downstream segment.

iii) The required discharge ($REQDIS_{id}$) in segment 'id' is calculated as:

$$REQDIS_{id} = \frac{(TWRCN_{id} + CANSEP + WRSN(IDS_{id}))}{RUNTIM_{id}} \qquad \ldots(3.21)$$

Maximum discharge is limited to the discharge capacity of segment 'id'.

iv) The discharge in a segment affects the wetted perimeter and water depth. If canal seepage uses either of these observations and the $REQDIS_{id}$ is not equal to the CAP_{id}, then the actual value of wetted perimeter and water depth is calculated before calculating the canal seepage. It is assumed that Manning's formula holds good for flow calculation in a canal section.

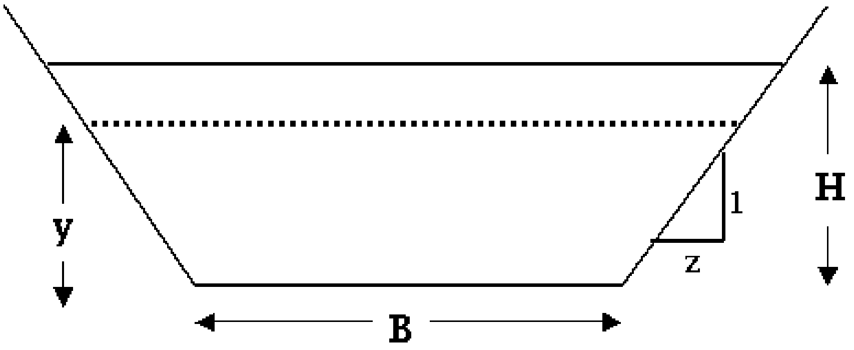

Figure – 3.2: Representation of a canal section

As shown in Figure – 3.2, let 'y' be actual water depth corresponding to discharge $REQDIS_{id}$ and 'H' be the maximum water depth corresponding to discharge capacity CAP_{id}. Let 'B' be the bed width of the segment. Then,

$$REQDIS_{id} = CAP_{id} * \frac{(B+zy)*y*\left[\dfrac{(B+zy)*y}{B+2y\sqrt{1+z^2}}\right]^{2/3}}{(B+zH)*H*\left[\dfrac{(B+zH)*H}{B+2H\sqrt{1+z^2}}\right]^{2/3}} \qquad \ldots(3.22)$$

Knowing $REQDIS_{id}$, CAP_{id}, B, z, and H, water depth 'y' is found by trial and error.

v) Canal seepage is calculated by one of the three methods adopted for the segment through the ISCOD. Canal seepage ($CSEEP_{id}$) in segment 'id' is calculated as:

If ISCOD = 1,

$$CSEEP_{id} = REQDIS_{id} * (1 - CEFF_{id}) * RUNTIM_{id} \qquad \ldots(3.23)$$

If ISCOD = 2,

$$CSEEP_{id} = \frac{(BEDW_{id} + y)^{0.667}}{200} * \frac{ALEN_{id}}{1000} * RUNTIM_{id} \qquad \ldots(3.24)$$

If ISCOD = 3,

$$CSEEP_{id} = (BEDW_{id} + 2 * y * \sqrt{1 + z^2}) * ALEN_{id} * SEEPR_{id} * RUNTIM_{id} \qquad \ldots(3.25)$$

vi) The canal seepage ($CSEEP_{id}$) as calculated in step (v) is compared with the assumed seepage (CANSEP). If there is difference between the two, then CANSEP is made equal to the $CSEEP_{id}$ and the calculations are revised from step (ii) again. The calculations are repeated till the difference between CANSEP and $CSEEP_{id}$ becomes negligible.

vii) After finalizing the run-time, required discharge, and canal seepage for a segment, the surface water demand and groundwater demand are computed as:

$$TWSCN_{id} = REQDIS_{id} * RUNTIM_{id} \qquad \ldots(3.26)$$

$$TWGCN_{id} = TWRCN_{id} + CSEEP_{id} + WRSN(IDS_{id}) - TWSCN_{id} \qquad \ldots(3.27)$$

$WRSN(IDS_{id})$ in a segment 'id' is computed by adding the canal water demand of all segments bifurcating from its downstream node.

viii) $TWSCN_{id}$ is then transferred from the segment to its upstream node. $TWSCN_{id}$ of all the segments meeting a node are added together to get the total canal water demand ($WRSN(IUS_{id})$) at the node. IUS_{id} represents the upstream node of segment 'id'. This way, total canal water demands at all the nodes are computed.

i) Incorporating canal capacity constraint

Using the subroutine COPR, $TWSCN_{id}$ and $TWGCN_{id}$ for each canal segment are found. Groundwater demand in an intermediate segment occurs when the canal water demand exceeds the conveyance capacity of segment. To settle groundwater demands in intermediate segments, demands in the downstream network need to be curtailed. Calculations proceed in upstream direction from the tail end. Groundwater depth is taken as the criteria for selecting segments whose canal water demands are to be curtailed. In this method, the free segment lying downstream of segment 'id' and having the least depth of groundwater is identified and its canal water demands are curtailed (provided it has sufficient groundwater potential). Subroutine COPR is run again and groundwater demands in the intermediate segment 'id' are found out in the revised scenario of demands. If groundwater demand still persists in segment 'id', then next segment lying downstream and having least depth of groundwater is identified for demand curtailment. This process is repeated till the groundwater demand at segment 'id' reduces to zero. If full curtailment of demands of a segment reduces the flow in segment 'id' below its discharge capacity, then the demands of last identified segment are curtailed partially so that canal water demand at segment 'id' becomes equal to its discharge capacity.

j) Incorporating canal water availability constraint

The canal water demand at the system head during a week, as calculated after satisfying capacity constraint, is compared with the canal water availability for the week. If the available water is more than or equal to the requirement, supply as per the calculated run-time and discharge is made in all the segments. However, if the canal water availability is less than the demand, then some allocation policy needs to be adopted. Three allocation policies have been specified in the simulation model and the user can choose any one policy for the simulation of canal operation. The stepwise procedure under the three allocation policies is described below:

Policy - 1: Head-reach priority

As specified earlier, water distribution under this policy is started from the head reaches in accordance with the canal water demands of different segments. Canal water is distributed as far as it can be made available in the canal system while satisfying all demands of the upstream segments. The computational steps are as follows:

i) If the water available at head is less than the demand, the segment having greatest distance from the head and having canal water demands is selected and its canal water demands are curtailed (provided it has sufficient groundwater availability).

ii) Subroutine COPR is run and revised demands at canal head are computed and compared with water supply.

iii) If the demands still exceed supply, then step (i) and (ii) are repeated iteratively till the supply exceeds or equals the demand at canal head.

v) Due to curtailment of full demands of the last identified segment, if the demands at head fall short of the supply, then only partial demands (found by iteration) of the last identified segment are curtailed till the demands at canal head match with the supply.

Policy – 2: Based on least depth of pumping

Under this policy, the identification of segments for demand curtailment is governed by the groundwater depth under different segments. The computations are performed as follows:

i) Calculate the water deficit at head.

ii) Segment having canal water demand and least depth of groundwater is identified for curtailment of canal water demands.

iii) Subroutine COPR is run to find the revised demands at head in light of the new demand scenario in the canal network.

iv) If deficit still persists at the head and the closure of curtailed segment causes the upstream segment to become a free segment, then suitable modifications are made in the system definition. Then, next segment with least depth of pumping is selected from the rest of the segments with canal water demand and the steps (ii) and (iii) are repeated.

v) If the curtailment of canal water demands of last selected segment results in reduction in total demands at head as compared to supply, then only partial demands of the last selected segment are curtailed which is found through iteration.

Policy-3: Conjunctive use with minimum energy demand

Under this policy, canal-run configuration corresponding to minimum energy demand for pumping groundwater in the irrigation system is derived. First, the Policy-2 related to conjunctive use of water is applied and the canal-run configuration corresponding to minimum depth of pumping is derived. This policy results in larger groundwater withdrawal and large canal seepage. Therefore, the canal-run configuration obtained for minimum depth of pumping is now iteratively refined such that the need of groundwater withdrawal reduces (with simultaneous reduction in energy demand for pumping) and groundwater is pumped from relatively shallower water depth area. Computational steps for this policy are as follows:

i) For the canal-run configuration corresponding to minimum depth of pumping, the most distant segment from the canal head with canal water supply is identified and its canal water demands are curtailed.

ii) Then, groundwater depth of all those upstream segments, which were curtailed (for canal water supply) while deriving the canal-run-configuration corresponding to policy-2, are compared and a segment with minimum depth of pumping among them is identified and its canal water demands are restored.

iii) Subroutine COPR is run to find the revised demand scenario at the canal head and corresponding energy requirement for pumping groundwater is estimated.

iv) For the new canal-run configuration, the most distant segment from the canal head is identified and steps from (i) to (iii) are repeated. This way, canal-run configuration is moved in upstream direction towards the head and corresponding energy demand for each configuration is estimated and saved.

v) When the canal-run configuration reaches the head of canal network, the iteration is stopped and the canal-run configuration corresponding to minimum energy demand becomes the outcome of Policy-3.

3.5.6 Output of the model

The output results of the model are presented in the form of maps and table. Maps are the means of easy visualization and understanding but one map can represent only one type of attribute. For detailed representation of results, a table is also generated by the model. Various forms of outputs of the model are discussed in the following:

a) Model results in map form

Output of the model is prepared in the form of an attribute table which can be imported in GIS and various attributes of canal network operation can be visualized in map form. Map corresponding to a particular attribute is displayed in color with different colors representing different values of the attribute. By clicking on any canal segment in the GIS, the corresponding value of attribute can be visualized. Various canal network maps that can be prepared from the attribute table include: average groundwater depth, groundwater availability, running/non-running canals, an indicator specifying the reason for not allocating canal water (waterlogging/capacity constraint/limited water supply), total canal water demands, canal water supply, canal seepage loss, required discharge, required run-time, water depth in canal, and required groundwater withdrawal.

Using the operation map showing running and non-running canals, the manager can instantly visualize the extent of canal network that can be served by the available canal water supply under the specified allocation policy. Results of adopting different allocation policies can be easily visualized and understood. The maps showing the required discharge and run-time in various canal segments can help the operator in deciding the opening and closure of different canal segments. The map showing the indicator (IR) can help the decision makers in knowing the cause of canal water deficiency in non-running canals. Similarly, the map showing the required groundwater withdrawal can help the irrigation authority in knowing the pumping requirement in different parts of the irrigation system.

b) Tabular presentation of results

Detailed results of the model are prepared in tabular form also. Two tables are prepared by the model. First table presents the operation results for each canal segment. Various details of the canal network operation include: identity of segment, upstream segment identity, average groundwater depth, groundwater availability in segment, total irrigation demands in local command area, canal water demands in local command area, canal water demands in the downstream network, canal seepage loss in the segment, total canal water demands in the segment, required discharge, required water depth, fill-time of segment, run-time of segment, and required groundwater pumping.

Second table specifies the canal segment identity and a code (0 or 1) signifying whether the segment is running at the end of a week or not. This table is used in finding the fill-time of different segments for operation in subsequent week.

c) Gross water use scenario over the whole command

Gross water demand and utilization scenario over the whole command is calculated by the model and is presented on the screen after execution of the model. Various quantities that are computed by the model include: total canal water available at the head, total irrigation demands in the command, total irrigation demand that were not considered because of waterlogging constraint, total canal water utilized in the area, total seepage loss in the canal water delivery, total groundwater pumping in the area, and the corresponding power requirement.

3.5.7 Advantages of the proposed model

Some of the advantages of proposed approach are enumerated in the following:

a) Simulation model considers the spatial variability of the irrigation demands and groundwater depths. It also considers the different characteristics of the canal system rather than assuming lumpsum values. In this sense, the model tries to simulate the operation quite close to the reality.
b) Model uses least number of assumptions in terms of canal seepage, recharge because of rainfall and irrigation, income and expenditure on various crops, and cost of providing surface and groundwater etc.
c) The model can be used to design or alter the system configuration. Different scenarios of canal capacities and canal locations can be simulated in the command area.

3.5.8 Limitations of the proposed model

Basic limitations of the approach are:

a) The data requirement of the model is quite high. The application of the approach requires digitization of Sajra maps (layout of command areas of all canal segments) of the command area. Though this is a one-time effort, yet it is quite a tedious work.

b) The approach requires the actual cropping pattern for the command area before the start of the season. There is a need to develop a system for getting such prior information from the farmers.

c) The approach requires a network of well-distributed groundwater observation wells and the collection of groundwater level data from the observation wells at weekly/monthly time step. At present, such data are collected at larger time interval, say once in two months or two times in a year (pre-monsoon and post-monsoon).

d) The approach suggests the operation plan for a week only. The aim is to satisfy the irrigation demands in the command area with least cost of pumping. The approach as such, does not ensure the sustenance of groundwater in the region on a long-term basis. If the water intensive crops are grown in the area and the withdrawal of groundwater exceeds the groundwater recharge, the water table may decline resulting in groundwater mining. To avoid such situation, there is a need to evaluate the groundwater potential at the end of the monsoon season so as to restrict its use in the non-monsoon season.

* * *

CHAPTER – 4
THE STUDY AREA & DATABASE GENERATION

4.1 THE GANGA CANAL SYSTEM

The agricultural land in western part of Uttar Pradesh state, India is served by major river diversion schemes on the Ganga and Yamuna rivers. The selected area for investigation is under the Madhya Ganga Canal Project (MGCP). The location map and a schematic diagram showing the development in and near the Upper Ganga Canal (UGC) Command and the linkage of Madhya Ganga Canal (MGC) with UGC and other canal systems is shown in Figure – 4.1. The MGCP envisages the utilisation of surplus water of River Ganga during the monsoon period for providing irrigation to 178000 hectares of command area for rice cultivation. Out of this, 114000 hectares is proposed in the command area of Upper Ganga Canal System through existing channels and 64000 hectares through new canal system in new command area in districts Bulandshahr and Aligarh.

The main components of the MGCP are: a) barrage across the Ganga River, 10 km west of Bijnor town, b) main canal, 115.45 km long, with a design discharge of 234 cumec, c) Lakhaoti branch system, 74.13 km long, taking off from main canal at 82.4 km with a design discharge of 63 cumec, and d) distributaries, minors and field channels serving a new CCA of 63000 hectares under the Mat branch for rice irrigation.

The main works of barrage and main canal have been completed. The main canal was run on trial from head to km. 92 in August, 1985. It was again run during full monsoon from 30 June to 9 October, 1986 and supplemented water to the Upper Ganga Canal. Currently, the canal is run in Kharif season supplementing water of UGC. The work on the Lakhaoti main branch is completed and the distribution system is under construction. The work on Mat branch feeder canal is also in progress.

4.2 THE LAKHAOTI BRANCH SYSTEM

The Lakhaoti branch command area that forms a part of the Madhya Ganga Canal Project has been selected for the present study. The command area lies in the districts of Bulandshahr, Aligarh and Ghaziabad in the Ganga-Yamuna doab between latitude 27°45′ N to 28°45′ N and longitude 77°45′ E to 78°35′ E. The study area is fertile one, irrigated by state tube wells, private tube wells and other minor irrigation works. Development of minor irrigation works is taking place at fast rate. Lakhaoti branch is supplying water during the monsoon period for Kharif irrigation. The command area is bounded by the Kali River in the west and the Nim River in the east. These are two main drainage of the area. During non-monsoon, these run mostly dry. An index map of the area showing the boundary rivers and the MGC is shown in Figure – 4.2.

In the absence of the surface water supplies till about 1988, irrigation water requirements were being met by pumpage from groundwater reservoir. Excessive pumpage

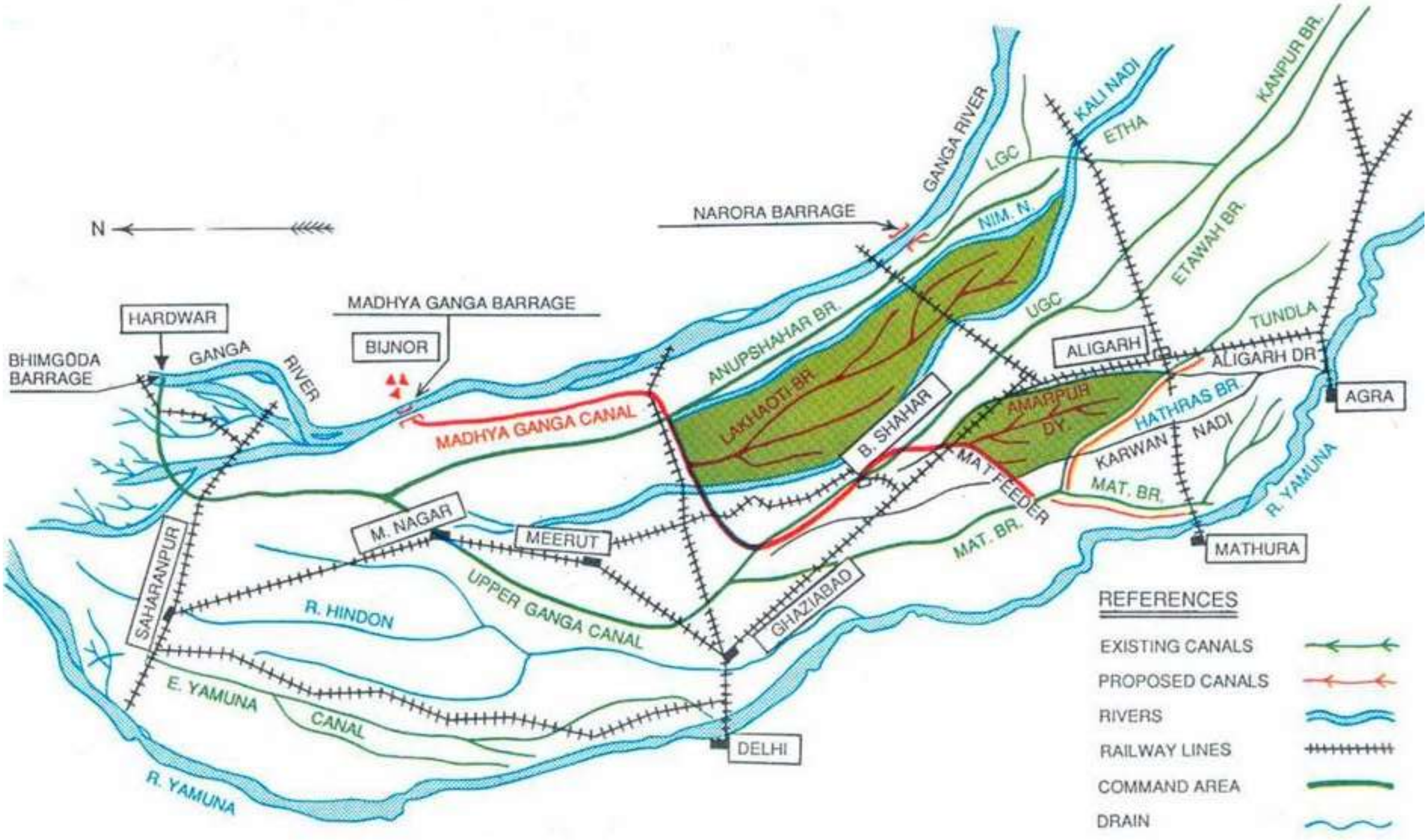

Figure – 4.1: Schematic diagram showing Upper Ganga Canal (UGC) & Madhya Ganga Canal (MGC) Systems

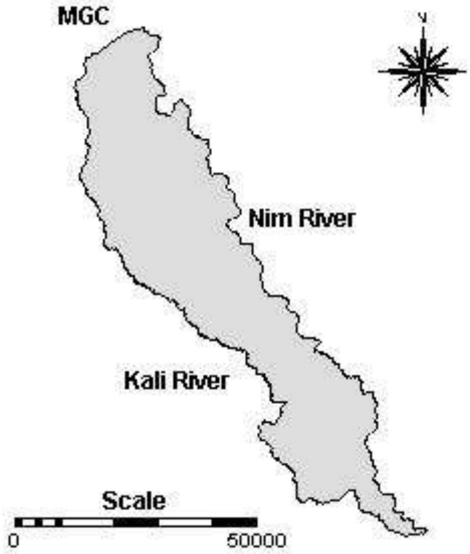

Figure – 4.2: Boundary of the Lakhaoti branch command

led to gradual depletion of water table in the area thereby increasing the cost of pumpage and causing loss of natural vegetation. Recent introduction of canal irrigation has led to greater recharge to ground water. Water table build-up in the command area needs to be monitored systematically to control waterlogging and soil salinity.

4.2.1 Climate and Rainfall

The area experiences moderate type of sub-tropical and monsoon climate. The maximum temperature rises up to 42°C in summer and falls up to 2°C in winter. Generally, the monsoon sets towards the end of June and lasts till the end of September. The winter rains are scanty. The average annual rainfall in the area is as per U.P. Groundwater Department 653.7 mm.

4.2.2 Topography

From the ground level study of the area, it is found that the average ground slope is 0.375% in longitudinal direction from North to South. It is within the recommended range (0.2 to 0.4 %) for efficient irrigation. As the longitudinal slope does not exceed 1 %, the hazard of erosion does not arise. The DEM of the area is presented in Figure – 4.3

4.2.3 Physiography & Soil Characteristics

The area is a part of the Indo-Gangetic alluvial plain and is made up of recent unconsolidated fluvial formation comprising sand, silt, clay and kankar with occasional beds of gravel deposited by the Ganges and its tributaries. The thickness of alluvium in Indo-Gangetic plain is known to be about 2500 to 3000 m.

The texture of the soil is generally light to medium loam with low infiltration rate. Clay percentage is less than 18%. There is no salinity problem in this area. The thickness of fertile soil at the top varies from 1.5 m to 2.0 m. In small patches in the districts of Bulandshahr and Aligarh, the soil is saline and alkali called Usar or Reh.

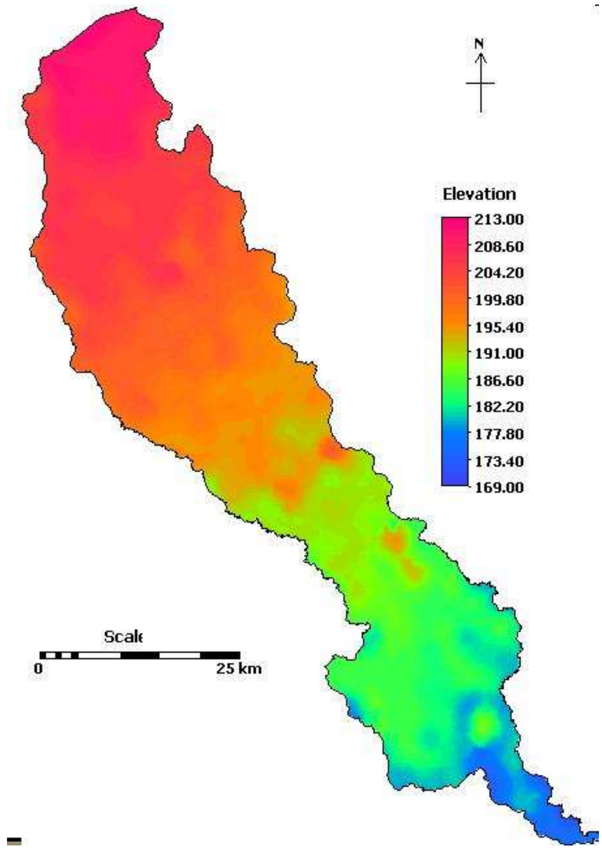

Figure – 4.3: Digital elevation map of Lakhaoti command

4.2.4 Groundwater Conditions in the Area

The water bearing formations range from 30 to 75 percent of the total material encountered down to 90 m depth. Ground water in the study area occurs under medium to deep water table conditions. The main aquifer of the region consists of sand beds. Most of the aquifers are generally in unconfined to semi-confined conditions. The depth of water table varies from 6 m to 16 m in the command. A perusal of the water level data in observation wells in different years indicates that the water table was progressively going down before the introduction of the Lakhaoti canal system in the area and has built up a lot since the canal introduction. Analysis of well data shows that water table rises during the monsoon period, as recharge to ground water is more than withdrawal and it falls during non-monsoon period as withdrawals exceed recharge. The quality of ground water in the study area is generally good and water is non-corrosive and non-incrusting. Water is slightly alkaline in nature (pH 7.78).

In irrigated areas, groundwater conditions vary spatially and temporally. In the proposed simulation scheme, groundwater conditions in the command are incorporated through the use of spatially distributed groundwater depth in the command area. Groundwater level data of 19 observation wells located within the Lakhaoti command are available for the year 1998-99 for the months of June (pre-monsoon), October and November (post-monsoon) and the same have been used for generating the groundwater surface for different months. A number of point interpolation techniques have been tried to generate the groundwater surface. For kriging, Gaussian model fits best to observed semi-variogram but the interpolation did not yield satisfactory results because of irregular jumps and troughs in the generated surface. Then, the trend-surface method has been used which did not result in sudden jumps and troughs but large difference has been found between the observed and generated levels at the observation points. Finally, the moving-surface method of point interpolation (method in which a polynomial surface is calculated by a moving least square fit) is used which provides satisfactory results with respect to groundwater surface and the match between observed and generated levels at observation points.

The groundwater surfaces for Lakhaoti command are generated for the month of June and October. The groundwater surface for October 1998 is shown in Figure – 4.4 (a). The groundwater elevation at each grid is subtracted from the DEM to get the groundwater depth. Groundwater depth map for October is shown in Figure – 4.4 (b).

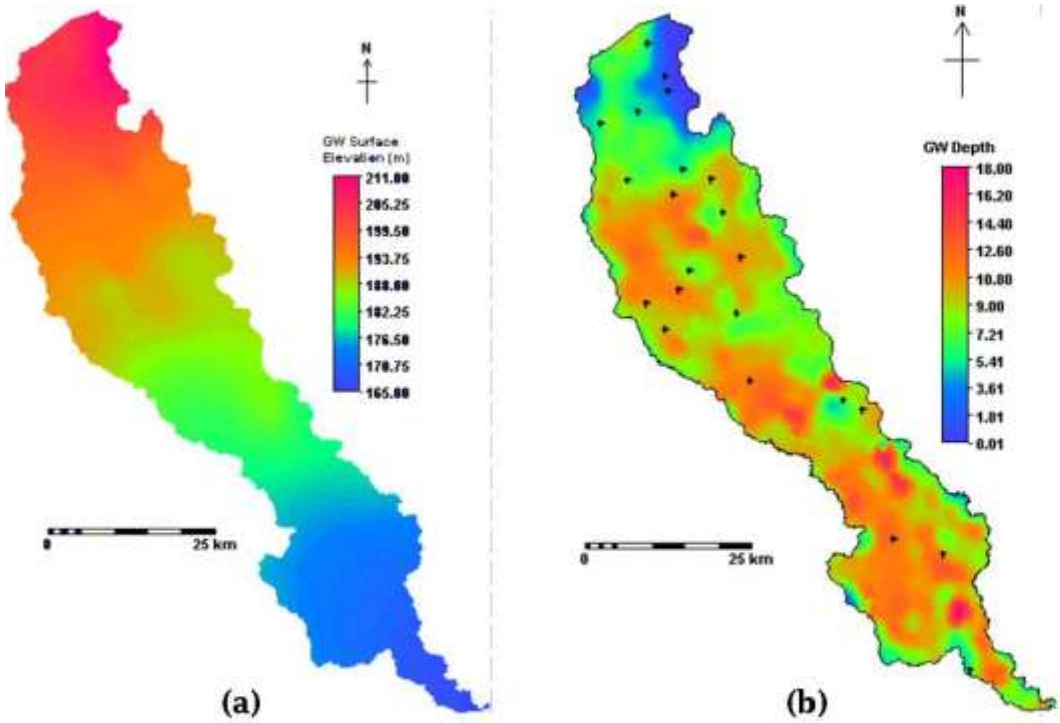

Figure – 4.4: (a) GW surface map for October, 1998, (b) GW depth map and location of wells

4.2.5 Existing Cropping Pattern

The principal crops in the area are wheat, sugarcane and maize. As canal supplies were not available earlier, the area under paddy was very small. The average area under various crops for the existing condition and as proposed by project authority under the conjunctive use plan after the introduction of canal are shown in Chapter – 4.

The existing cropping intensity during Kharif (monsoon season) and Rabi (winter-season) are 39 and 75 percent respectively. With the introduction of canal supplies, the area under Kharif paddy is proposed to be 48254 hectare, i.e., 25 % of the CCA.

4.2.6 Irrigation Demand map

The allocation model uses spatial information of irrigation demands in the command area during a week. DEMAND model is used to estimate irrigation demands at weekly time step. This model requires data of the actual cropping pattern in the command, a soil map, a Thiessen polygon map of rainfall stations, the daily/weekly rainfall data, the crop and soil properties, and the climate data for calculating crop evapo-transpiration. This model and the database generation for Lakhaoti command has been described in NIH report entitled "Optimum Water Management in a Command Area". The same is not discussed here. One of the outputs of the model is supplementary irrigation requirement for each week. This output becomes the input for the allocation model. Figure – 4.5 shows the irrigation demands in the Lakhaoti command during the week June 24 – 30, 1998 as calculated by *DEMAND* model.

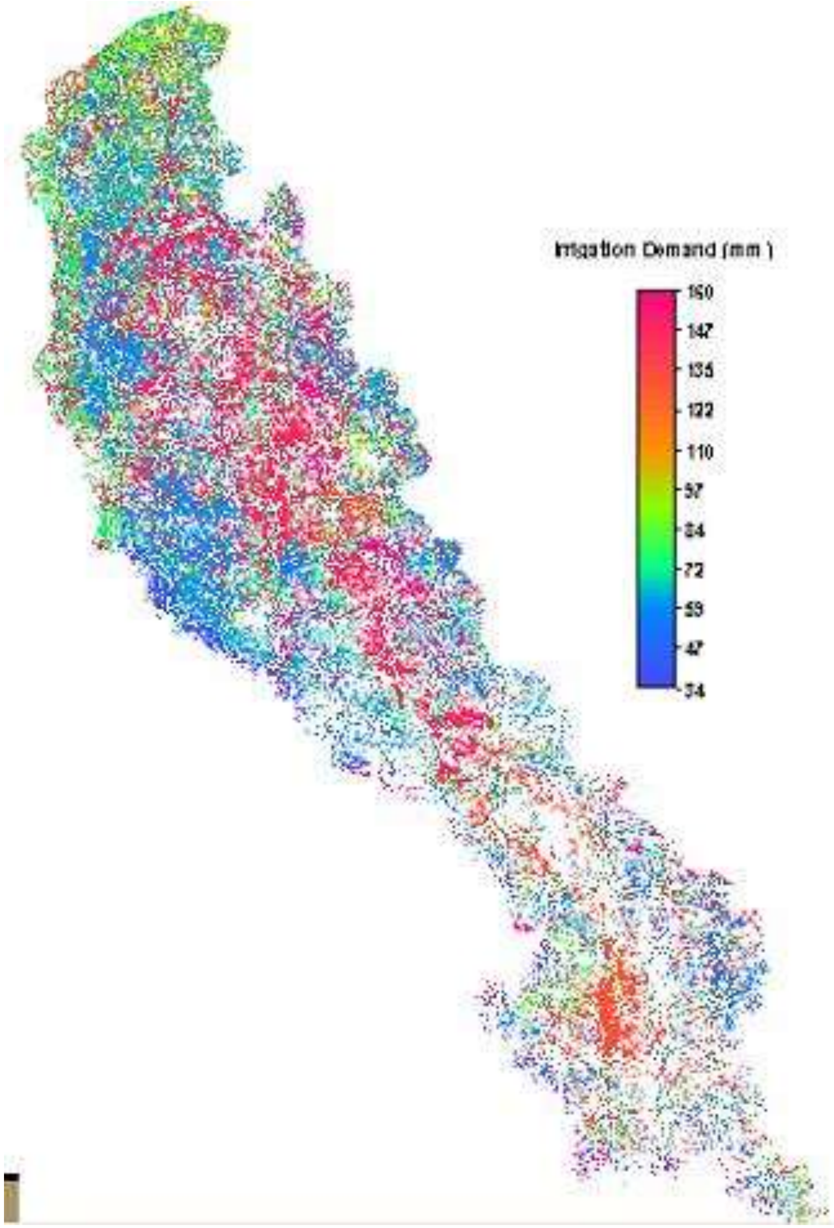

Figure – 4.5: Irrigation demand map in Lakhaoti command during a week as derived by DEMAND model

4.2.7 Surface Water Availability

The Lakhaoti branch is the only source of surface water to the cultivable command of 193000 hectares. Water is released in this canal only during the months of June to September at varying rates. Table – 4.1 shows the supply discharge and the corresponding volume of canal water available during June, July, August and September.

Table – 4.1
Availability of Water in Lakhaoti Branch

S. No.	Period		Discharge (cumec)	% of Full Supply Discharge	Volume of Water Allocated (ha-m)
	Month	Dates			
1.	June	08-15	12.6	020	870.9
		16-23	12.6	020	870.9
		24-30	12.6	020	762.0
2.	July	01-07	63.0	100	3810.2
		08-15	63.0	100	4354.5
		16-23	63.0	100	4354.5
		24-31	63.0	100	4354.5
3.	August	01-07	63.0	100	3810.2
		08-15	63.0	100	4354.5
		16-23	63.0	100	4354.5
		24-31	63.0	100	4354.5
4.	September	01-07	63.0	100	3810.2
		08-15	63.0	100	4354.5
		16-23	63.0	100	4354.5
		24-30	31.5	050	1905.1
5.	October	01-07	31.5	050	1905.1
		08-15	15.2	025	1051.9
Total Allocation					53632.5

4.2.8 Canal System Characteristics

The Lakhaoti canal is named after an important township "Lakhaoti" in the area. In all, 36 distributaries and minors directly take off from Lakhaoti branch. Of the total canal system, 101 distributaries and minors measuring 693 km lie in the Bulandshahr district while 37 distributaries and minors measuring 337 km lie in Aligarh district.

Known discharge capacity and conveyance efficiency of Lakhaoti branch and some major distributaries (WRDTC, 1992) have been used in deciding the capacities of different canal segments and in calculation of canal seepage losses. These are presented in Table – 4.2.

In addition, detailed information of various minors and distributaries in the canal network are collected from Irrigation Department in Bulandshahr and Aligarh. In this study,

Table – 4.2
Conveyance Efficiency of Lakhaoti Distribution System

RD	Discharge (Cumec)	Wetted Perimeter (m)	Length (m)	Wetted Area (Mm^2)	Losses (Cumec)	Reach Efficiency
1. Lakhaoti Main Canal						
0.0	63.00	37.78	4500	0.1700	0.3060	0.9951
4.5	62.00	37.48	9950	0.3729	0.6713	0.9890
14.0	55.21	35.37	3000	0.1061	0.1910	0.9965
17.0	46.12	32.33	12000	0.3879	0.6982	0.9849
29.0	41.66	30.72	8000	0.2458	0.4424	0.9894
37.0	31.84	26.86	12000	0.3223	0.5801	0.9818
49.0	27.10	24.78	23000	0.5699	1.0258	0.9621
72.0	--	--	--	--	--	--
2. Atrauli Distributary						
0.0	13.03	17.19	6500	0.1117	0.2011	0.9846
6.5	10.48	15.41	3500	0.0540	0.0971	0.9997
10.0	7.58	13.11	3650	0.0479	0.0862	0.9997
13.7	5.66	11.33	5750	0.0652	0.1173	0.9793
19.4	1.42	5.67	5440	0.0308	0.0555	0.9989
24.8	0.57	3.58	7100	0.0254	0.0458	0.9192
31.9	--	--	--	--	--	--
3. Shikarpur Distributary						
0.0	8.49	13.88	18500	0.2568	0.4622	0.9456
18.5	5.66	11.33	21500	0.2437	0.4386	0.9978
40.0	1.42	5.67	4000	0.0227	0.0408	0.9992
44.0	0.57	3.58	2000	0.0072	0.0129	0.9772
46.0	0.00	0.00	--	--	--	--
4. Debai Distributary						
0.0	3.6	9.03	8000	0.0722	0.1300	0.9639
8.0	2.83	8.01	15000	0.1202	0.2164	0.9237
23.0	1.42	5.67	6000	0.0340	0.0612	0.9568
29.0	0.57	3.58	4800	0.0172	0.0310	0.9454
33.8	0.00	0.00	0	0.0000	0.0000	--
5. Dharampur Distributary						
0.0	6.23	11.89	4000	0.0475	0.0856	0.9863
4.0	5.66	11.33	6000	0.0680	0.1224	0.9784
10.0	2.83	8.01	7920	0.0635	0.1142	0.9597
17.9	1.42	5.67	5500	0.0312	0.0561	0.9604
23.4	0.57	3.58	5700	0.0204	0.0368	0.9351
29.1	0.00	0.00	--	--	--	--
6. Chharra Minor						
0.0	3.83	9.32	7000	0.0653	0.1175	0.9694
7.0	2.83	8.01	9400	0.0753	0.1356	0.9522
16.4	1.42	5.67	7800	0.0442	0.0796	0.9439
24.2	0.57	3.58	1200	0.0043	0.0077	0.9863
25.4	0.00	--	--	--	--	--
7. Jadaul Distributary						
0.0	2.63	7.72	7000	0.0540	0.0973	0.9630
7.0	1.42	5.67	3200	0.0181	0.0326	0.9770
10.2	0.57	3.58	7200	0.0258	0.0464	0.9181
17.4	0.00	--	--	--	--	--

the canal network is represented by 218 segments and properties of each segment, such as discharge capacity, length, bed width, water depth etc. were required. Wherever not available, such details are determined by interpolation. The characteristics of various canal segments are presented in the following section.

4.2.9 Delineation of Canal Network in Lakhaoti Command

The database for canal network simulation model requires layout plan of the canal network up to minor level and corresponding irrigable command areas. The index map of Lakhaoti command showing the canal system has been collected from field records at the scale of 1 inch = 4 miles (≈ 1:250,000). The location of different canals on this map is approximate. Complete canal network layout at larger scale is not available. Hence, remote sensing data is considered best suited for accurately delineating the canal system. Line diagram of the canal system showing the names and lengths of various canal segments, as obtained from Irrigation Department, is utilized for this purpose.

Canal system in the Lakhaoti command is delineated using the PAN sensor data of IRS-1C satellite. This sensor has single band information (in spectral range 0.50 to 0.75 μm) with a spatial resolution of 5.8 m. Major part of the study area is covered in Path 097 and Row 051 of IRS-1C satellite (One full scene C0, and some sub-scenes A7, A8, and D7). Two sub-scenes (B1 and A3) in Path 097 and Row 052 also covered a part of the command area. All the scenes have been imported in ERDAS system. Lakhaoti branch, various distributaries and minors, and road network could be clearly visualized in these images. Various scenes have been geo-referenced to the spatial GIS database using various road crossings as control points. Road network in the image matched to a great extent with the one digitized from the toposheets. The mosaic of different PAN sensor scenes and sub-scenes has been prepared and the study area is extracted from total image of the area.

The PAN sensor image is imported in ILWIS GIS system for on-screen digitization of the canal network. Line diagram of the canal system has been used to identify different distributaries and minors in the PAN sensor image. A view of the zoomed PAN data showing a minor part of the canal system is shown in Figure – 4.6. The digitized information is saved in a segment file with each segment identity being represented by the name of canal. Layout of the canal system as obtained from the remote sensing data is presented in Figure – 4.7.

4.2.10 Digitization of irrigable command areas of canal segments

In the proposed scheme, each canal segment is linked to its irrigable command area for calculating irrigation demands. For this reason, it is necessary to digitize the irrigable command area of each individual segment in the canal network. The entire canal network has been bifurcated into individual segments and different numeric identities are assigned to each. A total of 217 individual segments have been identified in the network. Identities of various canal segments are also shown in Figure – 4.6.

Digitization of irrigable command areas of different segments required the availability of field layout maps of all individual canal segments showing the boundary of the area under the command of each canal segment. Collection of such maps for all canal segments was not possible under this study. An approximate layout of the irrigable command areas of different segments has been obtained from the Irrigation Department.

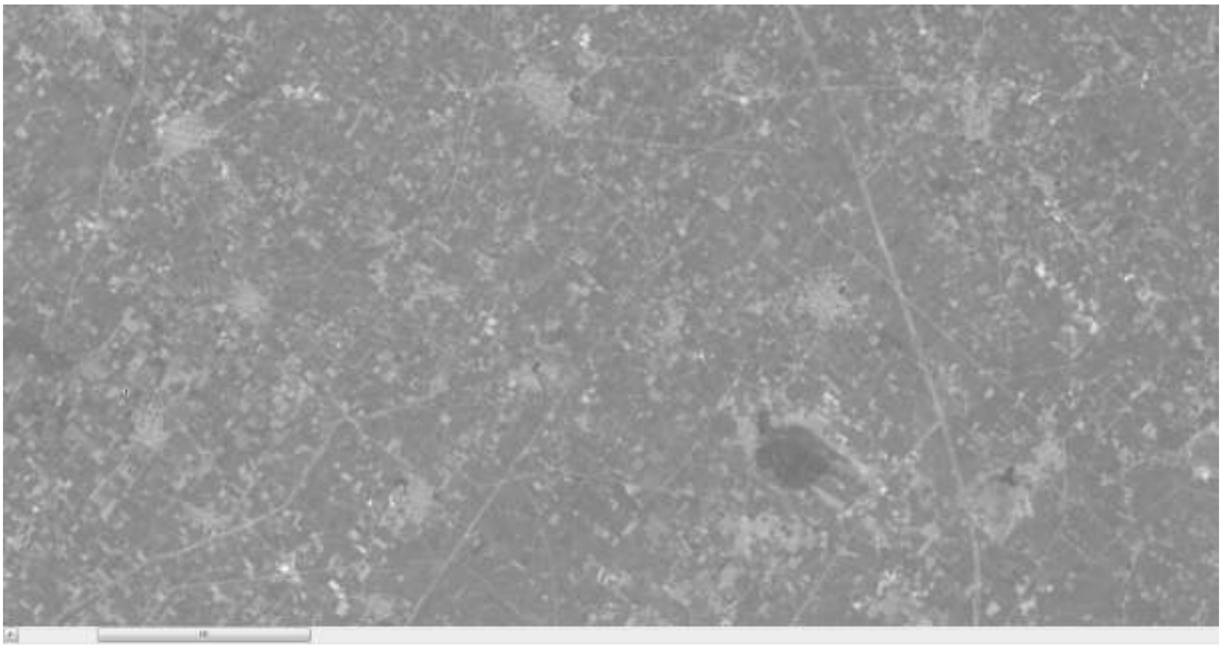

Figure – 4.6: PAN sensor image showing various roads, canals, and settlements in a part of Lakhaoti command

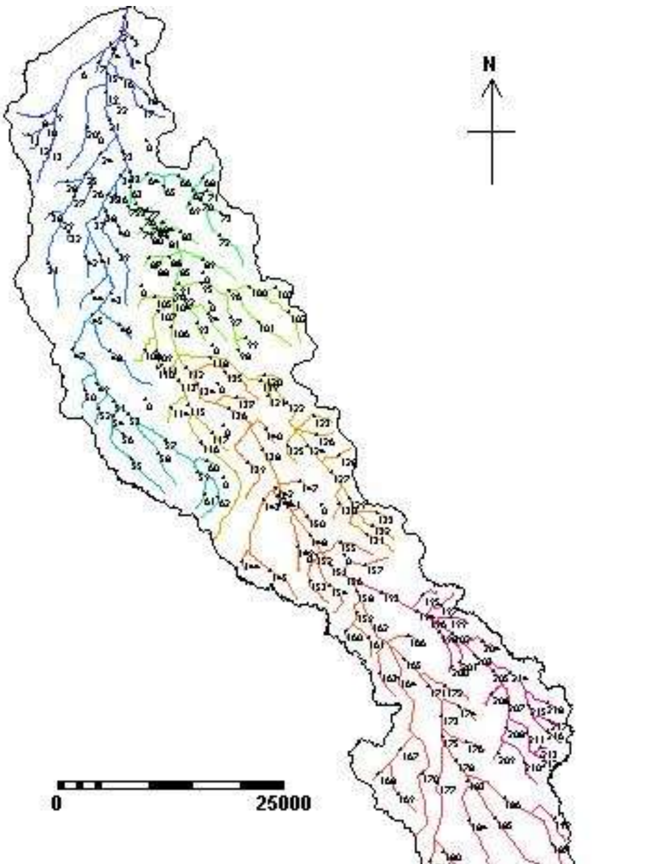

Figure – 4.7: Layout of canal network (up to minor level) in Lakhaoti command

The proposed profitable area (PPA), which specifies the profitable area from a canal segment, of each distributary/minor is also collected from field records. Some guidelines provided by the Irrigation Department, like a) at diversions of distributaries and minors, water is generally not withdrawn up to a distance of about 200 m from the diversion point so as to generate the required head in distributary/ minor, and b) in the head reaches of network, canal water hardly goes beyond 500 m from the canal segment, helped in digitizing irrigable area.

With these criteria, an approximate layout of the command of each individual canal segment is digitized such that it lies in the proximity of the canal segment. After digitization, the agriculture area under the area has been evaluated and matched with the field records (given as PPA). By trial and error, the irrigable area boundary for each segment has been adjusted till the irrigable area under canal segment matches close to the specified PPA of the segment. To differentiate irrigable commands of various segments, individual commands have been rasterized using same numeric identity as that of corresponding canal segment. Grids located outside of the irrigable command of any canal segment have been assigned a numeric identity of zero. Layout of the command area of each individual canal segment is presented in Figure – 4.8.

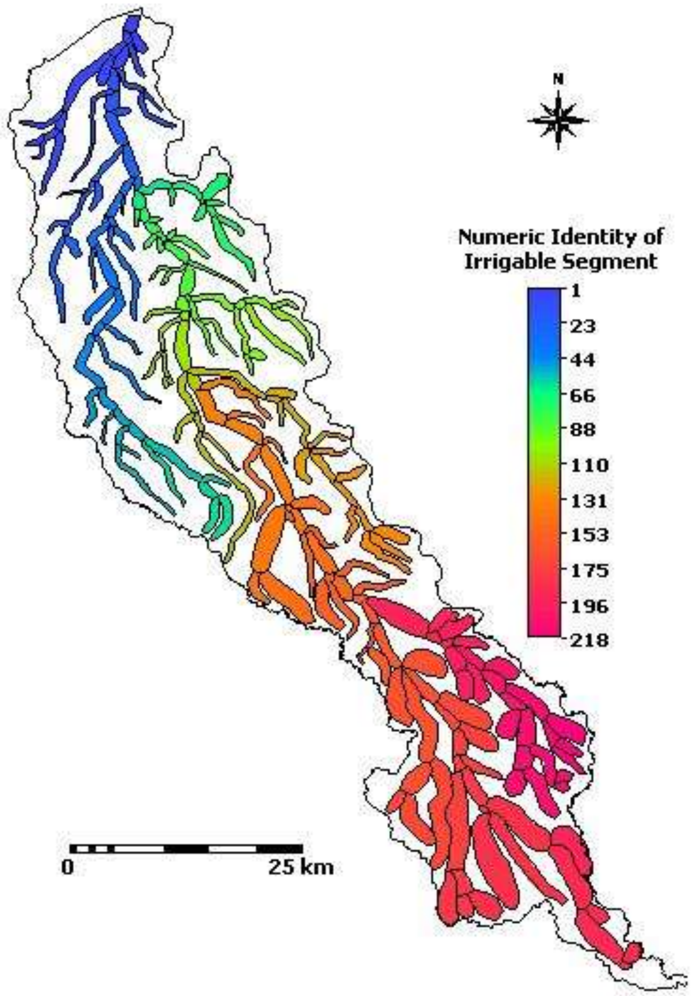

Figure – 4.8: Irrigable command areas of different canal segments in Lakhaoti command

4.2.11 Characterization of Different Canal Segments

In the simulation model, each canal segment represents a link in the network and various links are connected at nodes. Various canal characteristics are required in the model to compute irrigation demands, seepage losses and run-time of different canal segments. Discharge capacities at the head of branch, distributaries and minors are available. Discharge capacities at head of intermediate segments have been computed by linear interpolation and accounting for the diversions from the branch or distributaries. Conveyance efficiencies for major distributaries in the network have been collected from the Irrigation Department. For minor canals, the following empirical formula has been adopted:

$$\text{Canal Seepage} = [(\text{Bed width} + \text{Water depth})^{2/3}/200] * \text{Segment length} * \text{Run-time} \qquad \ldots(4.1)$$

where the bed width and water depth are in m, length of segment is in km, and canal seepage is calculated in cubic meter. Cross-sectional details of various segments (bed width and water depth) have been obtained from the Irrigation Department while the length of segments are obtained through GIS. The field channel efficiency below the outlets and the field application efficiency have been taken as 80% and 70% respectively. Further, it is assumed that 80% of the water lost in field channels and during field application reaches the groundwater table (Sakthivideval & Chawla, 2002). Before introduction of the canal system, the irrigation in command was fully dependent on the groundwater. Further, during the non-monsoon season, the canal water supply is not planned and therefore, the groundwater continues to be the only source of irrigation water supply during Rabi season. The characteristics of various canal segments used in the study are presented in Table – 4.3.

Table – 4.3
Characteristics of Lakhaoti Canal System

Segment Name	Numeric Identity	Discharge Capacity (cumec)	Length (m)	Bed Width (m)	Water Depth (m)	Design PPA (ha)	Calculated PPA (ha) at Head of Dist./Minor	Conveyance Efficiency	Head Node Number	Number of d/s Nodes	Tail Node Number	Number of Immediately d/s Segments	Numeric Identity of Immediately d/s Segments			
													N1	N2	N3	N4
Col. 1	Col. 2	Col. 3	Col. 4	Col. 5	Col. 6	Col. 7	Col. 8	Col. 9	Col. 10	Col. 11	Col. 12	Col. 13	C.14	C.15	C.16	C.17
B_Lakhaoti1	1	63.71	2344	35.00	2.25	5416	5447	0.9951	501	101	502	2	2	3	-	-
B_Lakhaoti2	2	63.13	1167	34.84	2.24	-	-	0.9951	502	100	503	3	4	5	14	-
M_Bahapur	3	0.18	2663	1.20	0.50	169	170	-	502	0	1000	0	-	-	-	-
B_Lakhaoti3	4	60.54	2963	33.70	2.22	-	-	0.9920	503	95	508	2	15	16	-	-
D_Partapur1	5	2.17	2222	7.00	0.80	1208	1202	-	503	4	504	2	6	7	-	-
D_Partapur2	6	1.72	8072	5.92	0.75	-	-	-	504	3	505	2	8	9	-	-
M_Bhimyari	7	0.30	2831	1.50	0.55	236	229	-	504	0	1000	0	-	-	-	-
M_Pali	8	0.25	5305	1.25	0.55	200	199	-	505	0	1000	0	-	-	-	-
D_Partapur3	9	0.92	2068	4.39	0.54	-	-	-	505	2	506	2	10	13	-	-
M_Tajpur1	10	0.28	1988	1.50	0.55	166	168	-	506	1	507	2	11	12	-	-
M_Tajpur2	11	0.10	2063	0.67	0.43	-	-	-	507	0	1000	0	-	-	-	-
M_Sherpur	12	0.09	2804	1.00	0.35	75	78	-	507	0	1000	0	-	-	-	-
D_Partapur4	13	0.50	7239	2.68	0.48	-	-	-	506	0	1000	0	-	-	-	-
M_Bainipur	14	0.22	4114	1.50	0.50	200	194	-	503	0	1000	0	-	-	-	-
B_Lakhaoti4	15	59.53	2467	33.60	2.19	-	-	0.9890	508	93	510	2	19	20	-	-
D_Kuchesar1	16	0.50	4298	1.80	0.60	214	230	-	508	1	509	2	17	18	-	-
M_Alabans	17	0.25	5954	1.00	0.50	190	192	-	509	0	1000	0	-	-	-	-
D_Kuchesar2	18	0.10	2846	0.52	0.42	-	-	-	509	0	1000	0	-	-	-	-
B_Lakhaoti5	19	58.61	2075	33.53	2.16	-	-	0.9890	510	92	511	2	21	22	-	-
D_Saidpur	20	0.50	11708	1.80	0.60	369	382	-	510	0	1000	0	-	-	-	-
B_Lakhaoti6	21	58.13	3898	33.42	2.15	-	-	0.9890	511	91	512	2	23	24	-	-
M_Kharkali	22	0.12	1927	1.25	0.37	95	90	-	511	0	1000	0	-	-	-	-
B_Lakhaoti7	23	54.80	3601	32.10	2.11	-	-	0.9907	512	86	517	2	33	34	-	-
D_Pabsara1	24	2.67	5013	4.50	1.00	1022	1046	-	512	4	513	2	25	26	-	-
D_Pabsara2	25	2.00	1073	4.00	0.84	-	-	-	513	3	514	2	27	28	-	-
M_Nimchana	26	0.21	3422	1.52	0.40	178	171	-	513	0	1000	0	-	-	-	-
D_Pabsara3	27	1.80	4209	3.80	0.80	-	-	-	514	2	515	2	29	30	-	-
M_Kisauli	28	0.10	3489	0.85	0.38	80	89	-	514	0	1000	0	-	-	-	-
D_Pabsara4	29	1.28	1454	3.22	0.67	-	-	-	515	1	516	2	31	32	-	-

Segment Name	Numeric Identity	Discharge Capacity (cumec)	Length (m)	Bed Width (m)	Water Depth (m)	Design PPA (ha)	Calculated PPA (ha) at Head of Dist./Minor	Conveyance Efficiency	Head Node Number	Number of d/s Nodes	Tail Node Number	Number of Immediately d/s Segments	Numeric Identity of Immediately d/s Segments			
Col. 1	Col. 2	Col. 3	Col. 4	Col. 5	Col. 6	Col. 7	Col. 8	Col. 9	Col. 10	Col. 11	Col. 12	Col. 13	C.14	C.15	C.16	C.17
M_Lohrara	30	0.14	2683	1.30	0.32	113	114	-	515	0	1000	0	-	-	-	-
D_Pabsara5	31	0.90	9752	2.43	0.62	-	-	-	516	0	1000	0	-	-	-	-
M_Bisundhra	32	0.25	2915	1.50	0.50	220	222	-	516	0	1000	0	-	-	-	-
B_Lakhaoti8	33	45.68	1356	27.28	2.07	-	-	0.9849	517	71	532	2	63	64	-	-
D_Shikarpur1	34	8.50	2159	6.70	1.55	3000	3000	0.9456	517	14	518	2	35	36	-	-
D_Shikarpur2	35	8.23	2927	6.70	1.50	-	-	0.9456	518	13	519	2	37	38	-	-
M_Pipala	36	0.07	2259	0.75	0.35	56	56	-	518	0	1000	0	-	-	-	-
D_Shikarpur3	37	7.27	4022	6.25	1.42	-	-	0.9456	519	11	521	2	41	42	-	-
D_Aurangabad1	38	0.70	1256	2.30	0.67	465	471	-	519	1	520	2	39	40	-	-
D_Aurangabad2	39	0.49	11046	1.73	0.63	-	-	-	520	0	1000	0	-	-	-	-
M_Khwajpur	40	0.15	3206	1.10	0.42	120	123	-	520	0	1000	0	-	-	-	-
D_Shikarpur4	41	6.71	4955	6.21	1.32	-	-	0.9456	521	10	522	2	43	44	-	-
M_Rajwana	42	0.19	4941	1.83	0.38	155	160	-	521	0	1000	0	-	-	-	-
D_Shikarpur5	43	5.90	4486	6.06	1.19	-	-	0.9456	522	9	523	2	45	46	-	-
M_Mathan	44	0.36	5153	1.80	0.55	341	340	-	522	0	1000	0	-	-	-	-
D_Shikarpur6	45	5.27	1577	5.96	1.08	-	-	0.9978	523	8	524	2	47	48	-	-
M_Adoli	46	0.23	5341	1.50	0.46	210	210	-	523	0	1000	0	-	-	-	-
D_Shikarpur7	47	4.22	7388	4.96	1.04	-	-	0.9978	524	7	525	2	49	50	-	-
D_Utrawli	48	0.90	10833	4.25	0.66	425	428	-	524	0	1000	0	-	-	-	-
D_Shikarpur8	49	3.26	2842	4.68	0.85	-	-	0.9978	525	6	526	2	51	52	-	-
M_Dhatoori	50	0.30	4982	2.15	0.52	244	240	-	525	0	1000	0	-	-	-	-
D_Shikarpur9	51	2.88	2243	4.50	0.78	-	-	0.9978	526	5	527	2	53	54	-	-
M_Jatpura	52	0.12	4233	1.51	0.36	102	108	-	526	0	1000	0	-	-	-	-
D_Shikarpur10	53	2.21	2191	3.75	0.72	-	-	0.9978	527	3	529	2	57	58	-	-
D_Surjawali1	54	0.46	2417	3.35	0.61	476	477	-	527	1	528	2	55	56	-	-
D_Surjawali2	55	0.29	10233	2.29	0.55	-	-	-	528	0	1000	0	-	-	-	-
M_Salempur	56	0.11	2805	1.20	0.34	77	77	-	528	0	1000	0	-	-	-	-
D_Shikarpur11	57	1.61	7690	2.98	0.66	-	-	0.9982	529	2	530	2	59	60	-	-
M_Mukhera	58	0.40	8597	1.80	0.60	351	350	-	529	0	1000	0	-	-	-	-
D_Shikarpur12	59	0.81	2467	2.12	0.47	-	-	0.9903	530	1	531	2	61	62	-	-
M_Haweli	60	0.10	3347	0.90	0.36	82	85	-	530	0	1000	0	-	-	-	-
D_Shikarpur13	61	0.36	3960	1.10	0.40	-	-	0.9772	531	0	1000	0	-	-	-	-
M_Dargahpur	62	0.23	5924	1.20	0.54	195	331	-	531	0	1000	0	-	-	-	-
B_Lakhaoti9	63	43.54	2081	26.12	2.06	-	-	0.9849	532	66	537	2	74	75	-	-
D_Khanpur1	64	1.91	4013	3.00	1.05	628	616	-	532	4	533	2	65	66	-	-
M_Rahimpur	65	0.08	1962	0.75	0.40	78	78	-	533	0	1000	0	-	-	-	-
D_Khanpur2	66	1.57	3685	2.97	0.87	-	-	-	533	3	534	2	67	68	-	-
D_Khanpur3	67	1.12	901	2.95	0.62	-	-	-	534	2	535	3	69	70	71	-
M_Chingraoti	68	0.21	3959	1.00	0.60	214	215	-	534	0	1000	0	-	-	-	-
M_Saikhpur	69	0.17	2202	1.20	0.45	146	87	-	535	0	1000	0	-	-	-	-
D_Khanpur4	70	0.82	1469	2.36	0.57	-	-	-	535	1	536	2	72	73	-	-
M_Ginora	71	0.07	2005	0.60	0.40	57	60	-	535	0	1000	0	-	-	-	-
M_Jawasa	72	0.50	8494	2.15	0.58	471	477	-	536	0	1000	0	-	-	-	-
D_Khanpur5	73	0.22	3466	0.74	0.50	-	-	-	536	0	1000	0	-	-	-	-
B_Lakhaoti10	74	42.95	1522	26.02	2.04	-	-	0.9849	537	65	538	2	76	77	-	-
M_Gangiri	75	0.23	1991	0.90	0.35	80	79	-	537	0	1000	0	-	-	-	-
B_Lakhaoti11	76	42.63	2299	25.95	2.03	-	-	0.9849	538	64	539	2	78	79	-	-
M_Lakhaoti	77	0.06	1571	0.60	0.35	51	54	-	538	0	1000	0	-	-	-	-
B_Lakhaoti12	78	42.15	1056	25.86	2.01	-	-	0.9849	539	63	540	3	80	81	82	-
M_Bakapur	79	0.08	1987	0.90	0.35	70	72	-	539	0	1000	0	-	-	-	-
M_Tikri	80	0.10	1724	0.90	0.40	80	77	-	540	0	1000	0	-	-	-	-
B_Lakhaoti13	81	41.77	4081	25.82	2.00	-	-	0.9849	540	61	542	3	85	86	89	-
M_Ramgarh1	82	0.28	472	1.50	0.50	210	222	-	540	1	541	2	83	84	-	-
M_Ramgarh2	83	0.20	5037	1.18	0.45	-	-	-	541	0	1000	0	-	-	-	-
M_Daultabad	84	0.06	1373	0.60	0.35	58	57	-	541	0	1000	0	-	-	-	-
B_Lakhaoti14	85	40.73	3466	25.56	1.97	-	-	0.9894	542	59	544	2	90	91	-	-
M_Parwana1	86	0.18	1952	0.90	0.53	92	93	-	542	1	543	2	87	88	-	-
M_Parwana2	87	0.07	2772	0.45	0.44	-	-	-	543	0	1000	0	-	-	-	-
M_Badshahpur	88	0.05	1971	0.50	0.30	43	45	-	543	0	1000	0	-	-	-	-
M_Sheorampur	89	0.21	7427	1.25	0.40	172	179	-	542	0	1000	0	-	-	-	-
B_Lakhaoti15	90	37.51	1671	23.90	1.94	-	-	0.9894	544	52	551	2	104	105	-	-
D_Jadaul1	91	2.63	675	4.50	1.02	863	866	0.9630	544	6	545	2	92	95	-	-
M_Khanpura1	92	0.55	2214	2.15	0.58	223	223	-	545	1	546	2	93	94	-	-
M_Khanpura2	93	0.19	4578	0.88	0.49	-	-	-	546	0	1000	0	-	-	-	-
M_Fatehpur	94	0.27	6632	1.50	0.50	215	222	-	546	0	1000	0	-	-	-	-
D_Jadaul2	95	2.05	5245	3.60	1.00	-	-	0.9630	545	4	547	2	96	97	-	-
D_Jadaul3	96	1.11	1237	3.16	0.78	-	-	0.9630	547	2	549	2	100	101	-	-
M_Kurena1	97	0.70	5474	2.40	0.65	278	281	-	547	1	548	2	98	99	-	-
M_Kurena2	98	0.11	2317	0.63	0.40	-	-	-	548	0	1000	0	-	-	-	-
M_Jahangirabad	99	0.32	2047	1.40	0.60	100	100	-	548	0	1000	0	-	-	-	-
D_Jadaul4	100	0.60	3042	1.81	0.73	-	-	0.9770	549	1	550	2	102	103	-	-
M_Bhopur	101	0.46	9271	2.25	0.52	450	445	-	549	0	1000	0	-	-	-	-
D_Jadaul5	102	0.33	7443	1.22	0.60	-	-	0.9181	550	0	1000	0	-	-	-	-
M_Madangarh	103	0.13	3143	0.90	0.42	110	109	-	550	0	1000	0	-	-	-	-
B_Lakhaoti16	104	37.01	869	23.83	1.92	-	-	0.9894	551	51	552	2	106	107	-	-
M_Joth	105	0.21	4624	1.52	0.43	170	177	-	551	0	1000	0	-	-	-	-
B_Lakhaoti17	106	36.38	5568	23.54	1.91	-	-	0.9818	552	48	555	3	112	113	118	-
D_Balka1	107	0.49	4851	2.27	0.58	224	244	-	552	2	553	2	108	109	-	-
M_Mursana	108	0.16	4010	1.00	0.40	115	114	-	553	0	1000	0	-	-	-	-
D_Balka2	109	0.17	2940	1.10	0.42	-	-	-	553	1	554	2	110	111	-	-
M_Dhanora	110	0.05	1295	0.51	0.31	39	38	-	554	0	1000	0	-	-	-	-
D_Balka3	111	0.03	827	0.50	0.33	-	-	-	554	0	1000	0	-	-	-	-
B_Lakhaoti18	112	30.32	2408	20.15	1.86	-	-	0.9818	555	39	564	2	134	135	-	-
D_Sarawa1	113	1.50	4968	3.50	0.77	913	897	-	555	2	562	2	114	115	-	-
M_Khalsia	114	0.16	3967	0.75	0.55	131	129	-	562	0	1000	0	-	-	-	-

Segment Name	Numeric Identity	Discharge Capacity (cumec)	Length (m)	Bed Width (m)	Water Depth (m)	Design PPA (ha)	Calculated PPA (ha) at Head of Dist./Minor	Conveyance Efficiency	Head Node Number	Number of d/s Nodes	Tail Node Number	Number of Immediately d/s Segments	Numeric Identity of Immediately d/s Segments			
Col. 1	Col. 2	Col. 3	Col. 4	Col. 5	Col. 6	Col. 7	Col. 8	Col. 9	Col. 10	Col. 11	Col. 12	Col. 13	C.14	C.15	C.16	C.17
D_Sarawa2	115	1.10	2132	2.96	0.67	-	-	-	562	1	563	2	116	117	-	-
D_Sarawa3	116	0.81	17356	2.30	0.63	-	-	-	563	0	1000	0	-	-	-	-
M_Taiyabpur	117	0.20	5866	0.75	0.54	164	170	-	563	0	1000	0	-	-	-	-
D_Debai1	118	3.60	9182	5.50	1.08	1473	1443	0.9587	555	6	556	2	119	120	-	-
D_Debai2	119	2.89	1650	5.45	0.87	-	-	0.9237	556	5	557	2	121	122	-	-
M_Bhaipur	120	0.27	3354	1.37	0.64	202	203	-	556	0	1000	0	-	-	-	-
M_Chakla	121	0.12	2776	1.10	0.38	90	89	-	557	0	1000	0	-	-	-	-
D_Debai3	122	2.69	6310	5.35	0.83	-	-	0.9237	557	4	558	4	123	124	125	126
M_Rajpura	123	0.20	5001	1.60	0.46	170	177	-	558	0	1000	0	-	-	-	-
D_Debai4	124	1.72	4708	4.11	0.69	-	-	0.9237	558	3	559	2	127	128	-	-
M_Khelia	125	0.30	4356	1.40	0.52	230	232	-	558	0	1000	0	-	-	-	-
M_Bibiyana	126	0.17	4721	1.22	0.43	130	128	-	558	0	1000	0	-	-	-	-
D_Debai5	127	1.29	3484	3.69	0.58	-	-	0.9458	559	2	560	2	129	130	-	-
M_Dabka	128	0.20	3756	1.60	0.46	174	170	-	559	0	1000	0	-	-	-	-
D_Debai6	129	0.93	3082	3.07	0.50	-	-	0.9568	560	1	561	3	131	132	133	-
M_Khudadia	130	0.20	4470	1.60	0.43	165	163	-	560	0	1000	0	-	-	-	-
M_Daulatpur	131	0.31	7651	2.37	0.55	212	215	-	561	0	1000	0	-	-	-	-
D_Debai7	132	0.26	5434	1.00	0.43	-	-	0.9454	561	0	1000	0	-	-	-	-
M_Icchawari	133	0.21	4127	2.00	0.40	173	163	-	561	0	1000	0	-	-	-	-
B_Lakhaoti19	134	29.41	4793	19.76	1.84	-	-	0.9818	564	38	565	2	136	137	-	-
M_Chandok	135	0.50	9658	2.50	0.52	407	398	-	564	0	1000	0	-	-	-	-
B_Lakhaoti20	136	28.39	4638	19.60	1.79	-	-	0.9621	565	37	566	3	138	139	140	-
M_Surkhuru	137	0.20	4980	1.20	0.48	180	180	-	565	0	1000	0	-	-	-	-
B_Lakhaoti21	138	26.96	7460	19.04	1.75	-	-	0.9621	566	36	567	3	141	142	147	-
M_Hazaratpur	139	0.50	10375	2.28	0.53	405	404	-	566	0	1000	0	-	-	-	-
M_Rasulpur	140	0.14	4311	1.37	0.33	124	129	-	566	0	1000	0	-	-	-	-
B_Lakhaoti22	141	23.50	3239	17.29	1.68	-	-	0.9621	567	33	570	3	148	149	150	-
D_Ahmedgarh1	142	1.90	828	4.50	0.75	933	860	-	567	2	568	2	143	146	-	-
D_Ahmedgarh2	143	1.74	7303	4.30	0.72	-	-	-	568	1	569	2	144	145	-	-
M_Pitampur	144	0.18	2795	1.52	0.40	135	126	-	569	0	1000	0	-	-	-	-
D_Ahmedgarh3	145	0.94	7711	3.39	0.51	-	-	-	569	0	1000	0	-	-	-	-
M_Rahmanpur	146	0.07	1589	0.55	0.40	52	52	-	568	0	1000	0	-	-	-	-
M_Domla	147	0.28	4443	1.52	0.55	259	252	-	567	0	1000	0	-	-	-	-
B_Lakhaoti23	148	22.53	5130	16.98	1.64	-	-	0.9621	570	32	571	3	151	152	155	-
M_Saidgarhi	149	0.27	6863	2.00	0.46	217	224	-	570	0	1000	0	-	-	-	-
M_Muradpur	150	0.14	4444	1.52	0.38	144	142	-	570	0	1000	0	-	-	-	-
B_Lakhaoti24	151	20.66	3234	15.96	1.60	-	-	0.9621	571	30	573	2	156	157	-	-
D_Salabad1	152	0.65	1189	2.60	0.60	450	271	-	571	1	572	2	153	154	-	-
D_Salabad2	153	0.31	5990	1.35	0.55	-	-	-	572	0	1000	0	-	-	-	-
M_Chaudera	154	0.28	7422	1.90	0.50	250	251	-	572	0	1000	0	-	-	-	-
M_Mohamadpur	155	0.34	6615	2.00	0.50	260	257	-	571	0	1000	0	-	-	-	-
B_Lakhaoti25	156	19.82	1391	15.70	1.56	-	-	0.9621	573	29	574	2	158	193	-	-
M_Danpur	157	0.31	6118	2.00	0.45	223	225	-	573	0	1000	0	-	-	-	-
D_Atrauli1	158	13.03	2642	12.19	1.54	1746	1731	0.9846	574	16	575	2	159	162	-	-
M_Pandrawal1	159	0.33	3093	1.52	0.55	97	125	-	575	1	576	2	160	161	-	-
M_Pandrawal2	160	0.07	2199	0.51	0.33	-	-	-	576	0	1000	0	-	-	-	-
M_Mohiddinpur	161	0.17	4910	0.92	0.52	135	136	-	576	0	1000	0	-	-	-	-
D_Atrauli2	162	12.57	5579	11.50	1.38	-	-	0.9846	575	14	577	4	163	164	165	166
M_Kasimpur	163	0.38	6976	2.13	0.76	568	326	-	577	0	1000	0	-	-	-	-
D_Izzatpur1	164	2.58	11407	7.30	0.90	1374	1374	-	577	2	578	2	167	170	-	-
D_Atrauli3	165	8.87	4997	10.20	1.30	-	-	0.9997	577	11	580	2	171	172	-	-
M_Suratgarh	166	0.47	4993	1.52	0.66	378	157	-	577	0	1000	0	-	-	-	-
M_Rahmapur1	167	0.96	4101	2.65	0.76	570	632	-	578	1	579	2	168	169	-	-
M_Chandoli	168	0.14	2945	0.91	0.46	115	115	-	579	0	1000	0	-	-	-	-
M_Rahmapur2	169	0.51	6615	1.83	0.58	-	-	-	579	0	1000	0	-	-	-	-
D_Izzatpur2	170	0.87	12958	3.60	0.62	-	-	-	578	0	1000	0	-	-	-	-
D_Atrauli4	171	8.19	3644	9.00	1.28	-	-	0.9793	580	10	581	2	173	174	-	-
M_Harchandpur	172	0.43	6493	1.98	0.53	351	340	-	580	0	1000	0	-	-	-	-
D_Atrauli5	173	7.71	3014	8.00	1.24	-	-	0.9793	581	9	582	2	175	176	-	-
M_Gijrauli	174	0.31	4886	1.52	0.52	177	164	-	581	0	1000	0	-	-	-	-
D_Atrauli6	175	7.24	1543	7.50	1.26	-	-	0.9989	582	8	583	2	177	178	-	-
M_Boolapur	176	0.33	5585	1.83	0.47	246	245	-	582	0	1000	0	-	-	-	-
D_Barla1	177	1.64	11099	6.00	0.90	1144	1131	-	583	2	584	2	179	180	-	-
D_Atrauli7	178	5.52	4496	6.70	1.15	-	-	0.9759	583	5	586	2	183	186	-	-
M_Azadpur	179	0.28	6311	1.50	0.50	236	237	-	584	0	1000	0	-	-	-	-
D_Barla2	180	0.69	3097	4.52	0.50	-	-	-	584	1	585	2	181	182	-	-
D_Barla3	181	0.15	2406	1.23	0.39	-	-	-	585	0	1000	0	-	-	-	-
M_Datawali	182	0.35	3879	1.52	0.55	208	166	-	585	0	1000	0	-	-	-	-
D_Atrauli8	183	1.48	1047	5.00	0.80	-	-	0.9192	586	1	587	2	184	185	-	-
M_Mohkampur	184	0.84	11688	2.59	0.70	653	642	-	587	0	1000	0	-	-	-	-
D_Atrauli9	185	0.60	12504	2.25	0.55	-	-	0.9192	587	0	1000	0	-	-	-	-
D_Chharra1	186	3.82	8353	7.32	0.97	1348	1326	0.9666	586	3	588	2	187	192	-	-
D_Chharra2	187	2.43	8171	4.57	0.66	-	-	0.9522	588	2	589	2	188	191	-	-
D_Chharra3	188	1.14	7358	1.52	0.43	-	-	0.9439	589	1	590	2	189	190	-	-
D_Chharra4	189	0.13	1009	1.22	0.30	-	-	0.9863	590	0	1000	0	-	-	-	-
M_Kanobi	190	0.08	2201	0.91	0.33	68	69	-	590	0	1000	0	-	-	-	-
M_Makhdumpur	191	0.26	2766	1.52	0.46	96	106	-	589	0	1000	0	-	-	-	-
M_Bhamori	192	0.34	6371	1.52	0.57	271	219	-	588	0	1000	0	-	-	-	-
D_Dharampur1	193	6.23	7436	7.31	1.28	1654	1636	0.9826	574	12	591	2	194	195	-	-
D_Dharampur2	194	5.58	1611	6.40	1.23	-	-	0.9784	591	11	592	2	196	197	-	-
M_Sherpur	195	0.16	4197	1.83	0.33	121	117	-	591	0	1000	0	-	-	-	-
D_Dharampur3	196	5.25	1388	6.10	1.10	-	-	0.9728	592	10	593	3	198	199	202	-
M_Udaipur	197	0.23	4426	1.83	0.40	182	181	-	592	0	1000	0	-	-	-	-
M_Jadonpur1	198	0.65	2962	1.83	0.70	329	259	-	593	1	594	2	200	201	-	-
M_Kharakwari	199	0.17	4155	0.91	0.46	126	126	-	593	0	1000	0	-	-	-	-

Segment Name	Numeric Identity	Discharge Capacity (cumec)	Length (m)	Bed Width (m)	Water Depth (m)	Design PPA (ha)	Calculated PPA (ha) at Head of Dist./Minor	Conveyance Efficiency	Head Node Number	Number of d/s Nodes	Tail Node Number	Number of Immediately d/s Segments	Numeric Identity of Immediately d/s Segments			
Col. 1	Col. 2	Col. 3	Col. 4	Col. 5	Col. 6	Col. 7	Col. 8	Col. 9	Col. 10	Col. 11	Col. 12	Col. 13	C.14	C.15	C.16	C.17
M_Jadonpur2	200	0.23	3495	0.87	0.52	-	-	-	594	0	1000	0	-	-	-	-
M_Dalpatpur	201	0.23	5057	0.91	0.61	191	191	-	594	0	1000	0	-	-	-	-
D_Dharampur4	202	4.33	4188	5.00	0.96	-	-	0.9597	593	8	595	2	203	204	-	-
D_Dharampur5	203	3.75	3150	4.00	0.82	-	-	0.9597	595	7	596	2	205	214	-	-
M_Baijla	204	0.31	5226	1.95	0.46	255	254	-	595	0	1000	0	-	-	-	-
D_Dharampur6	205	2.18	2667	3.20	0.80	-	-	0.9604	596	4	599	2	206	207	-	-
M_Bahal	206	0.33	3440	1.52	0.55	264	168	-	599	0	1000	0	-	-	-	-
D_Dharampur7	207	1.68	4004	2.60	0.70	-	-	0.9541	599	3	600	2	208	211	-	-
D_Dharampur8	208	0.93	2828	1.83	0.55	-	-	0.9351	600	1	602	2	209	210	-	-
M_Singhpur	209	0.31	2424	1.83	0.46	230	92	-	602	0	1000	0	-	-	-	-
D_Dharampur9	210	0.44	6621	0.91	0.38	-	-	0.9351	602	0	1000	0	-	-	-	-
M_Bhaupur1	211	0.48	5672	2.44	0.55	361	361	-	600	1	601	2	212	213	-	-
M_Bhaupur2	212	0.07	1544	0.56	0.35	-	-	-	601	0	1000	0	-	-	-	-
M_Benupur	213	0.16	1741	0.91	0.49	115	116	-	601	0	1000	0	-	-	-	-
D_Lohgarh1	214	1.36	6050	3.96	0.67	624	629	-	596	2	597	2	215	218	-	-
D_Lohgarh2	215	0.62	3023	1.52	0.46	-	-	-	597	1	598	2	216	217	-	-
D_Lohgarh3	216	0.27	4194	0.61	0.40	-	-	-	598	0	1000	0	-	-	-	-
M_Tandoli	217	0.16	3559	0.91	0.47	120	123	-	598	0	1000	0	-	-	-	-
M_Nagar	218	0.35	4885	1.68	0.52	293	296	-	597	0	1000	0	-	-	-	-

From the table, it is seen that the calculated PPA in most of the distributaries and minors match quite close with the design PPA which signifies that the layout of irrigable command of various canal segments lie very close to the one adopted in field. As seen from the table, suffixes 1, 2, 3 . . . have been added to the names of a branch or distributary (having more than one segment) to differentiate the names of different canal segments. Columns from number 10 to number 17 define the connectivity of various segments in the overall canal system. Numerals above 500 represent the numerical identity of different nodes in the system. A node with numerical identity of 1000 signifies that no d/s segment exists below the node.

* * *

CHAPTER – 5
ANALYSIS AND RESULTS

5.1 GENERAL

A water allocation model for conjunctive utilization of water resources in a command area has been developed and discussed in the previous chapters. The model uses spatial information of the irrigation demands and groundwater depth in the command area. In addition, it requires the layout of canal system in the command, irrigable areas of different canal segments and various characteristics of the canal system. For the model application, the database generation for the Lakhaoti command has been discussed in Chapter-4.

The objective of allocation model is to simulate the weekly operation of a canal system for satisfying water demands of existing crops giving particular emphasis on the spatial variation of canal system characteristics, irrigation demands, and groundwater conditions in the command area. Using the model, different policies of canal water allocation can be visualized. Results of allocation can be generated in the form of maps and table. The tabular results of the model can be imported in a GIS and various output attributes (such as running/non-running canals, discharge, run-time, canal water demand, groundwater pumping requirement, seepage losses, downstream network demands etc.) can be visualized in map form for easy comprehension.

5.2 MODEL RESULTS FOR A WEEK

The potential use of allocation model is presented here through application study of Lakhaoti command for the sample week 32 (July 23 – 29). Water application efficiency of 70% and field channel efficiency of 80% has been assumed for all canal segments. Since Lakhaoti command depends on groundwater for irrigation in Rabi season, sufficient pumping wells with average pump capacity of 3 horse power (HP) and power supply availability of 84 hours per week have been assumed. Taking initial moisture content at field capacity, the aggregated volume of initial moisture in the effective soil depth (root zone) in the Lakhaoti command comes out to be 226.41 Mm^3 and rainfall input in the command during the week is 58.89 Mm^3.

Using the layout of irrigable command areas and canal system details, grid-wise irrigation demands (as worked out by DEMAND model) are transferred to canal segments using specified field channel efficiency and water application efficiency and total demands (in terms of discharge and runtime) in all canal segments are worked out. Total canal water demands at the network head comes out to be 58.44 Mm^3. Table – 5.1 shows the initial calculations of irrigation demands, seepage losses, groundwater potential, required discharge, run-time, fill-time, and groundwater requirement for various canal segments. In these computations, canal capacity constraint (of intermediate segments) and canal water availability constraint are not considered.

Column-1 of the table shows the identity of canal segments while Column-2 shows the identity of segment located upstream of the current segment, thus illustrating the connectivity of canal network. In Column-1, the symbol ‘F’ along with the segment identity represents that the canal segment is free, i.e. it does not have any downstream connecting segment. Column–4 shows the groundwater availability in a canal segment, which depends on average groundwater depth (Column-3), number of pumping wells, average capacity of pumps, and duration of power supply. Column-5 shows the irrigation demands from the irrigable area of canal segment while Column-6 presents the irrigation demands that can be met from the existing canal capacity. It is seen that a number of segments (segment 3, 8, 17 … etc.) have capacity constraint in meeting full irrigation demands. Column-7 presents the water demands in a canal segment because of the downstream canal network while Column-8 shows the seepage loss in a canal segment which depends on the conveyance efficiency, wetted perimeter, discharge, and run-time of the segment. Total canal water demand (Column-9) is the sum of Column-6 to Column-8 and represents the total canal water demands in the segment including its seepage losses.

Column-10 presents the discharge required to meet total demands while Column-11 represents the required water depth (used for finding wetted perimeter and canal seepage). Column-12 represents the fill-time of a canal segment, which depends on the length and flow velocity in those canal segments that are not running at the end of previous week. Column-13 shows the required run-time, which is a function of total demands, discharge capacity, and run-time of downstream network. Column-14 represents the groundwater demands in canal segments which arise when full irrigation demands can not be met in the possible run-time during the week due to canal capacity constraint.

For free segments with groundwater demand, there is no other choice but to pump estimated amount of groundwater for meeting full demands. For intermediate segments with groundwater demands (like segments 6, 10, 16, 19 … etc.), it is possible to curtail the demands of downstream network so that the canal capacity constraint at intermediate segments is satisfied.

5.2.1 Computations after satisfying capacity constraint

As discussed in Chapter-4, some canal segments are selected for demand curtailment for satisfying the capacity constraint of the intermediate segments. The criterion for selection of canal segments is based on the depth of groundwater. D/s of the intermediate segment with capacity constraint, free segments with least depth of pumping are identified and their demands are assigned to be met from groundwater instead of canal water. The process is repeated iteratively till the capacity constraint is satisfied. Table - 5.2 shows the intermediate segments with capacity constraint and the affected downstream segments whose demands are curtailed to satisfy the capacity constraints.

It needs to be mentioned here that only free segments are selected for demand curtailment. However, if the demands of all the free segments below an intermediate segment

Table – 5.1
Initial computations of canal operation (without capacity and availability constraint)

Seg. Iden.	U/s Seg. Iden.	Average GW Depth (m)	GW Potential (Ham)	Local Irrigation Demand (Ham)	Canal Water Demand (Ham)	Total D/s Demand (Ham)	Canal Seepage Loss (Ham)	Total Canal Water Demand (Ham)	Required Discharge (Cumec)	Water Depth (m)	Fill Time (Hour)	Run Time (Hour)	Total GW Demand (Ham)
Col. 1	Col. 2	Col. 3	Col. 4	Col. 5	Col. 6	Col. 7	Col. 8	Col. 9	Col. 10	Col. 11	Col. 12	Col. 13	Col. 14
1	0	3.50	1749.31	4.75	4.75	3760.07	18.54	3783.35	62.56	2.25	0.00	168.00	0.00
2	1	4.14	1477.44	4.30	4.30	3727.97	18.38	3750.65	62.32	2.24	0.83	167.17	0.00
3F	1	3.51	1745.34	8.42	8.42	0.00	0.99	9.42	0.18	0.50	0.83	145.46	0.00
4	2	5.08	1204.98	2.10	2.10	3569.87	28.81	3600.78	59.98	2.22	1.24	166.76	0.00
5	2	5.03	1216.70	3.80	3.80	112.09	2.58	118.47	2.01	0.78	1.24	164.05	0.00
6	5	7.37	830.50	34.44	34.44	56.52	8.36	99.32	1.70	0.75	2.93	162.37	0.00
7F	5	6.10	1004.19	11.79	11.79	0.00	0.98	12.77	0.30	0.55	2.93	119.30	0.00
8F	6	7.39	828.33	11.58	11.58	0.00	2.16	13.74	0.25	0.55	9.06	152.59	0.00
9	6	8.96	683.17	7.42	7.42	33.69	1.67	42.78	0.76	0.48	9.06	156.23	0.00
10	9	8.54	717.24	11.31	11.31	3.39	0.89	15.59	0.28	0.55	10.63	154.66	0.00
11F	10	7.83	782.26	0.62	0.62	0.00	0.08	0.70	0.10	0.43	12.56	19.80	0.00
12F	10	8.43	726.07	2.18	2.18	0.00	0.51	2.70	0.09	0.35	12.56	83.14	0.00
13F	9	9.70	631.44	15.27	15.27	0.00	2.83	18.10	0.50	0.48	10.63	100.87	0.00
14F	2	4.57	1339.11	7.43	7.43	0.00	1.29	8.72	0.22	0.50	1.24	110.12	0.00
15	4	5.94	1030.91	14.15	14.15	3486.97	38.94	3540.06	59.34	2.19	2.29	165.71	0.00
16	4	5.51	1111.19	12.69	12.69	14.89	2.30	29.81	0.50	0.60	2.29	165.71	0.06
17F	16	4.80	1276.88	11.47	11.47	0.00	2.12	13.59	0.25	0.50	5.30	150.96	0.00
18F	16	4.77	1283.22	1.12	1.12	0.00	0.18	1.30	0.10	0.42	5.30	36.21	0.00
19	15	5.68	1078.21	8.04	8.04	3428.10	38.22	3474.36	58.55	2.16	3.17	164.83	0.00
20F	15	7.58	807.73	9.96	9.96	0.00	2.65	12.61	0.50	0.60	3.17	70.08	0.00
21	19	6.80	900.12	29.53	29.53	3354.97	37.64	3422.14	57.93	2.15	3.90	164.10	0.00
22F	19	5.91	1035.57	5.30	5.30	0.00	0.66	5.96	0.12	0.37	3.90	137.92	0.00
23	21	8.22	745.15	36.87	36.87	3148.47	29.85	3209.78	54.80	2.11	5.29	162.71	5.40
24	21	8.47	722.89	26.45	26.45	114.16	4.57	145.18	2.48	0.98	5.29	162.71	0.00
25	24	8.91	687.29	7.96	7.96	93.25	0.88	102.08	1.77	0.79	7.90	160.10	0.00
26F	24	9.26	661.56	26.29	10.55	0.00	1.52	12.08	0.21	0.40	7.90	160.10	15.74
27	25	9.23	663.74	28.56	28.56	55.87	3.31	87.73	1.53	0.72	8.45	159.55	0.00
28F	25	9.15	669.36	7.53	4.36	0.00	1.15	5.51	0.10	0.38	8.45	159.55	3.16
29	27	11.32	541.05	7.25	7.25	41.11	0.99	49.35	0.87	0.50	10.63	157.37	0.00
30F	27	11.35	539.31	5.65	5.65	0.00	0.86	6.51	0.14	0.32	10.63	129.36	0.00
31F	29	11.68	524.15	23.93	23.93	0.00	3.10	27.03	0.90	0.62	11.38	83.87	0.00
32F	29	10.54	581.00	14.47	12.78	0.00	1.30	14.08	0.25	0.50	11.38	156.62	1.69
33	23	9.14	669.71	9.59	9.59	2633.31	40.09	2654.76	45.68	2.07	6.56	161.44	28.23
34	23	9.25	661.78	23.78	23.78	479.86	26.86	493.71	8.50	1.55	6.56	161.44	36.79
35	34	9.34	655.39	37.17	37.17	457.49	25.89	476.00	8.23	1.50	7.38	160.62	44.56
36F	34	9.18	667.11	10.98	3.17	0.00	0.70	3.86	0.07	0.35	7.38	160.62	7.82
37	35	9.20	665.39	29.05	29.05	392.59	22.70	417.34	7.27	1.42	8.48	159.52	27.00
38	35	9.47	646.40	11.38	11.38	36.72	0.75	40.15	0.70	0.67	8.48	159.52	8.70
39F	38	12.00	510.16	46.72	22.58	0.00	5.59	28.17	0.49	0.63	9.37	158.63	24.14
40F	38	10.18	601.69	20.68	7.34	0.00	1.21	8.55	0.15	0.42	9.37	158.63	13.33
41	37	11.71	522.96	44.51	44.51	352.01	20.77	381.80	6.71	1.32	10.00	158.00	35.50
42F	37	11.24	544.60	14.55	8.41	0.00	2.38	10.79	0.19	0.38	10.00	157.99	6.14
43	41	13.35	458.75	42.31	42.31	277.13	18.05	331.80	5.90	1.19	11.86	156.14	5.70
44F	41	13.26	461.82	32.53	17.65	0.00	2.56	20.21	0.36	0.55	11.86	156.14	14.88
45	43	14.04	436.09	10.07	10.07	253.71	0.58	264.36	4.75	1.08	13.54	154.46	0.00
46F	43	13.97	438.48	23.70	10.44	0.00	2.33	12.77	0.23	0.46	13.54	154.46	13.25
47	45	13.67	447.81	32.88	32.88	173.98	0.46	207.31	3.74	1.04	14.12	153.88	0.00
48F	45	14.58	419.92	38.32	38.32	0.00	8.08	46.40	0.90	0.66	14.12	143.36	0.00
49	47	13.97	438.32	8.95	8.95	150.90	0.35	160.20	2.94	0.85	16.89	151.11	0.00
50F	47	13.59	450.76	11.54	11.54	0.00	2.23	13.78	0.30	0.52	16.89	129.31	0.00
51	49	12.49	490.11	7.61	7.61	139.17	0.32	147.10	2.72	0.78	17.94	150.06	0.00
52F	49	11.59	528.16	2.80	2.80	0.00	1.00	3.80	0.12	0.36	17.94	86.25	0.00
53	51	11.93	513.45	7.69	7.69	107.48	0.25	115.42	2.15	0.72	18.77	149.23	0.00
54	51	11.40	537.24	3.69	3.69	18.42	1.63	23.74	0.44	0.61	18.77	149.23	0.00
55F	54	10.13	604.71	14.00	9.59	0.00	5.39	14.99	0.29	0.55	22.00	146.00	4.41
56F	54	11.25	544.47	2.85	2.85	0.00	0.59	3.44	0.11	0.34	22.00	86.91	0.00
57	53	10.89	562.20	43.65	43.65	47.84	0.15	86.09	1.61	0.66	19.58	148.42	5.56
58F	53	10.79	567.74	18.11	17.28	0.00	4.12	21.39	0.40	0.60	19.58	148.42	0.84
59	57	12.83	477.43	15.01	15.01	30.67	0.41	42.61	0.81	0.47	22.48	145.52	3.49
60F	57	12.14	504.25	11.31	4.21	0.00	1.02	5.24	0.10	0.36	22.48	145.52	7.10
61F	59	13.30	460.51	34.22	18.29	0.00	0.43	18.72	0.36	0.40	23.41	144.59	15.93
62F	59	13.78	444.42	34.10	9.72	0.00	2.23	11.95	0.23	0.54	23.41	144.59	24.38
63	33	8.67	706.38	20.24	20.24	2489.03	38.09	2522.69	43.54	2.06	7.05	160.95	24.67
64	33	8.10	756.36	48.94	48.94	94.36	2.96	110.62	1.91	1.05	7.05	160.95	35.63
65F	64	8.25	742.10	11.28	4.22	0.00	0.62	4.84	0.08	0.40	9.21	158.79	7.06
66	64	8.75	699.68	23.84	23.84	73.75	2.58	89.52	1.57	0.87	9.21	158.79	10.66
67	66	10.96	558.86	1.57	1.57	59.52	0.59	61.68	1.09	0.62	11.14	156.86	0.00
68F	66	11.10	551.81	20.04	10.54	0.00	1.53	12.07	0.21	0.60	11.14	156.86	9.50
69F	67	11.41	536.86	10.33	8.70	0.00	0.87	9.57	0.17	0.45	11.60	156.40	1.63
70	67	13.00	471.20	8.00	8.00	40.49	0.85	46.01	0.82	0.57	11.60	156.40	3.33
71F	67	12.74	480.55	4.03	3.37	0.00	0.56	3.94	0.07	0.40	11.60	156.40	0.66

Seg. Iden.	U/s Seg. Iden.	Average GW Depth (m)	GW Potential (Ham)	Local Irrigation Demand (Ham)	Canal Water Demand (Ham)	Total D/s Demand (Ham)	Canal Seepage Loss (Ham)	Total Canal Water Demand (Ham)	Required Discharge (Cumec)	Water Depth (m)	Fill Time (Hour)	Run Time (Hour)	Total GW Demand (Ham)
Col. 1	Col. 2	Col. 3	Col. 4	Col. 5	Col. 6	Col. 7	Col. 8	Col. 9	Col. 10	Col. 11	Col. 12	Col. 13	Col. 14
72F	70	13.05	469.25	69.13	23.34	0.00	4.65	27.99	0.50	0.58	12.35	155.65	45.79
73F	70	14.56	420.68	17.41	11.38	0.00	1.12	12.50	0.22	0.50	12.35	155.65	6.02
74	63	8.28	739.40	17.29	17.29	2453.58	37.40	2477.00	42.95	2.04	7.79	160.21	31.28
75F	63	8.75	699.66	11.43	11.43	0.00	0.60	12.03	0.23	0.35	7.79	143.21	0.00
76	74	9.30	658.38	23.52	23.52	2414.99	37.00	2450.13	42.63	2.03	8.33	159.67	25.38
77F	74	8.61	711.18	10.92	3.01	0.00	0.44	3.45	0.06	0.35	8.33	159.66	7.90
78	76	10.30	594.66	9.83	9.83	2404.86	36.40	2410.58	42.15	2.01	9.15	158.85	40.51
79F	76	10.74	570.01	8.73	3.75	0.00	0.66	4.40	0.08	0.35	9.15	158.85	4.98
80F	78	11.25	544.56	12.10	5.05	0.00	0.59	5.64	0.10	0.40	9.53	158.47	7.05
81	78	11.90	514.52	24.22	24.22	2324.45	35.98	2383.07	41.77	2.00	9.53	158.47	1.58
82	78	10.88	562.78	1.99	1.99	15.02	0.21	16.15	0.28	0.50	9.53	158.47	1.07
83F	82	11.34	539.81	22.38	9.46	0.00	1.99	11.44	0.20	0.45	9.93	158.07	12.92
84F	82	10.61	577.27	6.75	3.20	0.00	0.38	3.58	0.06	0.35	9.93	158.06	3.55
85	81	10.99	557.30	56.02	56.02	2251.04	24.41	2302.52	40.73	1.97	10.98	157.02	28.95
86	81	12.90	474.65	8.53	8.53	6.93	0.70	9.92	0.18	0.53	10.98	157.02	6.24
87F	86	13.90	440.58	3.74	3.36	0.00	0.72	4.08	0.07	0.44	12.89	155.10	0.38
88F	86	13.79	444.04	5.80	2.37	0.00	0.47	2.85	0.05	0.30	12.89	155.11	3.43
89F	81	11.11	551.08	20.97	9.07	0.00	2.93	12.00	0.21	0.40	10.98	157.02	11.90
90	85	12.60	485.89	26.37	26.37	2079.55	22.30	2103.67	37.51	1.94	12.22	155.78	24.55
91	85	10.27	596.13	4.12	4.12	145.36	5.45	147.37	2.63	1.02	12.22	155.78	7.56
92	91	12.37	495.19	13.16	13.16	25.36	1.21	30.74	0.55	0.58	12.58	155.42	9.00
93F	92	13.13	466.53	19.69	8.90	0.00	1.56	10.46	0.19	0.49	14.17	153.83	10.80
94F	92	12.23	500.50	43.82	11.98	0.00	2.92	14.90	0.27	0.50	14.17	153.83	31.84
95	91	10.26	596.78	49.01	49.01	99.60	4.24	114.63	2.05	1.00	12.58	155.42	38.23
96	95	11.35	539.31	11.42	11.42	57.86	2.26	61.20	1.11	0.78	15.50	152.50	10.34
97	95	11.97	511.39	39.35	39.35	22.94	3.16	38.40	0.70	0.65	15.50	152.50	27.06
98F	97	11.53	530.97	14.32	5.43	0.00	0.63	6.06	0.11	0.40	19.35	148.65	8.89
99F	97	12.05	508.32	16.03	16.03	0.00	0.86	16.88	0.32	0.60	19.35	146.56	0.00
100	96	10.87	563.13	14.09	14.09	23.30	0.75	32.66	0.60	0.73	16.35	151.65	5.47
101F	96	12.83	477.21	42.10	20.21	0.00	4.99	25.20	0.46	0.52	16.35	151.65	21.90
102F	100	11.92	513.69	15.90	15.90	0.00	1.42	17.32	0.33	0.60	18.60	144.85	0.00
103F	100	11.26	543.62	5.11	5.11	0.00	0.87	5.98	0.13	0.42	18.60	127.56	0.00
104	90	15.85	386.42	7.74	7.74	2055.42	21.92	2067.85	37.01	1.92	12.82	155.18	17.24
105F	90	14.74	415.52	22.85	9.69	0.00	2.02	11.71	0.21	0.43	12.82	155.18	13.16
106	104	14.20	431.10	73.96	73.96	1949.38	36.91	2028.11	36.38	1.91	13.13	154.87	32.15
107	104	15.41	397.40	29.37	29.37	18.23	2.72	27.31	0.49	0.58	13.13	154.87	23.01
108F	107	13.97	438.33	10.81	7.55	0.00	1.36	8.92	0.16	0.40	17.21	150.79	3.26
109	107	13.80	443.82	13.30	13.30	4.17	1.06	9.32	0.17	0.42	17.21	150.79	9.21
110F	109	13.56	451.47	4.43	2.46	0.00	0.30	2.76	0.05	0.31	19.83	148.17	1.97
111F	109	13.42	456.31	2.06	1.21	0.00	0.19	1.40	0.03	0.33	19.83	148.16	0.85
112	106	12.37	494.85	27.61	27.61	1636.94	30.38	1669.01	30.32	1.86	15.12	152.88	25.92
113	106	12.93	473.75	56.60	56.60	68.49	3.60	82.45	1.50	0.77	15.12	152.88	46.24
114F	113	11.93	513.21	15.03	7.60	0.00	1.28	8.88	0.16	0.55	17.87	150.13	7.43
115	113	11.53	531.13	14.53	14.53	53.84	1.36	59.61	1.10	0.67	17.87	150.13	10.12
116F	115	11.96	512.13	59.46	33.68	0.00	9.53	43.21	0.81	0.63	19.06	148.94	25.78
117F	115	9.73	629.04	14.85	8.76	0.00	1.86	10.63	0.20	0.54	19.06	148.94	6.09
118	106	11.79	519.41	76.28	76.28	168.45	8.17	197.93	3.60	1.08	15.12	152.88	54.98
119	118	10.57	579.10	14.16	14.16	149.04	11.76	154.10	2.89	0.87	19.74	148.26	20.86
120F	118	11.07	552.95	24.71	12.93	0.00	1.43	14.36	0.27	0.64	19.74	148.26	11.78
121F	119	10.24	598.24	12.08	5.36	0.00	0.96	6.31	0.12	0.38	20.56	147.44	6.73
122	119	10.13	604.41	43.08	43.08	124.00	10.89	142.73	2.69	0.83	20.56	147.44	35.24
123F	122	10.22	599.01	9.06	8.19	0.00	2.10	10.30	0.20	0.46	23.67	144.32	0.86
124	122	9.76	627.29	36.48	36.48	76.31	6.81	89.28	1.72	0.69	23.67	144.33	30.32
125F	122	9.65	634.65	42.06	13.85	0.00	1.75	15.60	0.30	0.52	23.67	144.33	28.22
126F	122	10.13	604.41	10.53	7.11	0.00	1.71	8.83	0.17	0.43	23.67	144.32	3.42
127	124	8.92	686.21	22.57	22.57	43.44	3.59	66.18	1.29	0.58	26.01	141.99	3.43
128F	124	10.79	567.33	8.91	8.58	0.00	1.55	10.13	0.20	0.46	26.01	141.99	0.33
129	127	12.79	478.87	6.04	6.04	25.95	1.44	33.43	0.93	0.50	27.74	100.06	0.00
130F	127	8.41	728.07	9.31	8.20	0.00	1.81	10.01	0.20	0.43	27.74	140.26	1.12
131F	129	8.78	697.78	8.28	8.28	0.00	2.77	11.05	0.31	0.55	29.27	98.54	0.00
132F	129	11.48	533.29	8.41	8.41	0.00	0.49	8.89	0.26	0.43	29.27	94.80	0.00
133F	129	14.33	427.45	4.95	4.95	0.00	1.06	6.01	0.21	0.40	29.27	79.62	0.00
134	112	10.47	584.69	74.99	74.99	1546.92	29.30	1609.66	29.41	1.84	15.98	152.02	41.54
135F	112	11.56	529.68	56.50	21.75	0.00	5.52	27.27	0.50	0.52	15.98	152.02	34.74
136	134	9.53	642.31	54.26	54.26	1476.60	58.22	1536.19	28.39	1.79	17.70	150.30	52.89
137F	134	10.61	577.09	23.76	8.82	0.00	1.90	10.72	0.20	0.48	17.70	150.30	14.93
138	136	9.75	628.05	110.92	110.92	1320.93	54.67	1442.36	26.96	1.75	19.37	148.63	44.16
139F	136	10.35	591.39	44.48	21.14	0.00	5.53	26.67	0.50	0.53	19.37	148.63	23.34
140F	136	8.16	750.20	23.81	5.93	0.00	1.64	7.58	0.14	0.33	19.37	148.63	17.88
141	138	12.52	489.15	34.62	34.62	1195.68	46.79	1234.55	23.50	1.68	22.05	145.95	42.54
142	138	12.18	502.95	7.10	7.10	63.77	0.64	71.51	1.36	0.58	22.05	145.95	0.00
143	142	14.44	424.18	31.62	31.62	24.74	3.71	60.06	1.74	0.72	22.49	96.11	0.00
144F	143	15.20	402.95	4.12	4.12	0.00	0.56	4.67	0.18	0.40	26.41	71.60	0.00
145F	143	13.87	441.55	18.02	18.02	0.00	2.05	20.06	0.94	0.51	26.41	59.57	0.00

Seg. Iden.	U/s Seg. Iden.	Average GW Depth (m)	GW Potential (Ham)	Local Irrigation Demand (Ham)	Canal Water Demand (Ham)	Total D/s Demand (Ham)	Canal Seepage Loss (Ham)	Total Canal Water Demand (Ham)	Required Discharge (Cumec)	Water Depth (m)	Fill Time (Hour)	Run Time (Hour)	Total GW Demand (Ham)
Col. 1	Col. 2	Col. 3	Col. 4	Col. 5	Col. 6	Col. 7	Col. 8	Col. 9	Col. 10	Col. 11	Col. 12	Col. 13	Col. 14
146F	142	12.82	477.50	9.23	3.31	0.00	0.40	3.71	0.07	0.40	22.49	145.51	5.92
147F	138	9.31	657.50	29.76	12.98	0.00	1.90	14.88	0.28	0.55	22.05	145.95	16.78
148	141	12.39	494.28	52.70	52.70	1114.13	44.51	1174.42	22.53	1.64	23.21	144.79	36.92
149F	141	14.35	426.67	24.25	10.76	0.00	3.26	14.02	0.27	0.46	23.21	144.78	13.49
150F	141	11.47	533.93	24.29	5.46	0.00	1.78	7.23	0.14	0.38	23.21	144.78	18.83
151	148	9.55	640.99	34.69	34.69	1027.58	40.29	1063.13	20.66	1.60	25.06	142.94	39.43
152	148	14.68	417.13	3.40	3.40	30.19	0.66	33.51	0.65	0.60	25.06	142.94	0.75
153F	152	13.46	455.05	18.62	13.36	0.00	2.35	15.71	0.31	0.55	25.94	142.06	5.25
154F	152	11.26	543.79	48.90	11.08	0.00	3.40	14.48	0.28	0.50	25.94	142.06	37.82
155F	148	6.78	903.41	45.48	14.35	0.00	3.14	17.49	0.34	0.50	25.06	142.94	31.13
156	151	7.69	796.76	6.90	6.90	979.30	38.34	1011.68	19.82	1.56	26.23	141.77	12.87
157F	151	6.92	884.78	43.53	13.06	0.00	2.84	15.90	0.31	0.45	26.23	141.77	30.47
158	156	8.48	722.38	8.80	8.80	650.81	10.20	662.47	13.03	1.54	26.73	141.27	7.35
159	158	10.15	603.06	22.80	22.80	10.67	1.27	16.43	0.33	0.55	27.85	140.15	18.31
160F	159	12.39	494.29	1.92	1.92	0.00	0.34	2.26	0.07	0.33	30.46	96.36	0.00
161F	159	13.42	456.37	14.70	6.86	0.00	1.55	8.41	0.17	0.52	30.46	137.54	7.83
162	158	11.27	543.40	34.21	34.21	611.75	9.77	634.38	12.57	1.38	27.85	140.15	21.35
163F	162	14.57	420.22	25.72	15.48	0.00	3.52	19.00	0.38	0.76	29.93	138.07	10.24
164	162	13.03	469.96	42.03	42.03	85.37	11.54	128.42	2.58	0.90	29.93	138.07	10.51
165	162	12.74	480.63	35.37	35.37	421.96	0.13	441.10	8.87	1.30	29.93	138.07	16.36
166F	162	10.79	567.48	25.13	21.14	0.00	2.09	23.22	0.47	0.66	29.93	138.07	4.00
167	164	14.24	430.02	23.49	23.49	29.60	2.17	44.89	0.96	0.76	38.48	129.52	10.37
168F	167	14.92	410.40	6.34	5.63	0.00	0.83	6.46	0.14	0.46	41.20	126.80	0.71
169F	167	15.93	384.47	28.10	20.42	0.00	2.71	23.14	0.51	0.58	41.20	126.80	7.67
170F	164	15.72	389.57	114.63	32.59	0.00	7.89	40.48	0.87	0.62	38.48	129.52	82.04
171	165	13.20	463.96	8.97	8.97	387.82	8.30	400.77	8.19	1.28	32.13	135.87	4.32
172F	165	11.74	521.43	43.04	18.26	0.00	2.93	21.19	0.43	0.53	32.13	135.87	24.79
173	171	13.79	444.12	21.59	21.59	362.62	7.72	372.75	7.71	1.24	33.66	134.34	19.17
174F	171	12.30	497.88	28.22	13.16	0.00	1.90	15.06	0.31	0.52	33.66	134.34	15.05
175	173	13.84	442.58	9.11	9.11	341.93	0.38	347.01	7.24	1.26	34.82	133.18	4.41
176F	173	12.48	490.57	44.45	13.28	0.00	2.33	15.61	0.33	0.47	34.82	133.18	31.17
177	175	16.15	379.09	157.04	157.04	42.51	9.61	78.39	1.64	0.90	35.42	132.58	130.77
178	175	13.64	449.07	72.53	72.53	249.66	6.35	263.54	5.52	1.15	35.42	132.58	64.99
179F	177	15.24	401.80	41.30	10.21	0.00	2.19	12.40	0.28	0.50	46.32	121.68	31.09
180	177	17.97	340.74	18.06	18.06	21.36	1.99	30.10	0.69	0.50	46.32	121.68	11.30
181F	180	15.10	405.54	22.72	5.52	0.00	0.71	6.23	0.15	0.39	49.31	118.69	17.20
182F	180	15.72	389.53	18.40	13.78	0.00	1.35	15.12	0.35	0.55	49.31	118.69	4.63
183	178	13.28	461.26	9.77	9.77	66.97	5.64	69.81	1.48	0.80	37.32	130.68	12.58
184F	183	14.85	412.49	85.81	33.00	0.00	6.04	39.05	0.84	0.70	38.16	129.84	52.81
185F	183	12.26	499.37	58.01	25.67	0.00	2.26	27.93	0.60	0.55	38.16	129.84	32.34
186	178	12.60	486.06	80.92	80.92	114.45	6.01	179.85	3.82	0.97	37.32	130.68	21.53
187	186	13.88	441.28	41.05	41.05	53.24	4.73	99.02	2.18	0.66	41.91	126.09	0.00
188	187	13.70	447.11	32.79	32.79	6.68	2.35	41.82	0.94	0.43	44.93	123.07	0.00
189F	188	11.71	522.99	2.92	2.92	0.00	0.04	2.96	0.13	0.30	46.27	64.52	0.00
190F	188	9.97	614.27	10.69	3.17	0.00	0.56	3.72	0.08	0.33	46.27	121.73	7.52
191F	187	12.56	487.68	13.85	10.45	0.00	0.97	11.42	0.26	0.46	44.93	123.07	3.40
192F	186	12.48	490.67	25.69	13.06	0.00	2.36	15.42	0.34	0.57	41.91	126.09	12.63
193	156	8.71	703.27	74.30	74.30	285.02	5.51	316.83	6.23	1.28	26.73	141.27	48.00
194	193	14.05	435.99	6.87	6.87	270.27	5.98	276.93	5.58	1.23	30.10	137.90	6.19
195F	193	12.64	484.43	13.63	6.34	0.00	1.74	8.08	0.16	0.33	30.10	137.90	7.29
196	194	16.52	370.64	4.14	4.14	253.56	7.05	259.08	5.25	1.10	30.79	137.21	5.67
197F	194	15.31	400.04	27.61	9.32	0.00	1.87	11.19	0.23	0.40	30.79	137.21	18.29
198	196	14.91	410.59	17.79	17.79	22.14	1.35	32.04	0.65	0.70	31.33	136.67	9.24
199F	196	12.32	496.88	14.54	7.10	0.00	1.26	8.36	0.17	0.46	31.33	136.67	7.45
200F	198	14.02	436.80	12.76	10.10	0.00	1.06	11.15	0.23	0.52	33.26	134.74	2.66
201F	198	13.37	457.98	14.24	9.37	0.00	1.62	10.99	0.23	0.61	33.26	134.74	4.88
202	196	13.34	459.21	16.46	16.46	197.56	8.59	213.16	4.33	0.96	31.33	136.67	9.44
203	202	11.90	514.38	9.28	9.28	171.22	7.35	182.39	3.75	0.82	32.74	135.26	5.46
204F	202	11.73	521.83	21.93	12.88	0.00	2.29	15.17	0.31	0.46	32.74	135.26	9.05
205	203	11.72	522.66	15.60	15.60	96.25	4.18	105.45	2.18	0.80	33.59	134.41	10.58
206F	205	11.47	533.78	21.86	14.30	0.00	1.34	15.64	0.33	0.55	34.57	133.43	7.56
207	205	10.41	588.25	34.73	34.73	67.26	3.70	80.61	1.68	0.70	34.57	133.43	25.08
208	207	10.85	564.34	15.81	15.81	29.10	2.88	44.37	0.93	0.55	35.94	132.06	3.42
209F	208	13.75	445.39	9.41	9.41	0.00	0.68	10.09	0.31	0.46	36.91	89.96	0.00
210F	208	12.62	485.04	17.78	17.78	0.00	1.23	19.01	0.44	0.38	36.91	121.09	0.00
211	207	9.88	619.91	19.33	19.33	9.38	2.80	22.89	0.48	0.55	35.94	132.06	8.63
212F	211	11.16	548.54	3.51	2.86	0.00	0.33	3.19	0.07	0.35	40.82	127.17	0.66
213F	211	9.98	613.65	5.76	5.76	0.00	0.43	6.20	0.16	0.49	40.82	110.50	0.00
214	203	11.52	531.77	41.17	41.17	45.78	4.07	65.77	1.36	0.67	33.59	134.41	25.25
215	214	11.37	538.66	12.97	12.97	19.84	1.12	29.11	0.62	0.46	37.15	130.85	4.83
216F	215	10.09	607.20	18.84	11.58	0.00	0.99	12.57	0.27	0.40	38.24	129.76	7.26
217F	215	11.60	527.87	12.98	6.24	0.00	1.03	7.28	0.16	0.47	38.24	129.76	6.73
218F	214	11.66	525.25	26.17	14.73	0.00	1.95	16.67	0.35	0.52	37.15	130.85	11.44

Table – 5.2
Selection of canal segments for demand curtailment for satisfying capacity constraint

Intermediate Segment with Capacity Constraint	Affected Segment	Average GW Depth (m)
Col. 1	Col. 2	Col. 3
16	18	4.77
23	135	11.56
33	82	10.88
	115	11.53
	135	11.56
34	36	9.18
	44	13.26
	61	13.30
	50	13.59
35	39	12.00
	38	9.47
	44	13.26
37	42	11.24
	56	11.25
	54	11.40
	52	11.59
	44	13.26
38	40	10.18
	39	12.00
41	55	10.13
	58	10.79
	56	11.25
43	55	10.13
57	60	12.14
	61	13.30
59	61	13.30
63	75	8.75
	83	11.34
	82	10.88
64	65	8.25
	68	11.10
	69	11.41
	71	12.74
	72	13.05
66	68	11.10
70	72	13.05
74	77	8.61
	84	10.61
	79	10.74
	89	11.11
	80	11.25
	83	11.34
76	119	10.57
78	122	10.13
	207	10.41
82	84	10.61
85	122	10.13
86	88	13.79
	87	13.90
90	124	9.76
	122	10.13
91	97	11.97
92	94	12.23
95	102	11.92
	100	10.87
	97	11.97
96	102	11.92
97	98	11.53
	99	12.05
100	103	11.26
104	124	9.76
106	124	9.76
107	109	13.80
	108	13.97
109	111	13.42

Intermediate Segment with Capacity Constraint	Affected Segment	Average GW Depth (m)
Col. 1	Col. 2	Col. 3
109	110	13.56
112	207	10.41
113	114	11.93
	116	11.96
115	117	9.73
118	120	11.07
	133	14.33
	129	12.79
	127	8.92
119	121	10.24
	132	11.48
	133	14.33
122	125	9.65
	126	10.13
	123	10.22
	132	11.48
124	130	8.41
	131	8.78
	128	10.79
	132	11.48
127	130	8.41
134	137	10.61
	209	13.75
	208	10.85
136	140	8.16
	139	10.35
	153	13.46
	209	13.75
138	147	9.31
	210	12.62
	195	12.64
	146	12.82
	201	13.37
	153	13.46
141	150	11.47
	172	11.74
	174	12.30
	199	12.32
	210	12.62
148	155	6.78
	154	11.26
	172	11.74
151	157	6.92
	159	10.15
	166	10.79
	204	11.73
152	154	11.26
156	159	10.15
158	159	10.15
159	160	12.39
	161	13.42
162	166	10.79
164	170	15.72
165	172	11.74
167	168	14.92
	169	15.93
171	174	12.30
173	176	12.48
	187	13.88
175	187	13.88
177	179	15.24
	182	15.72
	180	17.97
178	185	12.26
	191	12.56
	188	13.70
180	181	15.10
	182	15.72
183	185	12.26

Intermediate Segment with Capacity Constraint	Affected Segment	Average GW Depth (m)
Col. 1	Col. 2	Col. 3
186	190	9.97
	189	11.71
	192	12.48
193	218	11.66
	214	11.52
194	218	11.66
196	218	11.66
198	201	13.37
202	206	11.47
	218	11.66
203	215	11.37
	206	11.47
205	206	11.47
207	212	11.16
	211	9.88
	210	12.62
208	210	12.62
211	213	9.98
	212	11.16
214	216	10.09
	217	11.60
	215	11.37
215	216	10.09

are curtailed, then the intermediate segment is also treated as a free segment. In Table- 5.2, for intermediate segment 35, it is found that first the demands of segment 39 with groundwater depth of 12 m are curtailed and then the demands of segment 38 with groundwater depth of 9.47 m are curtailed. The reason is that below segment 38, there lie two segments 39 and 40. Demands of segment 40 are curtailed to satisfy capacity constraint of segment 38. Now for satisfying capacity constraint of segment 35, segment 38 cannot be selected as long as it acts as intermediate segment (segment 39 is the downstream segment with canal water demands). So, first segment 39 is selected for demand curtailment and if its demands are fully curtailed and still capacity constraint exists at segment 35, then segment 38 (which becomes a free segment after the curtailment of demands of segment 39) is considered for curtailment. Further, it is noted from the table that one segment is selected again and again for demand curtailment (say segment 44 in Column-2). The reason is that corresponding to intermediate segments 34 and 35, only partial demands of segment 44 are curtailed. So this segment is still available until its demands are fully curtailed for satisfying capacity constraint of segment 37.

The revised canal operation scenario after satisfying the capacity constraint is presented in Table – 5.3. Table shows that groundwater demand of most of the intermediate segments has reduced to zero and for this reason, demands of a number of free segments are met through groundwater pumping. However, there are a few intermediate segments (such as segment 54, 97, 100, 109 etc.) that still require groundwater. The reason is that all downstream demands of these intermediate segments have been curtailed and these have now become free segments. For geographic depiction of the extent of canal system that can be supplied with canal water, output of allocation model is linked to GIS. Tabular output of model is imported in GIS and linked to the canal network layout through the identifiers of different canal segments. The depiction of operation results of Table – 5.3 in map form is presented in Figure – 5.1.

Table – 5.3

Revised canal operation scenario after capacity constraint satisfaction

Seg. Iden.	U/s Seg. Iden.	Average GW Depth (m)	GW Potential (Ham)	Local Irrigation Demand (Ham)	Canal Water Demand (Ham)	Total D/s Demand (Ham)	Canal Seepage Loss (Ham)	Total Canal Water Demand (Ham)	Required Discharge (Cumec)	Water Depth (m)	Fill Time (Hour)	Run Time (Hour)	Total GW Demand (Ham)
Col. 1	Col. 2	Col. 3	Col. 4	Col. 5	Col. 6	Col. 7	Col. 8	Col. 9	Col. 10	Col. 11	Col. 12	Col. 13	Col. 14
1	0	3.50	1749.31	4.75	4.75	3759.33	18.53	3782.61	62.54	2.25	0.00	168.00	0.00
2	1	4.14	1477.44	4.30	4.30	3727.24	18.37	3749.91	62.31	2.24	0.83	167.17	0.00
3F	1	3.51	1745.34	8.42	8.42	0.00	0.99	9.42	0.18	0.50	0.83	145.46	0.00
4	2	5.08	1204.98	2.10	2.10	3569.15	28.80	3600.05	59.97	2.22	1.24	166.76	0.00
5	2	5.03	1216.70	3.80	3.80	112.09	2.58	118.47	2.01	0.78	1.24	164.05	0.00
6	5	7.37	830.50	34.44	34.44	56.52	8.36	99.32	1.70	0.75	2.93	162.37	0.00
7F	5	6.10	1004.19	11.79	11.79	0.00	0.98	12.77	0.30	0.55	2.93	119.30	0.00
8F	6	7.39	828.33	11.58	11.58	0.00	2.16	13.74	0.25	0.55	9.06	152.59	0.00
9	6	8.96	683.17	7.42	7.42	33.69	1.67	42.78	0.76	0.48	9.06	156.23	0.00
10	9	8.54	717.24	11.31	11.31	3.39	0.89	15.59	0.28	0.55	10.63	154.66	0.00
11F	10	7.83	782.26	0.62	0.62	0.00	0.08	0.70	0.10	0.43	12.56	19.80	0.00
12F	10	8.43	726.07	2.18	2.18	0.00	0.51	2.70	0.09	0.35	12.56	83.14	0.00
13F	9	9.70	631.44	15.27	15.27	0.00	2.83	18.10	0.50	0.48	10.63	100.87	0.00
14F	2	4.57	1339.11	7.43	7.43	0.00	1.29	8.72	0.22	0.50	1.24	110.12	0.00
15	4	5.94	1030.91	14.15	14.15	3486.26	38.93	3539.34	59.33	2.19	2.29	165.71	0.00
16	4	5.51	1111.19	12.69	12.69	14.82	2.30	29.80	0.50	0.60	2.29	165.64	0.00
17F	16	4.80	1276.88	11.47	11.41	0.00	2.11	13.52	0.25	0.50	5.30	150.17	0.06
18F	16	4.77	1283.22	1.12	1.12	0.00	0.18	1.30	0.10	0.42	5.30	36.21	0.00
19	15	5.68	1078.21	8.04	8.04	3427.40	38.21	3473.65	58.54	2.16	3.17	164.83	0.00
20F	15	7.58	807.73	9.96	9.96	0.00	2.65	12.61	0.50	0.60	3.17	70.08	0.00
21	19	6.80	900.12	29.53	29.53	3354.27	37.64	3421.44	57.92	2.15	3.90	164.10	0.00
22F	19	5.91	1035.57	5.30	5.30	0.00	0.66	5.96	0.12	0.37	3.90	137.92	0.00
23	21	8.22	745.15	36.87	36.87	3142.38	29.84	3209.09	54.78	2.11	5.29	162.71	0.00
24	21	8.47	722.89	26.45	26.45	114.16	4.57	145.18	2.48	0.98	5.29	162.71	0.00
25	24	8.91	687.29	7.96	7.96	93.25	0.88	102.08	1.77	0.79	7.90	160.10	0.00
26F	24	9.26	661.56	26.29	10.55	0.00	1.52	12.08	0.21	0.40	7.90	160.10	15.74
27	25	9.23	663.74	28.56	28.56	55.87	3.31	87.73	1.53	0.72	8.45	159.55	0.00
28F	25	9.15	669.36	7.53	4.36	0.00	1.15	5.51	0.10	0.38	8.45	159.55	3.16
29	27	11.32	541.05	7.25	7.25	41.11	0.99	49.35	0.87	0.50	10.63	157.37	0.00
30F	27	11.35	539.31	5.65	5.65	0.00	0.86	6.51	0.14	0.32	10.63	129.36	0.00
31F	29	11.68	524.15	23.93	23.93	0.00	3.10	27.03	0.90	0.62	11.38	83.87	0.00
32F	29	10.54	581.00	14.47	12.78	0.00	1.30	14.08	0.25	0.50	11.38	156.62	1.69
33	23	9.14	669.71	9.59	9.59	2599.10	40.00	2648.69	45.57	2.07	6.56	161.44	0.00
34	23	9.25	661.78	23.78	23.78	443.06	26.86	493.70	8.49	1.55	6.56	161.44	0.00
35	34	9.34	655.39	37.17	37.17	378.13	23.89	439.19	7.60	1.50	7.38	160.62	0.00
36F	34	9.18	667.11	10.98	3.17	0.00	0.70	3.86	0.07	0.35	7.38	160.62	7.82
37	35	9.20	665.39	29.05	29.05	292.59	18.50	340.13	5.92	1.42	8.48	159.51	0.00
38	35	9.47	646.40	11.38	11.38	25.87	0.75	37.99	0.66	0.67	8.48	159.51	0.00
39F	38	12.00	510.16	46.72	13.87	0.00	3.44	17.31	0.49	0.63	9.37	97.48	32.85
40F	38	10.18	601.69	20.68	7.34	0.00	1.21	8.55	0.15	0.42	9.37	158.63	13.33
41	37	11.71	522.96	44.51	44.51	221.95	15.33	281.80	4.95	1.32	10.00	158.00	0.00
42F	37	11.24	544.60	14.55	8.41	0.00	2.38	10.79	0.19	0.38	10.00	157.99	6.14
43	41	13.35	458.75	42.31	42.31	148.45	10.97	201.74	3.59	1.19	11.86	156.14	0.00
44F	41	13.26	461.82	32.53	17.65	0.00	2.56	20.21	0.36	0.55	11.86	156.14	14.88
45	43	14.04	436.09	10.07	10.07	125.31	0.30	135.68	2.62	1.08	13.54	143.94	0.00
46F	43	13.97	438.48	23.70	10.44	0.00	2.33	12.77	0.23	0.46	13.54	154.46	13.25
47	45	13.67	447.81	32.88	32.88	45.86	0.17	78.92	1.66	1.04	14.12	132.08	0.00
48F	45	14.58	419.92	38.32	38.32	0.00	8.08	46.40	0.90	0.66	14.12	143.36	0.00
49	47	13.97	438.32	8.95	8.95	23.06	0.07	32.09	1.02	0.85	16.89	87.30	0.00
50F	47	13.59	450.76	11.54	11.54	0.00	2.23	13.78	0.30	0.52	16.89	129.31	0.00
51	49	12.49	490.11	7.61	7.61	11.61	0.04	19.26	2.20	0.78	17.94	24.32	0.00
52F	49	11.59	528.16	2.80	2.80	0.00	1.00	3.80	0.12	0.36	17.94	86.25	0.00
53	51	11.93	513.45	7.69	7.69	0.00	0.02	7.70	2.21	0.72	18.77	9.68	0.00
54	51	11.40	537.24	3.69	3.66	0.00	0.26	3.91	0.46	0.61	18.77	23.50	0.04
55F	54	10.13	604.71	14.00	0.00	0.00	0.00	0.00	0.00	0.00	22.00	0.00	14.00
56F	54	11.25	544.47	2.85	0.00	0.00	0.00	0.00	0.00	0.00	22.00	0.00	2.85
57	53	10.89	562.20	43.65	0.00	0.00	0.00	0.00	0.00	0.00	19.58	0.00	43.65
58F	53	10.79	567.74	18.11	0.00	0.00	0.00	0.00	0.00	0.00	19.58	0.00	18.11
59	57	12.83	477.43	15.01	0.00	0.00	0.00	0.00	0.00	0.00	22.48	0.00	15.01
60F	57	12.14	504.25	11.31	0.00	0.00	0.00	0.00	0.00	0.00	22.48	0.00	11.31
61F	59	13.30	460.51	34.22	0.00	0.00	0.00	0.00	0.00	0.00	23.41	0.00	34.22
62F	59	13.78	444.42	34.10	0.00	0.00	0.00	0.00	0.00	0.00	23.41	0.00	34.10
63	33	8.67	706.38	20.24	20.24	2431.52	37.59	2489.35	42.96	2.06	7.05	160.95	0.00
64	33	8.10	756.36	48.94	48.94	57.85	2.96	109.75	1.89	1.05	7.05	160.95	0.00
65F	64	8.25	742.10	11.28	4.22	0.00	0.62	4.84	0.08	0.40	9.21	158.79	7.06
66	64	8.75	699.68	23.84	23.84	26.72	2.45	53.01	0.93	0.58	9.21	158.79	0.00
67	66	10.96	558.86	1.57	1.57	12.53	0.55	14.65	0.26	0.19	11.14	156.85	0.00
68F	66	11.10	551.81	20.04	10.54	0.00	1.53	12.07	0.21	0.60	11.14	156.86	9.50
69F	67	11.41	536.86	10.33	0.40	0.00	0.04	0.44	0.17	0.45	11.60	7.27	9.93
70	67	13.00	471.20	8.00	8.00	0.00	0.15	8.15	0.82	0.57	11.60	27.70	0.00
71F	67	12.74	480.55	4.03	3.37	0.00	0.56	3.94	0.07	0.40	11.60	156.40	0.66

Seg. Iden.	U/s Seg. Iden.	Average GW Depth (m)	GW Potential (Ham)	Local Irrigation Demand (Ham)	Canal Water Demand (Ham)	Total D/s Demand (Ham)	Canal Seepage Loss (Ham)	Total Canal Water Demand (Ham)	Required Discharge (Cumec)	Water Depth (m)	Fill Time (Hour)	Run Time (Hour)	Total GW Demand (Ham)
Col. 1	Col. 2	Col. 3	Col. 4	Col. 5	Col. 6	Col. 7	Col. 8	Col. 9	Col. 10	Col. 11	Col. 12	Col. 13	Col. 14
72F	70	13.05	469.25	69.13	0.00	0.00	0.00	0.00	0.00	0.00	12.35	0.00	69.13
73F	70	14.56	420.68	17.41	0.00	0.00	0.00	0.00	0.00	0.00	12.35	0.00	17.41
74	63	8.28	739.40	17.29	17.29	2365.66	36.53	2419.49	41.95	2.04	7.79	160.21	0.00
75F	63	8.75	699.66	11.43	11.43	0.00	0.60	12.03	0.23	0.35	7.79	143.21	0.00
76	74	9.30	658.38	23.52	23.52	2303.02	35.67	2362.21	41.10	2.03	8.33	159.67	0.00
77F	74	8.61	711.18	10.92	3.01	0.00	0.44	3.45	0.06	0.35	8.33	159.66	7.90
78	76	10.30	594.66	9.83	9.83	2254.08	34.71	2298.62	40.20	2.01	9.15	158.85	0.00
79F	76	10.74	570.01	8.73	3.75	0.00	0.66	4.40	0.08	0.35	9.15	158.85	4.98
80F	78	11.25	544.56	12.10	5.05	0.00	0.59	5.64	0.10	0.40	9.53	158.47	7.05
81	78	11.90	514.52	24.22	24.22	2174.58	33.71	2232.51	39.13	2.00	9.53	158.47	0.00
82	78	10.88	562.78	1.99	1.99	13.73	0.21	15.93	0.28	0.50	9.53	158.47	0.00
83F	82	11.34	539.81	22.38	8.39	0.00	1.76	10.15	0.20	0.45	9.93	140.24	13.99
84F	82	10.61	577.27	6.75	3.20	0.00	0.38	3.58	0.06	0.35	9.93	158.06	3.55
85	81	10.99	557.30	56.02	56.02	2074.28	22.82	2153.12	38.09	1.97	10.98	157.02	0.00
86	81	12.90	474.65	8.53	8.53	0.26	0.67	9.46	0.18	0.53	10.98	149.68	0.00
87F	86	13.90	440.58	3.74	0.00	0.00	0.00	0.00	0.00	0.00	12.89	0.00	3.74
88F	86	13.79	444.04	5.80	0.22	0.00	0.04	0.26	0.05	0.30	12.89	14.07	5.59
89F	81	11.11	551.08	20.97	9.07	0.00	2.93	12.00	0.21	0.40	10.98	157.02	11.90
90	85	12.60	485.89	26.37	26.37	1880.66	20.43	1927.46	34.37	1.94	12.22	155.78	0.00
91	85	10.27	596.13	4.12	4.12	137.27	5.43	146.82	2.62	1.02	12.22	155.78	0.00
92	91	12.37	495.19	13.16	13.16	14.17	1.21	28.55	0.51	0.58	12.58	155.41	0.00
93F	92	13.13	466.53	19.69	8.90	0.00	1.56	10.46	0.19	0.49	14.17	153.83	10.80
94F	92	12.23	500.50	43.82	2.99	0.00	0.73	3.71	0.27	0.50	14.17	38.34	40.83
95	91	10.26	596.78	49.01	49.01	55.69	4.02	108.72	1.94	1.00	12.58	155.42	0.00
96	95	11.35	539.31	11.42	11.42	5.23	0.64	17.29	1.11	0.78	15.50	43.08	0.00
97	95	11.97	511.39	39.35	35.24	0.00	3.16	38.40	0.70	0.65	15.50	152.50	4.11
98F	97	11.53	530.97	14.32	0.00	0.00	0.00	0.00	0.00	0.00	19.35	0.00	14.32
99F	97	12.05	508.32	16.03	0.00	0.00	0.00	0.00	0.00	0.00	19.35	0.00	16.03
100	96	10.87	563.13	14.09	5.11	0.00	0.12	5.23	0.60	0.73	16.35	24.29	8.97
101F	96	12.83	477.21	42.10	0.00	0.00	0.00	0.00	0.00	0.00	16.35	0.00	42.10
102F	100	11.92	513.69	15.90	0.00	0.00	0.00	0.00	0.00	0.00	18.60	0.00	15.90
103F	100	11.26	543.62	5.11	0.00	0.00	0.00	0.00	0.00	0.00	18.60	0.00	5.11
104	90	15.85	386.42	7.74	7.74	1841.40	19.81	1868.95	33.45	1.92	12.82	155.18	0.00
105F	90	14.74	415.52	22.85	9.69	0.00	2.02	11.71	0.21	0.43	12.82	155.18	13.16
106	104	14.20	431.10	73.96	73.96	1707.11	33.02	1814.08	32.54	1.91	13.13	154.87	0.00
107	104	15.41	397.40	29.37	29.37	0.00	2.72	27.31	0.49	0.58	13.13	154.87	0.00
108F	107	13.97	438.33	10.81	0.00	0.00	0.00	0.00	0.00	0.00	17.21	0.00	10.81
109	107	13.80	443.82	13.30	0.00	0.00	0.00	0.00	0.00	0.00	17.21	0.00	13.30
110F	109	13.56	451.47	4.43	0.00	0.00	0.00	0.00	0.00	0.00	19.83	0.00	4.43
111F	109	13.42	456.31	2.06	0.00	0.00	0.00	0.00	0.00	0.00	19.83	0.00	2.06
112	106	12.37	494.85	27.61	27.61	1381.80	26.13	1435.54	26.08	1.86	15.12	152.88	0.00
113	106	12.93	473.75	56.60	56.60	21.99	3.59	82.18	1.50	0.77	15.12	152.39	0.00
114F	113	11.93	513.21	15.03	6.10	0.00	1.02	7.12	0.16	0.55	17.87	120.49	8.94
115	113	11.53	531.13	14.53	14.53	0.00	0.34	14.87	1.10	0.67	17.87	37.44	0.00
116F	115	11.96	512.13	59.46	0.00	0.00	0.00	0.00	0.00	0.00	19.06	0.00	59.46
117F	115	9.73	629.04	14.85	0.00	0.00	0.00	0.00	0.00	0.00	19.06	0.00	14.85
118	106	11.79	519.41	76.28	76.28	105.28	7.82	189.39	3.44	1.08	15.12	152.88	0.00
119	118	10.57	579.10	14.16	14.16	69.83	6.94	90.93	1.70	0.87	19.74	148.26	0.00
120F	118	11.07	552.95	24.71	12.93	0.00	1.43	14.36	0.27	0.64	19.74	148.26	11.78
121F	119	10.24	598.24	12.08	5.36	0.00	0.96	6.31	0.12	0.38	20.56	147.44	6.73
122	119	10.13	604.41	43.08	43.08	15.60	4.85	63.52	1.20	0.83	20.56	147.44	0.00
123F	122	10.22	599.01	9.06	0.00	0.00	0.00	0.00	0.00	0.00	23.67	0.00	9.06
124	122	9.76	627.29	36.48	0.00	0.00	0.00	0.00	0.00	0.00	23.67	0.00	36.48
125F	122	9.65	634.65	42.06	13.85	0.00	1.75	15.60	0.30	0.52	23.67	144.33	28.22
126F	122	10.13	604.41	10.53	0.00	0.00	0.00	0.00	0.00	0.00	23.67	0.00	10.53
127	124	8.92	686.21	22.57	0.00	0.00	0.00	0.00	0.00	0.00	26.01	0.00	22.57
128F	124	10.79	567.33	8.91	0.00	0.00	0.00	0.00	0.00	0.00	26.01	0.00	8.91
129	127	12.79	478.87	6.04	0.00	0.00	0.00	0.00	0.00	0.00	27.74	0.00	6.04
130F	127	8.41	728.07	9.31	0.00	0.00	0.00	0.00	0.00	0.00	27.74	0.00	9.31
131F	129	8.78	697.78	8.28	0.00	0.00	0.00	0.00	0.00	0.00	29.27	0.00	8.28
132F	129	11.48	533.29	8.41	0.00	0.00	0.00	0.00	0.00	0.00	29.27	0.00	8.41
133F	129	14.33	427.45	4.95	0.00	0.00	0.00	0.00	0.00	0.00	29.27	0.00	4.95
134	112	10.47	584.69	74.99	74.99	1254.89	24.65	1354.53	24.75	1.84	15.98	152.02	0.00
135F	112	11.56	529.68	56.50	21.75	0.00	5.52	27.27	0.50	0.52	15.98	152.02	34.74
136	134	9.53	642.31	54.26	54.26	1142.75	47.15	1244.16	22.99	1.79	17.70	150.30	0.00
137F	134	10.61	577.09	23.76	8.82	0.00	1.90	10.72	0.20	0.48	17.70	150.30	14.93
138	136	9.75	628.05	110.92	110.92	955.57	42.01	1108.51	20.72	1.75	19.37	148.63	0.00
139F	136	10.35	591.39	44.48	21.14	0.00	5.53	26.67	0.50	0.53	19.37	148.63	23.34
140F	136	8.16	750.20	23.81	5.93	0.00	1.64	7.58	0.14	0.33	19.37	148.63	17.88
141	138	12.52	489.15	34.62	34.62	801.62	32.94	869.18	16.54	1.68	22.05	145.95	0.00
142	138	12.18	502.95	7.10	7.10	63.77	0.64	71.51	1.36	0.58	22.05	145.95	0.00
143	142	14.44	424.18	31.62	31.62	24.74	3.71	60.06	1.74	0.72	22.49	96.11	0.00
144F	143	15.20	402.95	4.12	4.12	0.00	0.56	4.67	0.18	0.40	26.41	71.60	0.00
145F	143	13.87	441.55	18.02	18.02	0.00	2.05	20.06	0.94	0.51	26.41	59.57	0.00

Seg. Iden.	U/s Seg. Iden.	Average GW Depth (m)	GW Potential (Ham)	Local Irrigation Demand (Ham)	Canal Water Demand (Ham)	Total D/s Demand (Ham)	Canal Seepage Loss (Ham)	Total Canal Water Demand (Ham)	Required Discharge (Cumec)	Water Depth (m)	Fill Time (Hour)	Run Time (Hour)	Total GW Demand (Ham)
Col. 1	Col. 2	Col. 3	Col. 4	Col. 5	Col. 6	Col. 7	Col. 8	Col. 9	Col. 10	Col. 11	Col. 12	Col. 13	Col. 14
146F	142	12.82	477.50	9.23	3.31	0.00	0.40	3.71	0.07	0.40	22.49	145.51	5.92
147F	138	9.31	657.50	29.76	12.98	0.00	1.90	14.88	0.28	0.55	22.05	145.95	16.78
148	141	12.39	494.28	52.70	52.70	698.09	29.58	780.37	14.97	1.64	23.21	144.79	0.00
149F	141	14.35	426.67	24.25	10.76	0.00	3.26	14.02	0.27	0.46	23.21	144.78	13.49
150F	141	11.47	533.93	24.29	5.46	0.00	1.78	7.23	0.14	0.38	23.21	144.78	18.83
151	148	9.55	640.99	34.69	34.69	588.09	24.53	647.32	12.58	1.60	25.06	142.94	0.00
152	148	14.68	417.13	3.40	3.40	29.22	0.66	33.28	0.65	0.60	25.06	142.94	0.00
153F	152	13.46	455.05	18.62	13.36	0.00	2.35	15.71	0.31	0.55	25.94	142.06	5.25
154F	152	11.26	543.79	48.90	10.33	0.00	3.17	13.51	0.28	0.50	25.94	132.49	38.57
155F	148	6.78	903.41	45.48	14.35	0.00	3.14	17.49	0.34	0.50	25.06	142.94	31.13
156	151	7.69	796.76	6.90	6.90	543.61	21.69	572.20	11.21	1.56	26.23	141.77	0.00
157F	151	6.92	884.78	43.53	13.06	0.00	2.84	15.90	0.31	0.45	26.23	141.77	30.47
158	156	8.48	722.38	8.80	8.80	266.14	4.30	279.25	5.49	1.54	26.73	141.27	0.00
159	158	10.15	603.06	22.80	15.16	0.00	1.27	16.43	0.33	0.55	27.85	140.15	7.64
160F	159	12.39	494.29	1.92	0.00	0.00	0.00	0.00	0.00	0.00	30.46	0.00	1.92
161F	159	13.42	456.37	14.70	0.00	0.00	0.00	0.00	0.00	0.00	30.46	0.00	14.70
162	158	11.27	543.40	34.21	34.21	211.66	3.85	249.71	4.95	1.38	27.85	140.15	0.00
163F	162	14.57	420.22	25.72	15.48	0.00	3.52	19.00	0.38	0.76	29.93	138.07	10.24
164	162	13.03	469.96	42.03	42.03	17.85	5.91	65.79	2.58	0.90	29.93	70.73	0.00
165	162	12.74	480.63	35.37	35.37	68.25	0.03	103.65	2.09	1.30	29.93	138.07	0.00
166F	162	10.79	567.48	25.13	21.14	0.00	2.09	23.22	0.47	0.66	29.93	138.07	4.00
167	164	14.24	430.02	23.49	16.99	0.00	0.86	17.85	0.96	0.76	38.48	51.50	6.51
168F	167	14.92	410.40	6.34	0.00	0.00	0.00	0.00	0.00	0.00	41.20	0.00	6.34
169F	167	15.93	384.47	28.10	0.00	0.00	0.00	0.00	0.00	0.00	41.20	0.00	28.10
170F	164	15.72	389.57	114.63	0.00	0.00	0.00	0.00	0.00	0.00	38.48	0.00	114.63
171	165	13.20	463.96	8.97	8.97	37.11	0.97	47.06	0.96	1.28	32.13	135.87	0.00
172F	165	11.74	521.43	43.04	18.26	0.00	2.93	21.19	0.43	0.53	32.13	135.87	24.79
173	171	13.79	444.12	21.59	21.59	0.00	0.46	22.05	7.71	1.24	33.66	7.95	0.00
174F	171	12.30	497.88	28.22	13.16	0.00	1.90	15.06	0.31	0.52	33.66	134.34	15.05
175	173	13.84	442.58	9.11	0.00	0.00	0.00	0.00	0.00	0.00	34.82	0.00	9.11
176F	173	12.48	490.57	44.45	0.00	0.00	0.00	0.00	0.00	0.00	34.82	0.00	44.45
177	175	16.15	379.09	157.04	0.00	0.00	0.00	0.00	0.00	0.00	35.42	0.00	157.04
178	175	13.64	449.07	72.53	0.00	0.00	0.00	0.00	0.00	0.00	35.42	0.00	72.53
179F	177	15.24	401.80	41.30	0.00	0.00	0.00	0.00	0.00	0.00	46.32	0.00	41.30
180	177	17.97	340.74	18.06	0.00	0.00	0.00	0.00	0.00	0.00	46.32	0.00	18.06
181F	180	15.10	405.54	22.72	0.00	0.00	0.00	0.00	0.00	0.00	49.31	0.00	22.72
182F	180	15.72	389.53	18.40	0.00	0.00	0.00	0.00	0.00	0.00	49.31	0.00	18.40
183	178	13.28	461.26	9.77	0.00	0.00	0.00	0.00	0.00	0.00	37.32	0.00	9.77
184F	183	14.85	412.49	85.81	0.00	0.00	0.00	0.00	0.00	0.00	38.16	0.00	85.81
185F	183	12.26	499.37	58.01	0.00	0.00	0.00	0.00	0.00	0.00	38.16	0.00	58.01
186	178	12.60	486.06	80.92	0.00	0.00	0.00	0.00	0.00	0.00	37.32	0.00	80.92
187	186	13.88	441.28	41.05	0.00	0.00	0.00	0.00	0.00	0.00	41.91	0.00	41.05
188	187	13.70	447.11	32.79	0.00	0.00	0.00	0.00	0.00	0.00	44.93	0.00	32.79
189F	188	11.71	522.99	2.92	0.00	0.00	0.00	0.00	0.00	0.00	46.27	0.00	2.92
190F	188	9.97	614.27	10.69	0.00	0.00	0.00	0.00	0.00	0.00	46.27	0.00	10.69
191F	187	12.56	487.68	13.85	0.00	0.00	0.00	0.00	0.00	0.00	44.93	0.00	13.85
192F	186	12.48	490.67	25.69	0.00	0.00	0.00	0.00	0.00	0.00	41.91	0.00	25.69
193	156	8.71	703.27	74.30	74.30	185.46	4.60	264.36	5.20	1.28	26.73	141.27	0.00
194	193	14.05	435.99	6.87	6.87	166.68	3.83	177.38	3.57	1.23	30.10	137.90	0.00
195F	193	12.64	484.43	13.63	6.34	0.00	1.74	8.08	0.16	0.33	30.10	137.90	7.29
196	194	16.52	370.64	4.14	4.14	147.12	4.23	155.49	3.15	1.10	30.79	137.21	0.00
197F	194	15.31	400.04	27.61	9.32	0.00	1.87	11.19	0.23	0.40	30.79	137.21	18.29
198	196	14.91	410.59	17.79	17.79	11.30	1.35	30.44	0.62	0.70	31.33	136.67	0.00
199F	196	12.32	496.88	14.54	7.10	0.00	1.26	8.36	0.17	0.46	31.33	136.67	7.45
200F	198	14.02	436.80	12.76	10.10	0.00	1.06	11.15	0.23	0.52	33.26	134.74	2.66
201F	198	13.37	457.98	14.24	0.12	0.00	0.02	0.15	0.23	0.61	33.26	1.79	14.12
202	196	13.34	459.21	16.46	16.46	87.49	4.37	108.32	2.20	0.96	31.33	136.67	0.00
203	202	11.90	514.38	9.28	9.28	60.13	2.91	72.33	2.22	0.82	32.74	90.53	0.00
204F	202	11.73	521.83	21.93	12.88	0.00	2.29	15.17	0.31	0.46	32.74	135.26	9.05
205	203	11.72	522.66	15.60	15.60	0.00	0.64	16.24	2.18	0.80	33.59	20.71	0.00
206F	205	11.47	533.78	21.86	0.00	0.00	0.00	0.00	0.00	0.00	34.57	0.00	21.86
207	205	10.41	588.25	34.73	0.00	0.00	0.00	0.00	0.00	0.00	34.57	0.00	34.73
208	207	10.85	564.34	15.81	0.00	0.00	0.00	0.00	0.00	0.00	35.94	0.00	15.81
209F	208	13.75	445.39	9.41	0.00	0.00	0.00	0.00	0.00	0.00	36.91	0.00	9.41
210F	208	12.62	485.04	17.78	0.00	0.00	0.00	0.00	0.00	0.00	36.91	0.00	17.78
211	207	9.88	619.91	19.33	0.00	0.00	0.00	0.00	0.00	0.00	35.94	0.00	19.33
212F	211	11.16	548.54	3.51	0.00	0.00	0.00	0.00	0.00	0.00	40.82	0.00	3.51
213F	211	9.98	613.65	5.76	0.00	0.00	0.00	0.00	0.00	0.00	40.82	0.00	5.76
214	203	11.52	531.77	41.17	41.17	0.00	2.71	43.88	1.36	0.67	33.59	89.69	0.00
215	214	11.37	538.66	12.97	0.00	0.00	0.00	0.00	0.00	0.00	37.15	0.00	12.97
216F	215	10.09	607.20	18.84	0.00	0.00	0.00	0.00	0.00	0.00	38.24	0.00	18.84
217F	215	11.60	527.87	12.98	0.00	0.00	0.00	0.00	0.00	0.00	38.24	0.00	12.98
218F	214	11.66	525.25	26.17	0.00	0.00	0.00	0.00	0.00	0.00	37.15	0.00	26.17

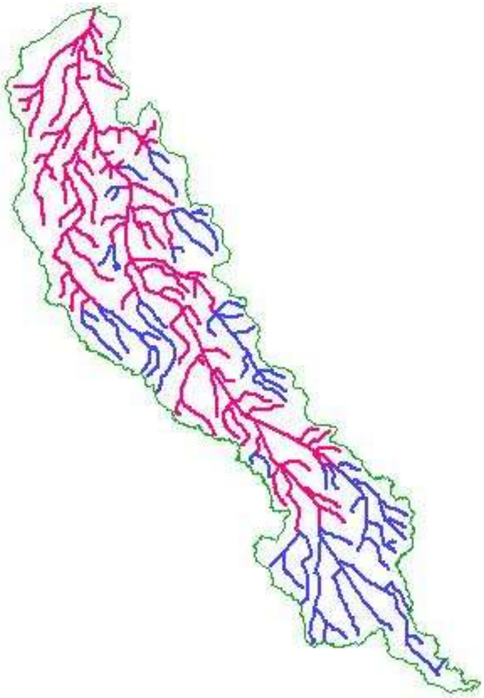

Figure – 5.1: Operation plan of Lakhaoti canal network with adequate canal water supply Running canal (red) and non-running canals (blue)

In addition to running/non-running canals, maps corresponding to various attributes such as required discharge, run-time, groundwater demand, canal seepage loss etc. can be visualized. The map corresponding to required discharge is presented in Figure – 5.2.

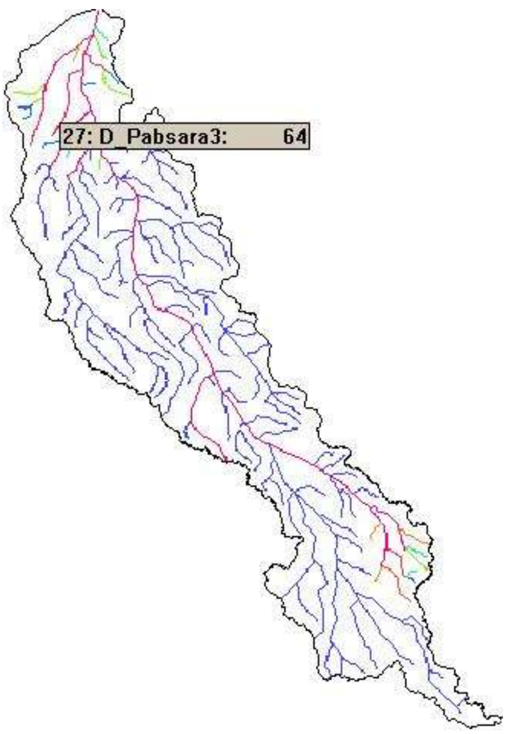

Figure – 5.2: Map showing discharge requirement in Lakhaoti canal network

By selecting a particular segment, details such as its identifier, name, and attribute value (say, required discharge) are displayed on the screen as shown in Figure – 5.2. The discharge requirement at the head of canal system comes out to be 62.54 cumec. The canal system can be run according to the derived plan (discharge and run-rime for various canal segments as obtained in Table - 5.3 if required discharge is available at canal head. However, if the discharge availability at head is less than the demand, then some allocation policy needs to be adopted for deriving the spatial distribution plan of available canal water.

5.2.2 Analysis of Different Allocation Policies

Under deficit condition, when the canal water supply at canal network head is less than the required demand, it is not possible to meet the complete demands of full network from existing surface water resources and some subjective criteria needs to be adopted for the allocation of available canal and groundwater. For deficit conditions, three allocation policies, as described in Chapter-3, have been included in the model. To compare the results of different allocation policies, it is assumed that 40 cumec of water is available at canal head (against the demand of 62.54 cumec).

Table - 5.4 shows the operation scenario generated while adopting the policy of head-reach priority (Policy-1). Under this policy, canal water is allocated starting from the network head and the demands of various canal segments (which are planned to be run as per Table - 5.3) are met in full as far as canal water could reach in the network. Operation results with Policy-1 are depicted in map form in Figure – 5.3.

Table - 5.5 shows the operation scenario generated while adopting the policy of conjunctive use (Policy-2). Under this policy, water deficit at the network head is compensated by curtailing the canal water demands of those segments which have least depth of water table. The irrigable area under these segments is then supplied with groundwater. The segment demands are curtailed iteratively till the water demand at canal head matches with the supply. The results in map form for Policy-2 are presented in Figure – 5.4. Generally, groundwater occurs at shallow depth in the head-reach of a command area due to greater availability and application of canal water in the absence of control mechanism and more seepage because of continuous running of head-reach canal.

Of the available water at canal head, maximum water is used under Policy-1 for irrigation with minimum loss through canal seepage. However, Policy-1 does not take the groundwater conditions into consideration (except that the waterlogged area is not supplied canal water) and supplies canal water in the area of relatively shallow groundwater table (head-reaches). This results in higher energy requirement for pumping groundwater in other areas of command which have relatively deeper water table. On the other hand, Policy-2 takes into account the groundwater conditions in the command while allocating canal water and groundwater. However, since deeper water table generally occurs in the tail-reaches of command, Policy-2 tries to allocate canal water in the tail reaches of command with the result that canal seepage losses increase and the effective water utilization for irrigation application decreases.

Table – 5.4
Operation scenario with water availability constraint using Policy-1

Seg. Iden.	U/s Seg. Iden.	Local Irrigation Demand (Ham)	Canal Water Demand (Ham)	Total D/s Demand (Ham)	Canal Seepage Loss (Ham)	Total Canal Water Demand (Ham)	Required Discharge (Cumec)	Water Depth (m)	Fill Time (Hour)	Run Time (Hour)	Total GW Demand (Ham)
1	0	4.75	4.75	2402.05	11.85	2418.65	39.99	2.25	0.00	168.00	0.00
2	1	4.30	4.30	2376.61	11.72	2392.63	39.76	2.24	0.83	167.17	0.00
3F	1	8.42	8.42	0.00	0.99	9.42	0.18	0.50	0.83	145.46	0.00
4	2	2.10	2.10	2229.32	18.00	2249.41	37.47	2.22	1.24	166.76	0.00
5	2	3.80	3.80	112.09	2.58	118.47	2.01	0.78	1.24	164.05	0.00
6	5	34.44	34.44	56.52	8.36	99.32	1.70	0.75	2.93	162.37	0.00
7F	5	11.79	11.79	0.00	0.98	12.77	0.30	0.55	2.93	119.30	0.00
8F	6	11.58	11.58	0.00	2.16	13.74	0.25	0.55	9.06	152.59	0.00
9	6	7.42	7.42	33.69	1.67	42.78	0.76	0.48	9.06	156.23	0.00
10	9	11.31	11.31	3.39	0.89	15.59	0.28	0.55	10.63	154.66	0.00
11F	10	0.62	0.62	0.00	0.08	0.70	0.10	0.43	12.56	19.80	0.00
12F	10	2.18	2.18	0.00	0.51	2.70	0.09	0.35	12.56	83.14	0.00
13F	9	15.27	15.27	0.00	2.83	18.10	0.50	0.48	10.63	100.87	0.00
14F	2	7.43	7.43	0.00	1.29	8.72	0.22	0.50	1.24	110.12	0.00
15	4	14.15	14.15	2161.18	24.19	2199.52	36.87	2.19	2.29	165.71	0.00
16	4	12.69	12.69	14.82	2.30	29.80	0.50	0.60	2.29	165.64	0.00
17F	16	11.47	11.41	0.00	2.11	13.52	0.25	0.50	5.30	150.17	0.06
18F	16	1.12	1.12	0.00	0.18	1.30	0.10	0.42	5.30	36.21	0.00
19	15	8.04	8.04	2116.89	23.63	2148.57	36.21	2.16	3.17	164.83	0.00
20F	15	9.96	9.96	0.00	2.65	12.61	0.50	0.60	3.17	70.08	0.00
21	19	29.53	29.53	2058.18	23.22	2110.93	35.73	2.15	3.90	164.10	0.00
22F	19	5.30	5.30	0.00	0.66	5.96	0.12	0.37	3.90	137.92	0.00
23	21	36.87	36.87	1858.34	17.79	1913.00	32.66	2.11	5.29	162.71	0.00
24	21	26.45	26.45	114.16	4.57	145.18	2.48	0.98	5.29	162.71	0.00
25	24	7.96	7.96	93.25	0.88	102.08	1.77	0.79	7.90	160.10	0.00
26F	24	26.29	10.55	0.00	1.52	12.08	0.21	0.40	7.90	160.10	15.74
27	25	28.56	28.56	55.87	3.31	87.73	1.53	0.72	8.45	159.55	0.00
28F	25	7.53	4.36	0.00	1.15	5.51	0.10	0.38	8.45	159.55	3.16
29	27	7.25	7.25	41.11	0.99	49.35	0.87	0.50	10.63	157.37	0.00
30F	27	5.65	5.65	0.00	0.86	6.51	0.14	0.32	10.63	129.36	0.00
31F	29	23.93	23.93	0.00	3.10	27.03	0.90	0.62	11.38	83.87	0.00
32F	29	14.47	12.78	0.00	1.30	14.08	0.25	0.50	11.38	156.62	1.69
33	23	9.59	9.59	1334.44	20.61	1364.64	23.48	2.07	6.56	161.44	0.00
34	23	23.78	23.78	443.06	26.86	493.70	8.49	1.55	6.56	161.44	0.00
35	34	37.17	37.17	378.13	23.89	439.19	7.60	1.50	7.38	160.62	0.00
36F	34	10.98	3.17	0.00	0.70	3.86	0.07	0.35	7.38	160.62	7.82
37	35	29.05	29.05	292.59	18.50	340.13	5.92	1.42	8.48	159.51	0.00
38	35	11.38	11.38	25.87	0.75	37.99	0.66	0.67	8.48	159.51	0.00
39F	38	46.72	13.87	0.00	3.44	17.31	0.49	0.63	9.37	97.48	32.85
40F	38	20.68	7.34	0.00	1.21	8.55	0.15	0.42	9.37	158.63	13.33
41	37	44.51	44.51	221.95	15.33	281.80	4.95	1.32	10.00	158.00	0.00
42F	37	14.55	8.41	0.00	2.38	10.79	0.19	0.38	10.00	157.99	6.14
43	41	42.31	42.31	148.45	10.97	201.74	3.59	1.19	11.86	156.14	0.00
44F	41	32.53	17.65	0.00	2.56	20.21	0.36	0.55	11.86	156.14	14.88
45	43	10.07	10.07	125.31	0.30	135.68	2.62	1.08	13.54	143.94	0.00
46F	43	23.70	10.44	0.00	2.33	12.77	0.23	0.46	13.54	154.46	13.25
47	45	32.88	32.88	45.86	0.17	78.92	1.66	1.04	14.12	132.08	0.00
48F	45	38.32	38.32	0.00	8.08	46.40	0.90	0.66	14.12	143.36	0.00
49	47	8.95	8.95	23.06	0.07	32.09	1.02	0.85	16.89	87.30	0.00
50F	47	11.54	11.54	0.00	2.23	13.78	0.30	0.52	16.89	129.31	0.00
51	49	7.61	7.61	11.61	0.04	19.26	2.20	0.78	17.94	24.32	0.00
52F	49	2.80	2.80	0.00	1.00	3.80	0.12	0.36	17.94	86.25	0.00
53	51	7.69	7.69	0.00	0.02	7.70	2.21	0.72	18.77	9.68	0.00
54	51	3.69	3.66	0.00	0.26	3.91	0.46	0.61	18.77	23.50	0.04
55F	54	14.00	0.00	0.00	0.00	0.00	0.00	0.00	22.00	0.00	14.00
56F	54	2.85	0.00	0.00	0.00	0.00	0.00	0.00	22.00	0.00	2.85
57	53	43.65	0.00	0.00	0.00	0.00	0.00	0.00	19.58	0.00	43.65
58F	53	18.11	0.00	0.00	0.00	0.00	0.00	0.00	19.58	0.00	18.11
59	57	15.01	0.00	0.00	0.00	0.00	0.00	0.00	22.48	0.00	15.01
60F	57	11.31	0.00	0.00	0.00	0.00	0.00	0.00	22.48	0.00	11.31
61F	59	34.22	0.00	0.00	0.00	0.00	0.00	0.00	23.41	0.00	34.22
62F	59	34.10	0.00	0.00	0.00	0.00	0.00	0.00	23.41	0.00	34.10
63	33	20.24	20.24	1185.97	18.49	1224.70	21.14	2.06	7.05	160.95	0.00
64	33	48.94	48.94	57.85	2.96	109.75	1.89	1.05	7.05	160.95	0.00
65F	64	11.28	4.22	0.00	0.62	4.84	0.08	0.40	9.21	158.79	7.06
66	64	23.84	23.84	26.72	2.45	53.01	0.93	0.58	9.21	158.79	0.00
67	66	1.57	1.57	12.53	0.55	14.65	0.26	0.19	11.14	156.85	0.00
68F	66	20.04	10.54	0.00	1.53	12.07	0.21	0.60	11.14	156.86	9.50
69F	67	10.33	0.40	0.00	0.04	0.44	0.17	0.45	11.60	7.27	9.93
70	67	8.00	8.00	0.00	0.15	8.15	0.82	0.57	11.60	27.70	0.00
71F	67	4.03	3.37	0.00	0.56	3.94	0.07	0.40	11.60	156.40	0.66
72F	70	69.13	0.00	0.00	0.00	0.00	0.00	0.00	12.35	0.00	69.13

Seg. Iden.	U/s Seg. Iden.	Local Irrigation Demand (Ham)	Canal Water Demand (Ham)	Total D/s Demand (Ham)	Canal Seepage Loss (Ham)	Total Canal Water Demand (Ham)	Required Discharge (Cumec)	Water Depth (m)	Fill Time (Hour)	Run Time (Hour)	Total GW Demand (Ham)
73F	70	17.41	0.00	0.00	0.00	0.00	0.00	0.00	12.35	0.00	17.41
74	63	17.29	17.29	1138.91	17.73	1173.94	20.35	2.04	7.79	160.21	0.00
75F	63	11.43	11.43	0.00	0.60	12.03	0.23	0.35	7.79	143.21	0.00
76	74	23.52	23.52	1094.80	17.15	1135.46	19.75	2.03	8.33	159.67	0.00
77F	74	10.92	3.01	0.00	0.44	3.45	0.06	0.35	8.33	159.66	7.90
78	76	9.83	9.83	1064.10	16.46	1090.39	19.07	2.01	9.15	158.85	0.00
79F	76	8.73	3.75	0.00	0.66	4.40	0.08	0.35	9.15	158.85	4.98
80F	78	12.10	5.05	0.00	0.59	5.64	0.10	0.40	9.53	158.47	7.05
81	78	24.22	24.22	1002.57	15.74	1042.53	18.27	2.00	9.53	158.47	0.00
82	78	1.99	1.99	13.73	0.21	15.93	0.28	0.50	9.53	158.47	0.00
83F	82	22.38	8.39	0.00	1.76	10.15	0.20	0.45	9.93	140.24	13.99
84F	82	6.75	3.20	0.00	0.38	3.58	0.06	0.35	9.93	158.06	3.55
85	81	56.02	56.02	914.69	10.40	981.11	17.36	1.97	10.98	157.02	0.00
86	81	8.53	8.53	0.26	0.67	9.46	0.18	0.53	10.98	149.68	0.00
87F	86	3.74	0.00	0.00	0.00	0.00	0.00	0.00	12.89	0.00	3.74
88F	86	5.80	0.22	0.00	0.04	0.26	0.05	0.30	12.89	14.07	5.59
89F	81	20.97	9.07	0.00	2.93	12.00	0.21	0.40	10.98	157.02	11.90
90	85	26.37	26.37	733.36	8.14	767.87	13.69	1.94	12.22	155.78	0.00
91	85	4.12	4.12	137.27	5.43	146.82	2.62	1.02	12.22	155.78	0.00
92	91	13.16	13.16	14.17	1.21	28.55	0.51	0.58	12.58	155.41	0.00
93F	92	19.69	8.90	0.00	1.56	10.46	0.19	0.49	14.17	153.83	10.80
94F	92	43.82	2.99	0.00	0.73	3.71	0.27	0.50	14.17	38.34	40.83
95	91	49.01	49.01	55.69	4.02	108.72	1.94	1.00	12.58	155.42	0.00
96	95	11.42	11.42	5.23	0.64	17.29	1.11	0.78	15.50	43.08	0.00
97	95	39.35	35.24	0.00	3.16	38.40	0.70	0.65	15.50	152.50	4.11
98F	97	14.32	0.00	0.00	0.00	0.00	0.00	0.00	19.35	0.00	14.32
99F	97	16.03	0.00	0.00	0.00	0.00	0.00	0.00	19.35	0.00	16.03
100	96	14.09	5.11	0.00	0.12	5.23	0.60	0.73	16.35	24.29	8.97
101F	96	42.10	0.00	0.00	0.00	0.00	0.00	0.00	16.35	0.00	42.10
102F	100	15.90	0.00	0.00	0.00	0.00	0.00	0.00	18.60	0.00	15.90
103F	100	5.11	0.00	0.00	0.00	0.00	0.00	0.00	18.60	0.00	5.11
104	90	7.74	7.74	706.26	7.65	721.65	12.92	1.92	12.82	155.18	0.00
105F	90	22.85	9.69	0.00	2.02	11.71	0.21	0.43	12.82	155.18	13.16
106	104	73.96	73.96	592.63	12.36	678.95	12.18	1.91	13.13	154.87	0.00
107	104	29.37	29.37	0.00	2.72	27.31	0.49	0.58	13.13	154.87	0.00
108F	107	10.81	0.00	0.00	0.00	0.00	0.00	0.00	17.21	0.00	10.81
109	107	13.30	0.00	0.00	0.00	0.00	0.00	0.00	17.21	0.00	13.30
110F	109	4.43	0.00	0.00	0.00	0.00	0.00	0.00	19.83	0.00	4.43
111F	109	2.06	0.00	0.00	0.00	0.00	0.00	0.00	19.83	0.00	2.06
112	106	27.61	27.61	306.33	6.19	340.13	6.18	1.86	15.12	152.88	0.00
113	106	56.60	56.60	21.99	3.59	82.18	1.50	0.77	15.12	152.39	0.00
114F	113	15.03	6.10	0.00	1.02	7.12	0.16	0.55	17.87	120.49	8.94
115	113	14.53	14.53	0.00	0.34	14.87	1.10	0.67	17.87	37.44	0.00
116F	115	59.46	0.00	0.00	0.00	0.00	0.00	0.00	19.06	0.00	59.46
117F	115	14.85	0.00	0.00	0.00	0.00	0.00	0.00	19.06	0.00	14.85
118	106	76.28	76.28	87.01	7.03	170.32	3.09	1.08	15.12	152.88	0.00
119	118	14.16	14.16	52.95	5.54	72.65	1.36	0.87	19.74	148.26	0.00
120F	118	24.71	12.93	0.00	1.43	14.36	0.27	0.64	19.74	148.26	11.78
121F	119	12.08	5.36	0.00	0.96	6.31	0.12	0.38	20.56	147.44	6.73
122	119	43.08	43.08	0.00	3.56	46.64	2.69	0.83	20.56	48.18	0.00
123F	122	9.06	0.00	0.00	0.00	0.00	0.00	0.00	23.67	0.00	9.06
124	122	36.48	0.00	0.00	0.00	0.00	0.00	0.00	23.67	0.00	36.48
125F	122	42.06	0.00	0.00	0.00	0.00	0.00	0.00	23.67	0.00	42.06
126F	122	10.53	0.00	0.00	0.00	0.00	0.00	0.00	23.67	0.00	10.53
127	124	22.57	0.00	0.00	0.00	0.00	0.00	0.00	26.01	0.00	22.57
128F	124	8.91	0.00	0.00	0.00	0.00	0.00	0.00	26.01	0.00	8.91
129	127	6.04	0.00	0.00	0.00	0.00	0.00	0.00	27.74	0.00	6.04
130F	127	9.31	0.00	0.00	0.00	0.00	0.00	0.00	27.74	0.00	9.31
131F	129	8.28	0.00	0.00	0.00	0.00	0.00	0.00	29.27	0.00	8.28
132F	129	8.41	0.00	0.00	0.00	0.00	0.00	0.00	29.27	0.00	8.41
133F	129	4.95	0.00	0.00	0.00	0.00	0.00	0.00	29.27	0.00	4.95
134	112	74.99	74.99	198.99	5.08	279.05	5.10	1.84	15.98	152.02	0.00
135F	112	56.50	21.75	0.00	5.52	27.27	0.50	0.52	15.98	152.02	34.74
136	134	54.26	54.26	126.87	7.14	188.26	3.48	1.79	17.70	150.30	0.00
137F	134	23.76	8.82	0.00	1.90	10.72	0.20	0.48	17.70	150.30	14.93
138	136	110.92	110.92	0.00	4.37	115.29	26.96	1.75	19.37	11.88	0.00
139F	136	44.48	3.17	0.00	0.83	4.00	0.50	0.53	19.37	22.29	41.31
140F	136	23.81	5.93	0.00	1.64	7.58	0.14	0.33	19.37	148.63	17.88
141	138	34.62	0.00	0.00	0.00	0.00	0.00	0.00	22.05	0.00	34.62
142	138	7.10	0.00	0.00	0.00	0.00	0.00	0.00	22.05	0.00	7.10
143	142	31.62	0.00	0.00	0.00	0.00	0.00	0.00	22.49	0.00	31.62
144F	143	4.12	0.00	0.00	0.00	0.00	0.00	0.00	26.41	0.00	4.12
145F	143	18.02	0.00	0.00	0.00	0.00	0.00	0.00	26.41	0.00	18.02
146F	142	9.23	0.00	0.00	0.00	0.00	0.00	0.00	22.49	0.00	9.23
147F	138	29.76	0.00	0.00	0.00	0.00	0.00	0.00	22.05	0.00	29.76

Seg. Iden.	U/s Seg. Iden.	Local Irrigation Demand (Ham)	Canal Water Demand (Ham)	Total D/s Demand (Ham)	Canal Seepage Loss (Ham)	Total Canal Water Demand (Ham)	Required Discharge (Cumec)	Water Depth (m)	Fill Time (Hour)	Run Time (Hour)	Total GW Demand (Ham)
148	141	52.70	0.00	0.00	0.00	0.00	0.00	0.00	23.21	0.00	52.70
149F	141	24.25	0.00	0.00	0.00	0.00	0.00	0.00	23.21	0.00	24.25
150F	141	24.29	0.00	0.00	0.00	0.00	0.00	0.00	23.21	0.00	24.29
151	148	34.69	0.00	0.00	0.00	0.00	0.00	0.00	25.06	0.00	34.69
152	148	3.40	0.00	0.00	0.00	0.00	0.00	0.00	25.06	0.00	3.40
153F	152	18.62	0.00	0.00	0.00	0.00	0.00	0.00	25.94	0.00	18.62
154F	152	48.90	0.00	0.00	0.00	0.00	0.00	0.00	25.94	0.00	48.90
155F	148	45.48	0.00	0.00	0.00	0.00	0.00	0.00	25.06	0.00	45.48
156	151	6.90	0.00	0.00	0.00	0.00	0.00	0.00	26.23	0.00	6.90
157F	151	43.53	0.00	0.00	0.00	0.00	0.00	0.00	26.23	0.00	43.53
158	156	8.80	0.00	0.00	0.00	0.00	0.00	0.00	26.73	0.00	8.80
159	158	22.80	0.00	0.00	0.00	0.00	0.00	0.00	27.85	0.00	22.80
160F	159	1.92	0.00	0.00	0.00	0.00	0.00	0.00	30.46	0.00	1.92
161F	159	14.70	0.00	0.00	0.00	0.00	0.00	0.00	30.46	0.00	14.70
162	158	34.21	0.00	0.00	0.00	0.00	0.00	0.00	27.85	0.00	34.21
163F	162	25.72	0.00	0.00	0.00	0.00	0.00	0.00	29.93	0.00	25.72
164	162	42.03	0.00	0.00	0.00	0.00	0.00	0.00	29.93	0.00	42.03
165	162	35.37	0.00	0.00	0.00	0.00	0.00	0.00	29.93	0.00	35.37
166F	162	25.13	0.00	0.00	0.00	0.00	0.00	0.00	29.93	0.00	25.13
167	164	23.49	0.00	0.00	0.00	0.00	0.00	0.00	38.48	0.00	23.49
168F	167	6.34	0.00	0.00	0.00	0.00	0.00	0.00	41.20	0.00	6.34
169F	167	28.10	0.00	0.00	0.00	0.00	0.00	0.00	41.20	0.00	28.10
170F	164	114.63	0.00	0.00	0.00	0.00	0.00	0.00	38.48	0.00	114.63
171	165	8.97	0.00	0.00	0.00	0.00	0.00	0.00	32.13	0.00	8.97
172F	165	43.04	0.00	0.00	0.00	0.00	0.00	0.00	32.13	0.00	43.04
173	171	21.59	0.00	0.00	0.00	0.00	0.00	0.00	33.66	0.00	21.59
174F	171	28.22	0.00	0.00	0.00	0.00	0.00	0.00	33.66	0.00	28.22
175	173	9.11	0.00	0.00	0.00	0.00	0.00	0.00	34.82	0.00	9.11
176F	173	44.45	0.00	0.00	0.00	0.00	0.00	0.00	34.82	0.00	44.45
177	175	157.04	0.00	0.00	0.00	0.00	0.00	0.00	35.42	0.00	157.04
178	175	72.53	0.00	0.00	0.00	0.00	0.00	0.00	35.42	0.00	72.53
179F	177	41.30	0.00	0.00	0.00	0.00	0.00	0.00	46.32	0.00	41.30
180	177	18.06	0.00	0.00	0.00	0.00	0.00	0.00	46.32	0.00	18.06
181F	180	22.72	0.00	0.00	0.00	0.00	0.00	0.00	49.31	0.00	22.72
182F	180	18.40	0.00	0.00	0.00	0.00	0.00	0.00	49.31	0.00	18.40
183	178	9.77	0.00	0.00	0.00	0.00	0.00	0.00	37.32	0.00	9.77
184F	183	85.81	0.00	0.00	0.00	0.00	0.00	0.00	38.16	0.00	85.81
185F	183	58.01	0.00	0.00	0.00	0.00	0.00	0.00	38.16	0.00	58.01
186	178	80.92	0.00	0.00	0.00	0.00	0.00	0.00	37.32	0.00	80.92
187	186	41.05	0.00	0.00	0.00	0.00	0.00	0.00	41.91	0.00	41.05
188	187	32.79	0.00	0.00	0.00	0.00	0.00	0.00	44.93	0.00	32.79
189F	188	2.92	0.00	0.00	0.00	0.00	0.00	0.00	46.27	0.00	2.92
190F	188	10.69	0.00	0.00	0.00	0.00	0.00	0.00	46.27	0.00	10.69
191F	187	13.85	0.00	0.00	0.00	0.00	0.00	0.00	44.93	0.00	13.85
192F	186	25.69	0.00	0.00	0.00	0.00	0.00	0.00	41.91	0.00	25.69
193	156	74.30	0.00	0.00	0.00	0.00	0.00	0.00	26.73	0.00	74.30
194	193	6.87	0.00	0.00	0.00	0.00	0.00	0.00	30.10	0.00	6.87
195F	193	13.63	0.00	0.00	0.00	0.00	0.00	0.00	30.10	0.00	13.63
196	194	4.14	0.00	0.00	0.00	0.00	0.00	0.00	30.79	0.00	4.14
197F	194	27.61	0.00	0.00	0.00	0.00	0.00	0.00	30.79	0.00	27.61
198	196	17.79	0.00	0.00	0.00	0.00	0.00	0.00	31.33	0.00	17.79
199F	196	14.54	0.00	0.00	0.00	0.00	0.00	0.00	31.33	0.00	14.54
200F	198	12.76	0.00	0.00	0.00	0.00	0.00	0.00	33.26	0.00	12.76
201F	198	14.24	0.00	0.00	0.00	0.00	0.00	0.00	33.26	0.00	14.24
202	196	16.46	0.00	0.00	0.00	0.00	0.00	0.00	31.33	0.00	16.46
203	202	9.28	0.00	0.00	0.00	0.00	0.00	0.00	32.74	0.00	9.28
204F	202	21.93	0.00	0.00	0.00	0.00	0.00	0.00	32.74	0.00	21.93
205	203	15.60	0.00	0.00	0.00	0.00	0.00	0.00	33.59	0.00	15.60
206F	205	21.86	0.00	0.00	0.00	0.00	0.00	0.00	34.57	0.00	21.86
207	205	34.73	0.00	0.00	0.00	0.00	0.00	0.00	34.57	0.00	34.73
208	207	15.81	0.00	0.00	0.00	0.00	0.00	0.00	35.94	0.00	15.81
209F	208	9.41	0.00	0.00	0.00	0.00	0.00	0.00	36.91	0.00	9.41
210F	208	17.78	0.00	0.00	0.00	0.00	0.00	0.00	36.91	0.00	17.78
211	207	19.33	0.00	0.00	0.00	0.00	0.00	0.00	35.94	0.00	19.33
212F	211	3.51	0.00	0.00	0.00	0.00	0.00	0.00	40.82	0.00	3.51
213F	211	5.76	0.00	0.00	0.00	0.00	0.00	0.00	40.82	0.00	5.76
214	203	41.17	0.00	0.00	0.00	0.00	0.00	0.00	33.59	0.00	41.17
215	214	12.97	0.00	0.00	0.00	0.00	0.00	0.00	37.15	0.00	12.97
216F	215	18.84	0.00	0.00	0.00	0.00	0.00	0.00	38.24	0.00	18.84
217F	215	12.98	0.00	0.00	0.00	0.00	0.00	0.00	38.24	0.00	12.98
218F	214	26.17	0.00	0.00	0.00	0.00	0.00	0.00	37.15	0.00	26.17

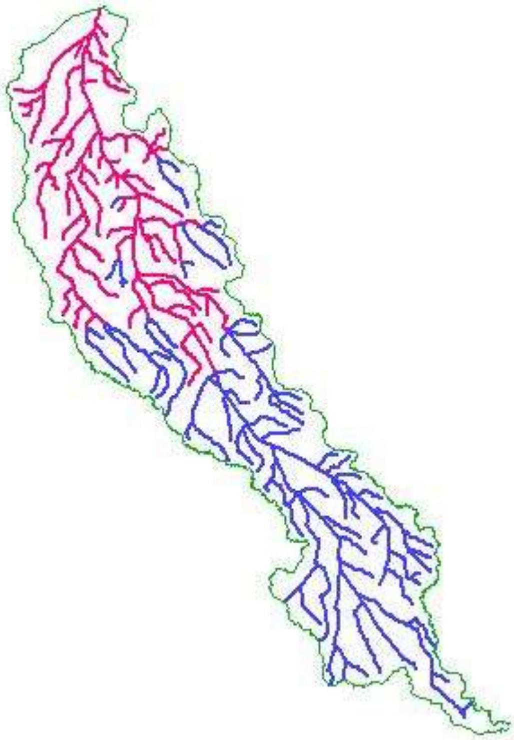

Figure – 5.3: Operation plan of Lakhaoti canal network with policy of head-reach priority with available head Q of 40 cumec (Red – running, Blue – non-running canals)

Table – 5.5
Operation scenario with water availability constraint using Policy-2

Seg. Iden.	U/s Seg. Iden.	Local Irrigation Demand (Ham)	Canal Water Demand (Ham)	Total D/s Demand (Ham)	Canal Seepage Loss (Ham)	Total Canal Water Demand (Ham)	Required Discharge (Cumec)	Water Depth (m)	Fill Time (Hour)	Run Time (Hour)	Total GW Demand (Ham)
1	0	4.75	4.75	2402.10	11.85	2418.70	39.99	2.25	0.00	168.00	0.00
2	1	4.30	4.30	2386.03	11.77	2402.10	39.91	2.24	0.83	167.17	0.00
3F	1	8.42	0.00	0.00	0.00	0.00	0.00	0.00	0.83	0.00	8.42
4	2	2.10	2.10	2364.85	19.09	2386.03	39.75	2.22	1.24	166.76	0.00
5	2	3.80	0.00	0.00	0.00	0.00	0.00	0.00	1.24	0.00	3.80
6	5	34.44	0.00	0.00	0.00	0.00	0.00	0.00	2.93	0.00	34.44
7F	5	11.79	0.00	0.00	0.00	0.00	0.00	0.00	2.93	0.00	11.79
8F	6	11.58	0.00	0.00	0.00	0.00	0.00	0.00	9.06	0.00	11.58
9	6	7.42	0.00	0.00	0.00	0.00	0.00	0.00	9.06	0.00	7.42
10	9	11.31	0.00	0.00	0.00	0.00	0.00	0.00	10.63	0.00	11.31
11F	10	0.62	0.00	0.00	0.00	0.00	0.00	0.00	12.56	0.00	0.62
12F	10	2.18	0.00	0.00	0.00	0.00	0.00	0.00	12.56	0.00	2.18
13F	9	15.27	0.00	0.00	0.00	0.00	0.00	0.00	10.63	0.00	15.27
14F	2	7.43	0.00	0.00	0.00	0.00	0.00	0.00	1.24	0.00	7.43
15	4	14.15	14.15	2324.69	26.01	2364.85	39.64	2.19	2.29	165.71	0.00
16	4	12.69	0.00	0.00	0.00	0.00	0.00	0.00	2.29	0.00	12.69
17F	16	11.47	0.00	0.00	0.00	0.00	0.00	0.00	5.30	0.00	11.47
18F	16	1.12	0.00	0.00	0.00	0.00	0.00	0.00	5.30	0.00	1.12
19	15	8.04	8.04	2291.07	25.57	2324.69	39.18	2.16	3.17	164.83	0.00
20F	15	9.96	0.00	0.00	0.00	0.00	0.00	0.00	3.17	0.00	9.96
21	19	29.53	29.53	2236.34	25.20	2291.07	38.78	2.15	3.90	164.10	0.00
22F	19	5.30	0.00	0.00	0.00	0.00	0.00	0.00	3.90	0.00	5.30
23	21	36.87	36.87	2178.68	20.80	2236.34	38.18	2.11	5.29	162.71	0.00
24	21	26.45	0.00	0.00	0.00	0.00	0.00	0.00	5.29	0.00	26.45
25	24	7.96	0.00	0.00	0.00	0.00	0.00	0.00	7.90	0.00	7.96
26F	24	26.29	0.00	0.00	0.00	0.00	0.00	0.00	7.90	0.00	26.29
27	25	28.56	0.00	0.00	0.00	0.00	0.00	0.00	8.45	0.00	28.56
28F	25	7.53	0.00	0.00	0.00	0.00	0.00	0.00	8.45	0.00	7.53
29	27	7.25	0.00	0.00	0.00	0.00	0.00	0.00	10.63	0.00	7.25
30F	27	5.65	0.00	0.00	0.00	0.00	0.00	0.00	10.63	0.00	5.65
31F	29	23.93	0.00	0.00	0.00	0.00	0.00	0.00	11.38	0.00	23.93
32F	29	14.47	0.00	0.00	0.00	0.00	0.00	0.00	11.38	0.00	14.47
33	23	9.59	9.59	1852.96	28.56	1891.11	32.54	2.07	6.56	161.44	0.00
34	23	23.78	23.78	248.15	15.64	287.57	5.29	1.55	6.56	150.91	0.00
35	34	37.17	37.17	197.47	13.50	248.15	4.59	1.50	7.38	150.10	0.00
36F	34	10.98	0.00	0.00	0.00	0.00	0.00	0.00	7.38	0.00	10.98

Seg. Iden.	U/s Seg. Iden.	Local Irrigation Demand (Ham)	Canal Water Demand (Ham)	Total D/s Demand (Ham)	Canal Seepage Loss (Ham)	Total Canal Water Demand (Ham)	Required Discharge (Cumec)	Water Depth (m)	Fill Time (Hour)	Run Time (Hour)	Total GW Demand (Ham)
37	35	29.05	29.05	157.69	10.74	197.47	3.68	1.42	8.48	148.99	0.00
38	35	11.38	0.00	0.00	0.00	0.00	0.00	0.00	8.48	0.00	11.38
39F	38	46.72	0.00	0.00	0.00	0.00	0.00	0.00	9.37	0.00	46.72
40F	38	20.68	0.00	0.00	0.00	0.00	0.00	0.00	9.37	0.00	20.68
41	37	44.51	44.51	104.59	8.58	157.69	2.97	1.32	10.00	147.47	0.00
42F	37	14.55	0.00	0.00	0.00	0.00	0.00	0.00	10.00	0.00	14.55
43	41	42.31	42.31	56.59	5.69	104.59	2.00	1.19	11.86	145.61	0.00
44F	41	32.53	0.00	0.00	0.00	0.00	0.00	0.00	11.86	0.00	32.53
45	43	10.07	10.07	46.40	0.12	56.59	1.09	1.08	13.54	143.94	0.00
46F	43	23.70	0.00	0.00	0.00	0.00	0.00	0.00	13.54	0.00	23.70
47	45	32.88	0.00	0.00	0.00	0.00	0.00	0.00	14.12	0.00	32.88
48F	45	38.32	38.32	0.00	8.08	46.40	0.90	0.66	14.12	143.36	0.00
49	47	8.95	0.00	0.00	0.00	0.00	0.00	0.00	16.89	0.00	8.95
50F	47	11.54	0.00	0.00	0.00	0.00	0.00	0.00	16.89	0.00	11.54
51	49	7.61	0.00	0.00	0.00	0.00	0.00	0.00	17.94	0.00	7.61
52F	49	2.80	0.00	0.00	0.00	0.00	0.00	0.00	17.94	0.00	2.80
53	51	7.69	0.00	0.00	0.00	0.00	0.00	0.00	18.77	0.00	7.69
54	51	3.69	0.00	0.00	0.00	0.00	0.00	0.00	18.77	0.00	3.69
55F	54	14.00	0.00	0.00	0.00	0.00	0.00	0.00	22.00	0.00	14.00
56F	54	2.85	0.00	0.00	0.00	0.00	0.00	0.00	22.00	0.00	2.85
57	53	43.65	0.00	0.00	0.00	0.00	0.00	0.00	19.58	0.00	43.65
58F	53	18.11	0.00	0.00	0.00	0.00	0.00	0.00	19.58	0.00	18.11
59	57	15.01	0.00	0.00	0.00	0.00	0.00	0.00	22.48	0.00	15.01
60F	57	11.31	0.00	0.00	0.00	0.00	0.00	0.00	22.48	0.00	11.31
61F	59	34.22	0.00	0.00	0.00	0.00	0.00	0.00	23.41	0.00	34.22
62F	59	34.10	0.00	0.00	0.00	0.00	0.00	0.00	23.41	0.00	34.10
63	33	20.24	20.24	1759.80	27.29	1807.33	31.19	2.06	7.05	160.95	0.00
64	33	48.94	44.41	0.00	1.22	45.63	1.91	1.05	7.05	66.39	4.53
65F	64	11.28	0.00	0.00	0.00	0.00	0.00	0.00	9.21	0.00	11.28
66	64	23.84	0.00	0.00	0.00	0.00	0.00	0.00	9.21	0.00	23.84
67	66	1.57	0.00	0.00	0.00	0.00	0.00	0.00	11.14	0.00	1.57
68F	66	20.04	0.00	0.00	0.00	0.00	0.00	0.00	11.14	0.00	20.04
69F	67	10.33	0.00	0.00	0.00	0.00	0.00	0.00	11.60	0.00	10.33
70	67	8.00	0.00	0.00	0.00	0.00	0.00	0.00	11.60	0.00	8.00
71F	67	4.03	0.00	0.00	0.00	0.00	0.00	0.00	11.60	0.00	4.03
72F	70	69.13	0.00	0.00	0.00	0.00	0.00	0.00	12.35	0.00	69.13
73F	70	17.41	0.00	0.00	0.00	0.00	0.00	0.00	12.35	0.00	17.41
74	63	17.29	17.29	1715.93	26.57	1759.80	30.51	2.04	7.79	160.21	0.00
75F	63	11.43	0.00	0.00	0.00	0.00	0.00	0.00	7.79	0.00	11.43
76	74	23.52	23.52	1666.50	25.91	1715.93	29.85	2.03	8.33	159.67	0.00
77F	74	10.92	0.00	0.00	0.00	0.00	0.00	0.00	8.33	0.00	10.92
78	76	9.83	9.83	1631.51	25.16	1666.50	29.14	2.01	9.15	158.85	0.00
79F	76	8.73	0.00	0.00	0.00	0.00	0.00	0.00	9.15	0.00	8.73
80F	78	12.10	0.00	0.00	0.00	0.00	0.00	0.00	9.53	0.00	12.10
81	78	24.22	24.22	1582.65	24.64	1631.51	28.60	2.00	9.53	158.47	0.00
82	78	1.99	0.00	0.00	0.00	0.00	0.00	0.00	9.53	0.00	1.99
83F	82	22.38	0.00	0.00	0.00	0.00	0.00	0.00	9.93	0.00	22.38
84F	82	6.75	0.00	0.00	0.00	0.00	0.00	0.00	9.93	0.00	6.75
85	81	56.02	56.02	1509.86	16.78	1582.65	28.00	1.97	10.98	157.02	0.00
86	81	8.53	0.00	0.00	0.00	0.00	0.00	0.00	10.98	0.00	8.53
87F	86	3.74	0.00	0.00	0.00	0.00	0.00	0.00	12.89	0.00	3.77
88F	86	5.80	0.00	0.00	0.00	0.00	0.00	0.00	12.89	0.00	5.80
89F	81	20.97	0.00	0.00	0.00	0.00	0.00	0.00	10.98	0.00	20.97
90	85	26.37	26.37	1467.49	16.00	1509.86	26.92	1.94	12.22	155.78	0.00
91	85	4.12	0.00	0.00	0.00	0.00	0.00	0.00	12.22	0.00	4.12
92	91	13.16	0.00	0.00	0.00	0.00	0.00	0.00	12.58	0.00	13.16
93F	92	19.69	0.00	0.00	0.00	0.00	0.00	0.00	14.17	0.00	19.69
94F	92	43.82	0.00	0.00	0.00	0.00	0.00	0.00	14.17	0.00	43.82
95	91	49.01	0.00	0.00	0.00	0.00	0.00	0.00	12.58	0.00	49.01
96	95	11.42	0.00	0.00	0.00	0.00	0.00	0.00	15.50	0.00	11.42
97	95	39.35	0.00	0.00	0.00	0.00	0.00	0.00	15.50	0.00	39.35
98F	97	14.32	0.00	0.00	0.00	0.00	0.00	0.00	19.35	0.00	14.32
99F	97	16.03	0.00	0.00	0.00	0.00	0.00	0.00	19.35	0.00	16.03
100	96	14.09	0.00	0.00	0.00	0.00	0.00	0.00	16.35	0.00	14.09
101F	96	42.10	0.00	0.00	0.00	0.00	0.00	0.00	16.35	0.00	42.10
102F	100	15.90	0.00	0.00	0.00	0.00	0.00	0.00	18.60	0.00	15.90
103F	100	5.11	0.00	0.00	0.00	0.00	0.00	0.00	18.60	0.00	5.47
104	90	7.74	7.74	1432.60	15.43	1455.78	26.06	1.92	12.82	155.18	0.00
105F	90	22.85	9.69	0.00	2.02	11.71	0.21	0.43	12.82	155.18	13.16
106	104	73.96	73.96	1305.75	25.58	1405.29	25.21	1.91	13.13	154.87	0.00
107	104	29.37	24.59	0.00	2.72	27.31	0.49	0.58	13.13	154.87	4.78
108F	107	10.81	0.00	0.00	0.00	0.00	0.00	0.00	17.21	0.00	10.81
109	107	13.30	0.00	0.00	0.00	0.00	0.00	0.00	17.21	0.00	13.30
110F	109	4.43	0.00	0.00	0.00	0.00	0.00	0.00	19.83	0.00	4.43
111F	109	2.06	0.00	0.00	0.00	0.00	0.00	0.00	19.83	0.00	2.06

Seg. Iden.	U/s Seg. Iden.	Local Irrigation Demand (Ham)	Canal Water Demand (Ham)	Total D/s Demand (Ham)	Canal Seepage Loss (Ham)	Total Canal Water Demand (Ham)	Required Discharge (Cumec)	Water Depth (m)	Fill Time (Hour)	Run Time (Hour)	Total GW Demand (Ham)
112	106	27.61	27.61	1254.38	23.76	1305.75	23.72	1.86	15.12	152.88	0.00
113	106	56.60	0.00	0.00	0.00	0.00	0.00	0.00	15.12	0.00	56.60
114F	113	15.03	0.00	0.00	0.00	0.00	0.00	0.00	17.87	0.00	15.03
115	113	14.53	0.00	0.00	0.00	0.00	0.00	0.00	17.87	0.00	14.53
116F	115	59.46	0.00	0.00	0.00	0.00	0.00	0.00	19.06	0.00	62.63
117F	115	14.85	0.00	0.00	0.00	0.00	0.00	0.00	19.06	0.00	16.21
118	106	76.28	0.00	0.00	0.00	0.00	0.00	0.00	15.12	0.00	76.28
119	118	14.16	0.00	0.00	0.00	0.00	0.00	0.00	19.74	0.00	15.00
120F	118	24.71	0.00	0.00	0.00	0.00	0.00	0.00	19.74	0.00	24.71
121F	119	12.08	0.00	0.00	0.00	0.00	0.00	0.00	20.56	0.00	12.08
122	119	43.08	0.00	0.00	0.00	0.00	0.00	0.00	20.56	0.00	43.08
123F	122	9.06	0.00	0.00	0.00	0.00	0.00	0.00	23.67	0.00	9.06
124	122	36.48	0.00	0.00	0.00	0.00	0.00	0.00	23.67	0.00	36.48
125F	122	42.06	0.00	0.00	0.00	0.00	0.00	0.00	23.67	0.00	42.06
126F	122	10.53	0.00	0.00	0.00	0.00	0.00	0.00	23.67	0.00	10.53
127	124	22.57	0.00	0.00	0.00	0.00	0.00	0.00	26.01	0.00	22.57
128F	124	8.91	0.00	0.00	0.00	0.00	0.00	0.00	26.01	0.00	8.91
129	127	6.04	0.00	0.00	0.00	0.00	0.00	0.00	27.74	0.00	6.04
130F	127	9.31	0.00	0.00	0.00	0.00	0.00	0.00	27.74	0.00	9.31
131F	129	8.28	0.00	0.00	0.00	0.00	0.00	0.00	29.27	0.00	8.28
132F	129	8.41	0.00	0.00	0.00	0.00	0.00	0.00	29.27	0.00	8.41
133F	129	4.95	0.00	0.00	0.00	0.00	0.00	0.00	29.27	0.00	4.95
134	112	74.99	74.99	1156.56	22.83	1254.38	22.92	1.84	15.98	152.02	0.00
135F	112	56.50	0.00	0.00	0.00	0.00	0.00	0.00	15.98	0.00	56.50
136	134	54.26	54.26	1058.47	43.83	1156.56	21.38	1.79	17.70	150.30	0.00
137F	134	23.76	0.00	0.00	0.00	0.00	0.00	0.00	17.70	0.00	23.76
138	136	110.92	110.92	907.43	40.12	1058.47	19.78	1.75	19.37	148.63	0.00
139F	136	44.48	0.00	0.00	0.00	0.00	0.00	0.00	19.37	0.00	44.48
140F	136	23.81	0.00	0.00	0.00	0.00	0.00	0.00	19.37	0.00	23.81
141	138	34.62	34.62	793.58	32.63	860.82	16.38	1.68	22.05	145.95	0.00
142	138	7.10	7.10	39.17	0.34	46.61	1.70	0.71	22.05	75.97	0.00
143	142	31.62	31.62	4.67	2.88	39.17	1.44	0.64	22.49	75.52	0.00
144F	143	4.12	4.12	0.00	0.56	4.67	0.18	0.40	26.41	71.60	0.00
145F	143	18.02	0.00	0.00	0.00	0.00	0.00	0.00	26.41	0.00	18.02
146F	142	9.23	0.00	0.00	0.00	0.00	0.00	0.00	22.49	0.00	9.23
147F	138	29.76	0.00	0.00	0.00	0.00	0.00	0.00	22.05	0.00	29.76
148	141	52.70	52.70	710.80	30.08	793.58	15.23	1.64	23.21	144.79	0.00
149F	141	24.25	0.00	0.00	0.00	0.00	0.00	0.00	23.21	0.00	24.25
150F	141	24.29	0.00	0.00	0.00	0.00	0.00	0.00	23.21	0.00	24.29
151	148	34.69	34.69	645.83	26.81	707.33	13.75	1.60	25.06	142.94	0.00
152	148	3.40	3.40	0.00	0.07	3.47	0.65	0.60	25.06	14.80	0.00
153F	152	18.62	0.00	0.00	0.00	0.00	0.00	0.00	25.94	0.00	18.62
154F	152	48.90	0.00	0.00	0.00	0.00	0.00	0.00	25.94	0.00	48.90
155F	148	45.48	0.00	0.00	0.00	0.00	0.00	0.00	25.06	0.00	45.48
156	151	6.90	6.90	614.45	24.48	645.83	12.65	1.56	26.23	141.77	0.00
157F	151	43.53	0.00	0.00	0.00	0.00	0.00	0.00	26.23	0.00	43.53
158	156	8.80	8.80	479.32	7.63	495.76	9.75	1.54	26.73	141.27	0.00
159	158	22.80	0.00	0.00	0.00	0.00	0.00	0.00	27.85	0.00	22.80
160F	159	1.92	0.00	0.00	0.00	0.00	0.00	0.00	30.46	0.00	1.92
161F	159	14.70	0.00	0.00	0.00	0.00	0.00	0.00	30.46	0.00	14.70
162	158	34.21	34.21	437.73	7.38	479.32	9.50	1.38	27.85	140.15	0.00
163F	162	25.72	15.48	0.00	3.52	19.00	0.38	0.76	29.93	138.07	10.24
164	162	42.03	42.03	72.45	11.40	125.88	2.56	0.90	29.93	136.50	0.00
165	162	35.37	35.37	257.39	0.09	292.85	5.89	1.30	29.93	138.07	0.00
166F	162	25.13	0.00	0.00	0.00	0.00	0.00	0.00	29.93	0.00	25.13
167	164	23.49	23.49	18.71	2.14	44.35	0.96	0.76	38.48	127.95	0.00
168F	167	6.34	0.00	0.00	0.00	0.00	0.00	0.00	41.20	0.00	6.34
169F	167	28.10	16.52	0.00	2.20	18.71	0.51	0.58	41.20	102.55	11.58
170F	164	114.63	22.62	0.00	5.48	28.10	0.87	0.62	38.48	89.91	92.00
171	165	8.97	8.97	243.09	5.33	257.39	5.26	1.28	32.13	135.87	0.00
172F	165	43.04	0.00	0.00	0.00	0.00	0.00	0.00	32.13	0.00	43.04
173	171	21.59	21.59	216.47	5.03	243.09	5.03	1.24	33.66	134.34	0.00
174F	171	28.22	0.00	0.00	0.00	0.00	0.00	0.00	33.66	0.00	28.22
175	173	9.11	9.11	207.13	0.24	216.47	4.51	1.26	34.82	133.18	0.00
176F	173	44.45	0.00	0.00	0.00	0.00	0.00	0.00	34.82	0.00	44.45
177	175	157.04	68.78	0.00	9.61	78.39	1.64	0.90	35.42	132.58	88.26
178	175	72.53	72.53	53.11	3.10	128.74	2.70	1.15	35.42	132.58	0.00
179F	177	41.30	0.00	0.00	0.00	0.00	0.00	0.00	46.32	0.00	41.30
180	177	18.06	0.00	0.00	0.00	0.00	0.00	0.00	46.32	0.00	18.06
181F	180	22.72	0.00	0.00	0.00	0.00	0.00	0.00	49.31	0.00	22.72
182F	180	18.40	0.00	0.00	0.00	0.00	0.00	0.00	49.31	0.00	18.40
183	178	9.77	9.77	39.05	4.29	53.11	1.13	0.80	37.32	130.68	0.00
184F	183	85.81	33.00	0.00	6.04	39.05	0.84	0.70	38.16	129.84	52.81
185F	183	58.01	0.00	0.00	0.00	0.00	0.00	0.00	38.16	0.00	58.01
186	178	80.92	0.00	0.00	0.00	0.00	0.00	0.00	37.32	0.00	80.92

Seg. Iden.	U/s Seg. Iden.	Local Irrigation Demand (Ham)	Canal Water Demand (Ham)	Total D/s Demand (Ham)	Canal Seepage Loss (Ham)	Total Canal Water Demand (Ham)	Required Discharge (Cumec)	Water Depth (m)	Fill Time (Hour)	Run Time (Hour)	Total GW Demand (Ham)
187	186	41.05	0.00	0.00	0.00	0.00	0.00	0.00	41.91	0.00	41.05
188	187	32.79	0.00	0.00	0.00	0.00	0.00	0.00	44.93	0.00	34.52
189F	188	2.92	0.00	0.00	0.00	0.00	0.00	0.00	46.27	0.00	2.92
190F	188	10.69	0.00	0.00	0.00	0.00	0.00	0.00	46.27	0.00	10.69
191F	187	13.85	0.00	0.00	0.00	0.00	0.00	0.00	44.93	0.00	13.85
192F	186	25.69	0.00	0.00	0.00	0.00	0.00	0.00	41.91	0.00	26.73
193	156	74.30	74.30	42.32	2.07	118.69	2.33	1.28	26.73	141.27	0.00
194	193	6.87	6.87	34.54	0.91	42.32	0.85	1.23	30.10	137.90	0.00
195F	193	13.63	0.00	0.00	0.00	0.00	0.00	0.00	30.10	0.00	13.63
196	194	4.14	4.14	18.58	0.64	23.35	0.81	1.10	30.79	79.76	0.00
197F	194	27.61	9.32	0.00	1.87	11.19	0.23	0.40	30.79	137.21	18.29
198	196	17.79	17.79	0.00	0.78	18.58	0.65	0.70	31.33	79.23	0.00
199F	196	14.54	0.00	0.00	0.00	0.00	0.00	0.00	31.33	0.00	14.54
200F	198	12.76	0.00	0.00	0.00	0.00	0.00	0.00	33.26	0.00	12.76
201F	198	14.24	0.00	0.00	0.00	0.00	0.00	0.00	33.26	0.00	14.24
202	196	16.46	0.00	0.00	0.00	0.00	0.00	0.00	31.33	0.00	16.46
203	202	9.28	0.00	0.00	0.00	0.00	0.00	0.00	32.74	0.00	9.28
204F	202	21.93	0.00	0.00	0.00	0.00	0.00	0.00	32.74	0.00	22.32
205	203	15.60	0.00	0.00	0.00	0.00	0.00	0.00	33.59	0.00	15.60
206F	205	21.86	0.00	0.00	0.00	0.00	0.00	0.00	34.57	0.00	21.86
207	205	34.73	0.00	0.00	0.00	0.00	0.00	0.00	34.57	0.00	34.73
208	207	15.81	0.00	0.00	0.00	0.00	0.00	0.00	35.94	0.00	15.81
209F	208	9.41	0.00	0.00	0.00	0.00	0.00	0.00	36.91	0.00	9.41
210F	208	17.78	0.00	0.00	0.00	0.00	0.00	0.00	36.91	0.00	17.78
211	207	19.33	0.00	0.00	0.00	0.00	0.00	0.00	35.94	0.00	19.33
212F	211	3.51	0.00	0.00	0.00	0.00	0.00	0.00	40.82	0.00	3.51
213F	211	5.76	0.00	0.00	0.00	0.00	0.00	0.00	40.82	0.00	5.76
214	203	41.17	0.00	0.00	0.00	0.00	0.00	0.00	33.59	0.00	43.84
215	214	12.97	0.00	0.00	0.00	0.00	0.00	0.00	37.15	0.00	12.97
216F	215	18.84	0.00	0.00	0.00	0.00	0.00	0.00	38.24	0.00	18.84
217F	215	12.98	0.00	0.00	0.00	0.00	0.00	0.00	38.24	0.00	12.98
218F	214	26.17	0.00	0.00	0.00	0.00	0.00	0.00	37.15	0.00	26.17

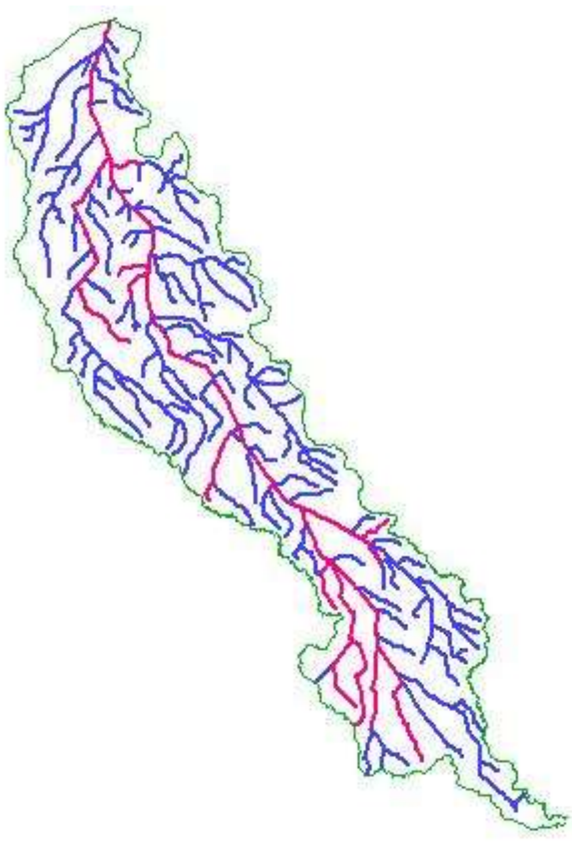

Figure – 5.4: Operation plan of Lakhaoti canal network with policy of conjunctive use with head Q of 40 cumec (Red – running and Blue – non-running canals)

Increased canal seepage in Policy-2 results in increased withdrawal of groundwater, though from a shallower water table area. The overall energy requirement for groundwater pumping under Policy-2 may be less or more than that under Policy-1 depending on the extent and location of additional groundwater pumping as compared to Policy-1.

Based on these observations, it has been concluded that though the Policy-2 allocates canal water in areas of deeper water table, thus saving energy demand, still a lot of canal water is lost through seepage in transporting it to areas of deep water table. Therefore, there may lie a canal-run configuration in-between canal-run configuration of Policy-1 and Policy-2 that may result in lesser requirement of energy. With this background, Policy-3 has been formulated in which operation simulation is carried out iteratively for various canal-run configurations and corresponding energy demand in the system is worked out. The canal-run configuration that requires minimum energy is finally adopted under Policy-3. Simulation analysis is started from the canal-run configuration of Policy-2 (shown in Figure – 5.4). The canal-run configuration is iteratively moved in the upstream direction towards the head by curtailing the canal water demands of most distant canal segment (from the network head) and using the saved water to meet the demands of upstream segments. Energy requirement for pumping groundwater in the command is computed for all canal-run configurations. Finally, the configuration which requires least energy for groundwater pumping is recommended under Policy-3. The variation of energy requirement in the command area as the canal-run configuration moves from Policy-2 in upstream direction for a week is presented in Figure – 5.5. The results of canal operation with Policy-3 are shown in Figure – 5.6.

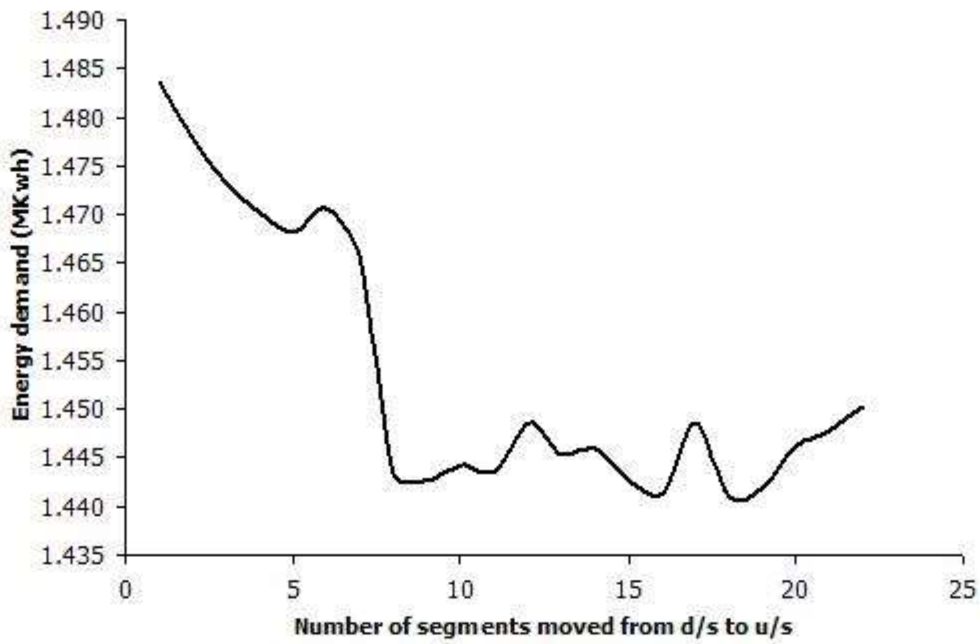

Figure – 5.5: Variation of energy demand for different canal-run configuration

Figure – 5.6: Operation plan of Lakhaoti canal network with policy of conjunctive use with minimum energy (Policy-3) with head Q of 40 cumec

Summary results of the three policies are compiled in Table – 5.6.

Table – 5.6
Summary results of three allocation policies

Performance Measure	Policy-1	Policy-2	Policy-3
Surface Water Available at Canal Head (Mm3)	24.19	24.19	24.19
Irrigation Demand at Head (Mm3)	50.75	50.75	50.75
Surface Water Utilized for Irrigation (Mm3)	18.84	16.50	18.56
Canal Seepage Loss (Mm3)	5.35	7.69	5.62
Groundwater Use in Command (Mm3)	31.91	34.37	32.31
Energy Demand in Canal-irrigable Area (MKwh)	1.2942	1.3269	1.286

Comparison of results of Policy-3 with two other policies shows that Policy-3 results in least requirement of energy for meeting irrigation demands of the irrigable command. In comparison to results of Policy-1, it is observed that some amount of energy can be saved by judicious operation of the canal system as illustrated for the particular case taken for week 32.

The effective use of available water for irrigation in Policy-3 is also high as compared to the policy of conjunctive use (Policy-2). Thus, policy of conjunctive use with minimum energy demand results in increased effective utilization of the canal water, relatively increased seepage in areas of deeper groundwater and least energy demand for pumping groundwater.

The developed allocation model, in conjunctive with demand model, can help the irrigation manager in optimally utilizing the available canal and groundwater resources in an irrigation system. Consideration of groundwater conditions in the command in the operation of a canal network along with the irrigation demand and supply situation can help a long way for sustainable use of water resources in a command. A tool is now available to integrate the multi-disciplinary information in a scientific way to converge at some meaningful decision-making. The presentation of results in map form can help a great deal in comprehending and understanding the system in great detail.

* * *

CHAPTER – 6
CONCLUSIONS

Information is vital in reducing uncertainty, evaluating alternative courses of action and revealing new avenues. Availability of the right information at the right time is a crucial factor in decision-making. Large amount of information about various processes is necessary for irrigation management in a command area. Conjunctive management of water in irrigation systems requires huge volume of data pertaining to hydrological, hydro-geological, hydro-meteorological, soil, agronomic, and cropping pattern parameters in command areas. For the operation of canal system in a command area, information on the existing cropping pattern, irrigation demands, groundwater conditions, canal system characteristics, and their spatial distribution is a prerequisite. These data need to be effectively analyzed, stored and retrieved whenever required. It is also required to continuously update this information for real-time management. For this purpose a database is used in conjunction with simulation model to evaluate the system operation and provide an integrated picture of the total system.

Simulation of water systems are mostly computational and contain equations involved in the process of water storage and transfer. Computers now make possible the use of larger data sets, more sophisticated analytical techniques and a variety of graphical means for presenting analysis results. The objective of data analysis is to provide decision-makers with the kind of information that cannot be efficiently provided by conventional methods.

While the demands for water by all the sectors (municipal, industrial, irrigation, hydropower etc.) are rising, investments for development of additional water resources are limited. Keeping this in view, the National Water Policy adopted in 1987, advocated scientific, objective, integrated, and multidisciplinary development and management of water resources systems. The implementation of the policy is feasible in the irrigation sector only if a formal framework for water resources decision-making that enables spatial assessment of water supplies and demands in real-time and a balancing of the two to meet specified objectives, is available. To realize these objectives, there is a need to develop a canal network system that can utilize real-time data and can help the operator in decision-making process.

A GIS based procedure has been developed in the present study for conjunctive operation of the canal system in a command area. Based on the water balance of the root zone for each week, spatially distributed irrigation water demands in the canal system are worked out. The model uses the real-time irrigation demands in the command area and calculates the total flow requirement at each minor, distributory, and branch in the canal system after accounting for the water application efficiency, field channel efficiency, seepage losses in the canal system, canal capacity, and water availability constraints.

In addition to the surface water availability and capacity constraints, the model uses the information about the groundwater depth at each grid in the system for the week under consideration. The model aims at utilizing the available canal water to the maximum extent provided that groundwater conditions in the area permit. In case of shortage of surface water, the demands of a minor/distributory with highest water table are met from the groundwater. This way, the model tries to find allocation pattern for least cost of pumping. Subsequently, through iterative simulation of canal operation, the model finds a canal-run configuration that provides higher effective utilization of canal water, relatively higher canal seepage in the areas of deeper groundwater and in least energy requirement for pumping groundwater. In the development of this procedure, it is inherently assumed that it is always economical to utilize the surface water as compared to the groundwater provided that surface water is available.

A computer program has been written for the allocation model and applied to the Lakhaoti command area under the Madhya Ganga Canal system. Layout of the canal system of the Lakhaoti branch up to the minor level has been delineated using the PAN sensor data of IRS-1C satellite. Minor-wise command area has been digitized and linked to the corresponding minors through unique identifiers. The location of groundwater wells and the groundwater depths in various wells in the year 1998-99 have been collected from field offices and groundwater surfaces have been generated in the GIS system (ILWIS) using different methods of interpolation/kriging. Based on the groundwater surface and the DEM of the topography, the depth of pumping at each grid has been calculated. Characteristics of different canal segments have also been collected from the field offices of the Madhya Ganga Canal system. The operation of canal system is based on the irrigation demands (as worked out by another model), canal water availability and the groundwater depth in any week.

Major advantages of the allocation model are that it operates the system for the actual cropping pattern in the command and uses real-time information about the spatially distributed irrigation demands and groundwater depths. It considers different characteristics of the canal segments and utilizes the information of different irrigation practices in different parts of the command area rather than assuming lumpsum values. The model tries to simulate the operation quite close to the reality. Further, the model uses least number of assumptions in terms of canal seepage, recharge because of rainfall and irrigation, income and expenditure on various crops, and cost of providing surface and groundwater etc. The model can be used to design or alter the system configuration and different scenarios of canal capacities and canal system layout, and area actually irrigated by them can be evaluated.

Data requirement of the approach is quite high. The model requires digitization of the Sajra maps for the whole canal system. Further, the approach requires the determination of actual cropping pattern for the command area before the start of the season. There is a need to develop a system for getting such information from the farmers. The approach also requires a network of well-distributed groundwater observation wells and the collection of groundwater level data from the observation wells at weekly/monthly time step. The approach suggests the operation plan for each week. The aim is to satisfy the irrigation demands in the command area with least cost of pumping. To approach also tries to ensure groundwater stabilization by curtailing canal water supply in the water logged area, pumping groundwater in the shallow water table area and using canal water in deeper groundwater area.

REFERENCES

Abrol, I. P., (1999), "*Sustaining Rice-Wheat System Productivity in the Indo-Gangetic Plains: Water Management-Related Issues*", Agricultural Water Management, 40, pp. 31-35.

Ahmad, S., and Heermann, D. F., (1990), "*Computerized Scheduling for Irrigation Management and Pumping Operations in the Watercourse Command*", Agricultural Water Management, 18, pp. 1-13.

Bredehoeft, J. D., and Young, R. A., (1983), "*Conjunctive Use of Groundwater and Surface Water for Irrigated Agriculture Risk Aversion*", Water Resources Research, Vol. 19 (5), pp. 1111 - 1121.

Cabelguenne, M., Debaeke, P., Puech, J., and Bosc, N., (1997), "*Real-Time Irrigation Management using the EPIC-PHASE Model and Weather Forecasts*", Agricultural Water Management, 32, pp. 227-238.

Chandra, S., Pande, P. K., and Kashyap, D., (1979), "*Conjunctive Use of Water Planing with Additional Surface Inputs from Tehri Reservoir*", International Seminar on Develoment & Management of Groundwater Resources, Roorkee.

Chaves-Morales, J., Marino, M. A., and Holzapfel, A. H., (1992), "*Planning Simulation Model of Irrigation District*," Journal of IDE, ASCE, Vol. 118(1), pp. 74-87.

Garg, N. K., and Ali, A., (1998), "*Two-Level Optimization Model for Lower Indus Basin*", Agricultural Water Management, 36, pp. 1-21.

Garg, N. K., and Ali, A., (2000), "*Groundwater Management for Lower Indus Basin*", Agricultural Water Management, 42, pp. 273-290.

Kalu, I. L., Paudyal, G. N., and Gupta, A. D., (1995), "*Equity and Efficiency Issues in Irrigation Water Distribution*", Agricultural Water Management, 28, pp. 335-348.

Kashyap, D., and Chandra, S., (1982), "*A distributed conjunctive use model for optimal cropping pattern*", IAHS Publication 135, pp. 377-384.

Kumar, R., and Pathak, S. K., (1989), "*Optimal cropping pattern in India by conjunctive use of surface and ground water*", Water Resources Development, Vol. 5(2), pp. 99-105.

Lakshminarayan, V., and Rajgopalan, S. M., (1977), "*Optimal cropping pattern for basin in India*", Journal of Irrigation and Drainage Engineering, ASCE, pp. 53-70.

Latif, M., and James, L. D., (1991), "*Conjunctive water use to control water logging and salinization*", Journal of water Resources Planning and Management, ASCE, Vol. 117(6), pp. 611-628.

Logenbaugh, R. A., (1970), "*Determining optimum operational policies for conjunctive use for ground and surface water using linear programming*", Paper presented at Hydraul. Div. Spec. Conf., ASCE, Minneapolis, Minn., pp. 19-21.

Liu, Y., Teixeira, J. L., Zhang, H. J., and Pereira, L. S., (1998), "*Model Validation and Crop Coefficients for Irrigation Scheduling in the North China Plain*", Agricultural Water Management, 36, pp. 233-246.

Louie, P. W. F., Yeh, W. W. G. and Hsu, N. S., (1984), "*Multiobjective Water Resources Management Planning*", Journal of water Resources Planning and Management, ASCE, Vol. 110(1), pp. 39-56.

Mainuddin, M., Gupta, A. D., and Onta, P. R.,(1997), "*Optimal Crop Planning Model for an Existing Groundwater Irrigation Project in Thailand*", Agricultural Water Management, 33, pp. 43-62.

Matsukawa, J., Finney, B. A., and Willis, R., (1982*), "Conjunctive use planning in Mad river basin, California*", Journal of Water Resources Planning and Management, ASCE, Vol. 118(2), pp. 115-132.

Morel-Seytoux, H. J., and Restrepo, J. I., (1986), "*SAMSON: A model for conjunctive operation of surface and groundwaters*", In: S.M. Gorelick (Ed.), Conjunctive Water Use, IAHS Publication No. 156, pp. 415-423.

Noel, J. E., and Howitt, R. E., (1982), "*Conjunctive multibasin management - An optimal control approach*", Water Res., pp. 753-763.

O'Mara, G. T., and Duloy, J. H., (1984), "*Modeling efficient water allocation in a conjunctive use regime*", Water Res. Res., pp. 1489-1498.

Onta, P. R., Das Gupta, A., and Harboe, R., (1991), "*Multistep planning for conjunctive use of surface and ground water resources*", Journal of Water Resources Planning and Management , ASCE, Vol. 117(6), pp. 662-678.

Paudyal, G. N., and Das Gupta, A., (1987), "*Operation of groundwater reservoir in conjunction with surface water*", Water Resour. Development, Vol. 3(1), pp. 31-43.

Paudyal, G. N., and Das Gupta, A., (1990), "*Irrigation planning by multilevel optimization*", Journal of Irrigation and Drainage Engineering, ASCE, Vol. 116(2), pp. 273-291.

Ranjha, A. Y., Peralta, R. C. and Yazanian, A., (1990), "*Conjunctive use/sustained ground water yield planning : case history*", ICID Bulletin, Vol. 39(1). pp. 1-12.

Rao, N. H., Sarma, P.B.S., and Chander, S., (1988), "*Irrigation Scheduling Under a Limited Water Supply*", Agricultural Water Management, 15, pp. 165-175.

Rao, N. H., Sarma, P.B.S., and Chander, S., (1992), "*Real-Time Irrigation Scheduling Under a Limited Water Supply*", Agricultural Water Management, 20, pp. 267-279.

Sarma, P.B.S., and Oad, R.,C.,(1990), "*Variable - Time Model for Irrigation Water Distribution*", Agricultural Water Management, 17, pp. 367-377.

Shyam, R., Chauhan, H..S., and Sharma, J..S., (1994), "*Optimal Operation Scheduling Model for a Canal System*", Agricultural Water Management, 26, pp. 213-225.

Wardlaw, R.,(1999), "*Computer Optimisation for Better Water Allocation*", Agricultural Water Management, 40, pp. 65-70.

Wesseling, J. G., and Van Den Broek, B., J., (1988), "*Prediction of Irrigation Scheduling with the Numerical Model Swatre*", Agricultural Water Management, 14, pp. 299-306.

Yoganarasimhan, G. N., and Chand, J. P., (1979), "*Integrated planning of surface and ground water*", Proc. of workshop on conjunctive use of surface and ground water, WRDTC, Roorkee.

* * *