Simulation of Conjunctive Operation in a Command Area

आपो हिष्ठा मयो भुवः

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PREFACE

While the demands for water by all the sectors 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. 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 available information to evaluate the system operation and provide an integrated picture of the total system.

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 information of groundwater depth in the irrigation system for finding the optimum canal-run configuration during a 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 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. The model application is cited for the Lakhaoti command area under the Madhya Ganga Canal system. Detailed database has been developed for the Lakhaoti command.

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. One major limitation of the model is extensive database requirement. 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 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.

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ABSTRACT

Success of an irrigation system depends on efficient water management. Efforts to improve agricultural practice by making more efficient use of available water resources require mathematical models to simulate the dynamics of water distribution in an irrigation system. A number of computer-based models have been reported in the literature (such as SIMIS, CAMSIS, INCA, OMIS etc.) to help irrigation manager in real-time operation of a canal system. Such models analyze the system operation in terms of water demands and supply and optimize the water allocation to meet some performance-based criteria/objectives. Irrigation command areas may exhibit marked spatial heterogeneity in terms of cropping pattern, physiographic characteristics, irrigation practices, water availability and utilization etc. Groundwater availability in an irrigation command varies spatially as well as temporally depending on the depth of groundwater table below the land surface, and groundwater extraction facilities. Often, gross simplifying assumptions, such as areal average cropping pattern, uniform physiographic and agro-climatic characteristics and average groundwater availability etc. are made in planning and operation of canal irrigation projects. This may lead to glaring discrepancies with ground situation resulting in inefficient utilisation of water resources.

The objective of this study is to develop a geo-simulation model that can integrate the spatial information on different variables related to water supply and water demand for real-time operation of a canal network. Broad aims of developing the scheme are: a) to integrate the spatial and temporal database for rational operation of an irrigation system, b) to integrate various processes of irrigation water management in the command area, and c) to depict the results of simulation model and performance parameters in form of maps for easy comprehension and decision-making. It is envisaged that such a model will help the irrigation manager for judicious operation of a canal network on the basis of current state of the system.

The developed model operates at weekly time step and consists of two major distributed models [Soil Water Balance Model (SWBM) and Canal Network Simulation Model (CNSM)] and a number of sub-models for database generation and linking various models of the scheme. The purpose of SWBM is to simulate the moisture variation in root zone of crops for finding spatially distributed irrigation demands, groundwater recharge, water stress conditions in crops, and soil moisture content at the end of each week. SWBM is based on a book keeping procedure and incorporates spatial variability of crop, soil, rainfall, and topography in the dynamics of soil-water-plant interaction. The purpose of CNSM is to simulate the weekly operation of a canal network and allocate the available canal water and groundwater on the basis of irrigation demands (calculated by SWBM), system characteristics, and prevailing groundwater conditions in the area. For allocation of canal water under deficit conditions, five different water allocation policies have been proposed: a) Head-reach priority, b) Conjunctive utilisation of water, c) Proportionate supply, d) Tail-reach priority, and e) Conjunctive use with minimum energy demand. For generating revised

groundwater conditions corresponding to different canal operation scenarios, an existing groundwater simulation model (Visual MODFLOW) is linked to the modeling scheme.

To analyze its performance and utilisation, the developed modeling scheme is applied to a branch canal command (with a gross area of about 1956 sq. km) under the Madhya Ganga Canal System in U.P. State, India. ILWIS GIS system is used for database development (soil map, Thiessen polygon map, digital elevation map, flow direction map, groundwater table map, irrigable command map etc.) and various spatial analysis. ERDAS IMAGINE system is used for processing of satellite data. Since the scheme provides a large area simulation, its calibration and validation is carried out using the analysis of groundwater behavior in the area. Application of the scheme is demonstrated for one crop season of the year 1998. Maps corresponding to irrigation demands, groundwater recharge, water stress conditions in crops, various canal operation details, such as discharge and run-time etc. can be prepared with the developed scheme.

To summarize, the problem of integrated operation of a canal network considering real-time spatial information is analyzed in this study. A distributed simulation scheme is developed to study various operation scenarios for the canal system. Using remote sensing and GIS for database generation and management, representation of geographic characteristics of the command area has been made quite realistic. Using the simulation scheme iteratively, optimization is performed to find the canal run configuration for least requirement of pumping energy in the system. Using the geo-simulation scheme, the operation of a canal network can be planned, eco-system of a command area can be maintained, and energy demands for pumping groundwater can be optimized. The results of the scheme can be presented in pictorial form for easy understanding. The scheme can be used as a decision support tool for irrigation water management in command areas.

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CHAPTER – 1
INTRODUCTION

1.1 GENERAL

Nature seldom provides adequate amount of water to meet crop requirements at the desired place and time. 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.

Modern agriculture practices are based on the development of surface and groundwater irrigation facilities and their scientific management. Currently, irrigated agriculture is practiced on approximately 270 M ha around the world (≈ 17% of total arable land) and produces almost one-third of total food production. During the last 25 years, half of the increase in food production has come from the irrigated area. The projected population growth during the coming years will require an increase in food production of 3 to 4% per year, the largest share of which is expected to come from irrigated agriculture, particularly in developing countries (Tardieu, 2000). This formidable challenge of increasing food production will require improvements in the management of water for irrigation. Irrigation potential (gross area capable of being irrigated from created facilities) in India has increased from 22.6 M ha in the year 1951 to 85.1 M ha by March, 1995 and total investment made in the irrigation sector up to the end of eighth plan (1992-97) has been more than Rs.870,000 million [Government of India (GOI), 1999].

However, in the present circumstances, it has also been established that inappropriate irrigation management practices around the globe have converted around 100 M ha of arable land into unusable land because of waterlogging and salinity (Tardieu, 2000). Because of the indiscipline in irrigation water distribution, excess water is used in the head reach of command area in the belief that more the water supplied for the crop the higher would be the yield. Excess irrigation causes water logging due to rise in the subsoil water table. Continued water logging results in salinity development and may render the land unproductive in some cases. Water logging is a national problem and has been widely reported, especially in the head reaches of some canal irrigation projects. Groundwater table has risen by 2 to 9.3 m in certain areas in Madhya Pradesh State, and 2 to 11.2 m in certain areas in Punjab State (Vaidyanathan, 1999). The World Bank (1994) has estimated that water logging problems have already developed on about 250,000 ha of land in northwest India and it is foreseen that some 3 M ha may be in jeopardy over the next 30 to 50 years. 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. Singh (1985) provides an analysis of management deficiencies of irrigation water in India. Mistry et al. (1983) have estimated that even 2% improvement in operating efficiency of major and medium irrigation projects in India can create an additional irrigation potential of 0.5 M ha.

The importance of conjunctive 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.

Usually, a command area in developing countries like India, has a large number of subsistence holdings (unlike large commercial farms in developed countries) due to fragmentation of land holdings having occurred over centuries of traditional agricultural practices. There are marginal farmers (with plot holding less than 2 ha), small farmers (with plot holding in between 2 to 10 ha), and large farmers (with plot holding more than 10 ha) with marginal farmers covering 24% of area, small farmers covering 53% of area, and large farmers covering 23% of area (Singh, 1985). Because of the small land holdings and the liking and preference of each farmer, spatial heterogeneity within the command area prevails in terms of cropping pattern, agronomic practices, irrigation practices, water availability and utilization, support services etc. There is a need to utilize an information system that can store, analyze, and process spatial and temporal data pertaining to hydrological, hydro-geological, hydro-meteorological, soil, agronomical, and cropping pattern parameters in ana irrigation command and can interact with a modeling system for real-time conjunctive operation of the system. 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.

1.2 NEED OF A GEO-SIMULATION MODEL

Introduction of canal irrigation facilities in a command area sets new hydrological regime with revised conditions of groundwater recharge and withdrawal. If the water is not utilized as per the developed plan or if there is significant difference in the actual and design values of demands and supply, an imbalance is created in the ecosystem that can lead to deterioration of the system. It is, thus, important to manage the water resources conjunctively in the command areas after the new infrastructure is developed. Under conjunctive plan, available surface and groundwater resources are used such that one supplements the other to compensate for the inadequacies (in terms of quantity and quality in time and space) for getting increased productivity while mitigating environmental hazards like high water table, salinity, and aquifer mining.

During the last three decades, application of operation research techniques to water resources has produced a number of models for planning and management of water management in irrigation systems. Often, gross simplifying assumptions are made in planning and implementation of irrigation projects leading to significant differences with respect to ground situation. Some examples of such simplifying assumptions include: areal average cropping pattern, uniform physiographic and agro-climatic characteristics and average groundwater availability and groundwater conditions in the command area.

In actual practice, variables, parameters, and processes related to irrigation water management vary spatially as well as temporally. A few examples are quoted here. Because of smaller landholdings and different preferences of the farmers, crops in a command may vary from field to field and so does their associated properties such as root depth, ET demand, standing water requirement, wilting coefficient etc. Variation of crops in a command affects the crop water requirements at any time, which directly governs the operation of the canal system. Moisture holding capacity of soil depends on its properties such as field capacity, permanent wilting point, specific gravity etc., which may show marked variation over larger areas of the command. Rainfall in a command varies spatially as well as temporally. Depending on the topography and water table position, groundwater depth below the surface may vary from place to place and also with each week/month depending on the recharge and withdrawal in the groundwater reservoir. Similarly, canal system characteristics vary along the network. One portion of the canal system may be lined while the other portion may be unlined, thus affecting the seepage rate and consequently, the water demand in different parts of the canal system and recharge into the aquifer. The application efficiency and channel conveyance efficiency may vary spatially depending on the prevalent method of irrigation application and channel conditions. All such variations need to be considered in developing operation plans on a scientific basis.

Vastness of the command areas, time and manpower constraints in data collection and seasonal changes in the information require fast inventory of agricultural areas. In all these circumstances, remote sensing can be looked upon as an aid in planning and decision-making (Vidal, 2000). The usefulness of remote sensing techniques in inventory of irrigated areas, identification of crop types, stress conditions, crop yield estimation, crop ET determination, and identification of waterlogged and saline areas have been demonstrated in various studies [Govardhan (1993), Bastiaanssen (1998, 2000), and Menenti (2000)]. So, remote sensing data can be used for providing spatial information about the command area. Further a GIS (Geographic Information System), which is a computer-based system designed to store, process and analyze geo-referenced spatial data and their attributes, can assist in judicious water resources management in an irrigation system by efficiently handling spatial and temporal information of the command area.

A geo-simulation model uses geographically referenced data to enable different scenarios to be simulated. Remote sensing observations and spatial database can be integrated with mathematical models to analyze a variety of strategies for real-time management of irrigation networks. A model is required that can incorporate spatial variability of different data related to the water management in an irrigation command and can integrate real-time information coming from different sources to analyze the system performance under different policies of canal operation. The model must present the results in a form that can be easily understood by the decision makers.

1.3 OBJECTIVES AND SCOPE OF THE STUDY

The objective of present study is to develop a generalized geo-simulation scheme for analyzing the operation of an irrigation system. While developing the scheme, the aims are as follows:

a) to integrate the spatial (crop type, soil type, rainfall, surface elevation, canal system characteristics, canal irrigable areas, irrigation practices etc.) and temporal (rainfall, ET, canal system operation, groundwater depth etc.) information coming from different sources;
b) to integrate various processes of irrigation management such as estimation of crop water demands, transfer of spatial demands to canal network, allocation of surface and groundwater, prediction of groundwater table as a result of allocation plan, evaluation of performance indicators;
c) to consider system details necessary for realistic analysis;
d) to develop a generalized and computationally efficient scheme;
e) to display the results in form of maps for easy visualization and understanding.

It is envisaged that the developed scheme can act as a decision support tool for irrigation managers in guiding the operation of the canal system on the basis of current state of the system. It is also planned to incorporate options (like priority of canal operation, use of augmentation supply etc.) so that a variety of system operation scenarios can be simulated.

The model application is cited for one crop season for the Lakhaoti command area under the Madhya Ganga Canal system. Different scenarios of canal operation have been simulated and illustrated under different conditions of water availability, canal priority, and augmentation supply.

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CHAPTER – 2
DESCRIPTION OF GEO-SIMULATION MODEL

2.1 REGULATION OF WATER DELIVERY SYSTEMS

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 existing 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.

Different methods of water distribution are followed in canal irrigation systems. In the conventional canal system, flow is controlled through a system of regulators situated at intervals along the length of the canal. These gates are located just on the downstream of a turnout or water withdrawal point. Their main functions are to control the flow-rate on the downstream side and to control the water level on the upstream side close to the gate. Such a system is termed as “upstream control”.

The system of rotational scheduling of irrigation water is known as “Warabandi” in North India. This is a system of delivery of water in rotation amongst cultivators sharing water from a canal outlet. “On Demand” irrigation, involving total flexibility and freedom, is an inherently opposite idea to Warabandi system. While “Warabandi” is employed on many canal systems in India, the “On Demand Delivery” system has 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 requirements of conventional upstream control and rotational schedules in India. Upstream control together with Warabandi is not the ideal or the best system, yet it has the merit of workability with low cost, low technology inputs and is probably suitable for developing countries in comparison to highly sophisticated system of “on Demand Delivery”.

2.1.1 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 practiced 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 CONJUNCTIVE USE APPROACH FOR IRRIGATION MANAGEMENT

The concept of conjunctive use recognizes the unified nature of the surface and ground water resources. 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. The practice of planning surface irrigation without much consideration of groundwater status has often resulted in waterlogging and salinity problems in command areas caused by irrigation recharge. It is therefore important that surface and groundwater resources are used in an integrated manner by planning conjunctive use of water. 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.

Integration of the use of water from two sources on land may involve different levels of time and space integration. General strategies available for conjunctive operation in an irrigation system are as follows:

a) 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. Use of such strategy is feasible in alluvial areas because of the appreciable movement of groundwater. In hard rocks and clay soils, this strategy may not be feasible.

b) 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, 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, either the two water are physically mixed to have resultant water of acceptable quality or rotations are distributed amongst the two sources.

c) 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 stable 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.

While conjunctive use can effectively take care of the extra recharge caused by the surface irrigation, it is not a solution to the bad management practices for surface irrigation such as over-irrigation and inequitable distribution.

2.2.1 Conjunctive Use Modeling

Under conjunctive management plan, the surface and groundwater resources are used 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. 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. 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.

Water resources studies generally aim at finding an optimal solution with respect to the water resources development and management for a certain region. “Optimal” is generally used in the sense of least cost, greatest benefits, most efficient water use, and so on.

Different approaches can be followed for modelling the conjunctive operation in a command area, viz. simulation approach and optimization approach. Optimization directly leads to an optimal solution, according to a predefined set of objectives. Use of the optimization model has the advantage that it automatically sorts through the possible combinations based on a specified objective and a set of equations describing the operation process and its limitations. The disadvantage is that the trade-offs in operation are rigidly internalized within a mathematical formulation. Different techniques of optimization are available. Linear programming, though numerically very elegant, is rather restrictive in the sense that it requires objective function and associated constraints to be a linear function of decision variables. The use of dynamic programming for solving complex problems of conjunctive use management is observed to restrict the specification of the groundwater and surface water systems to low dimensioned representations of the system. Although nonlinear programming formulation is the most general, rate of convergence of the algorithm and computer requirements are major obstacles in the solution of large-scale problems.

On the other hand, simulation provides “only” an illustration of the consequences of one pre-defined situation. Simulation approach is not limited to linear or simpler systems but requires making successive feedback iterations to resolve simultaneous management decisions. For a large combination problem, this may require large number of simulations. However, the approach is indispensable to analyze systems with real-time operation aspects.

2.3 IRRIGATION WATER DELIVERY MODELS

Irrigation water delivery models possess immense potential to assist on implementation of water and environmental policy. The objective of developing irrigation management models is to assist the managers in integrated and comprehensive analysis of an irrigation system. Such models can be used to:

- design a canal system,
- analyse alternatives and identify appropriate operational practices,
- identify network constraints and evaluate effect of possible design modifications on performance of canal system, or
- improve the understanding of system behaviour and performance,
- train irrigation system operators/managers.

Depending on the level of analysis, irrigation management models can be classified as: main system level, tertiary level, and field level. Main system level models simulate the canal network, reservoir behavior, and delivery of water to tertiary units. These are usually employed to assist in real-time operation of irrigation systems. Tertiary level models simulate the water demand of the tertiary system and water distribution among farmers and field systems. Field level models simulate the water application to individual fields. Each of these levels has its own management authority: the irrigation authority for operation of the main system, formal or informal group of organized farmers or water users for water utilization in tertiary unit, and the individual farmer for field application.

Depending on the mode of operation, a water distribution scheme may be classified as supply-based or demand-based. In supply-based scheme, water is distributed according to pre-determined procedures and the users are required to arrange their activities in accordance with the availability of water. In demand-based scheme, specific crop needs are met. Supply-based scheme is generally easier to manage since the infrastructure is designed to support pre-determined operational rules and real-time response to variable events within the season is not required. Demand-based scheme responds to events in which the operating agency responds to changing users' needs in a complex infrastructure involving intensive management. In principle, demand-based systems meet the requirements of crops more accurately and avoid wastage of water but, in practice, they are difficult to manage, especially in developing countries such as India, given the large number of farmers, small farms and field sizes.

Based on the procedure adopted for flow simulation, irrigation management models may be classified as steady state models and unsteady state models. Steady state models simulate conditions in which flow remains steady with time. Inputs for such models include channel geometry, roughness, and flows. Unsteady state models simulate flow conditions in which flow varies with time and distance. Selection of an appropriate model depends on the nature of problem, e.g., accurate simulation of control structure operation may require an unsteady flow model while inadequate management of canal network may be resolved through a steady flow model.

Computer simulation of irrigation systems has been attempted by several workers for planning, scheduling, monitoring and improving operational performance of schemes. The irrigation model proposed by Jensen, Robb and Franzoy (1970) uses the climatic, crop and soil data for scheduling irrigation. Anderson and Maass (1971) have developed simulation models to study the effect of water supplies and operation rules on the production and income of irrigated farms. The U.S. Department of Interior, Bureau of Reclamation (USBR), has developed programs to assist in irrigation project management (Brower & Buchheim, 1982). Several manuals are available to assist in the management of irrigation schemes (FAO, 1982; Skogerboe and Merkley, 1996), which set out concepts for managing these facilities and describe relevant procedures for planning, operation, maintenance, administration, monitoring, and performance assessment. A review of different models used in irrigation system management is given by Lenselink and Jurriens (1992) and FAO (1994). Goussard (2000) has brought out a catalogue of various canal operation simulation models developed in the past.

A number of optimization and simulation models have been developed by various researchers for irrigation system analysis (Dudley et al. 1971; Yaron et al. 1987; Onta et al. 1991; Chavez-Morales et al. 1992; Srivastava & Patel 1992; Burton 1994; Loof et al. 1994; Onta et al. 1995). Laxminarayan and Rajagopalan (1977) have applied Smith's model to Bari Doab system in Punjab, India for allocation of area to alternative crops and the amount of seasonal water releases from the canals and tube wells to maximize benefits from the system.

O'Mara and Duloy (1984) have used a simulation model to examine alternative policies for achieving efficient conjunctive use in Indus basin. This model links the hydrology of stream-aquifer system to an economic model of agricultural production together with a network flow model in river reaches, link canals and irrigation canal. Rao et al. (1988) have developed a two-level mathematical formulation for irrigation scheduling at weekly intervals for a single crop under limited water supply. The model is based on dated water-production function and weekly soil water balance. At the first level, water-production function is maximized to obtain optimal allocations for growth stages while at second level, the water allocated to each growth stage is re-allocated to satisfy weekly water deficits.

Paudyal and Das Gupta (1990) have applied multi-level optimization technique for solving problem of irrigation management in a large heterogeneous basin. The model aims 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. Ahmad et al. (1990) have 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, net farm return is reduced by 28 to 43% and extra water pumping to the tune of 17 to 39% is required as compared to demand-based strategy. Chavez- Morales et al. (1992) have used a simulation model that considers alternative cropping pattern, profits for the farmers in irrigation district, monthly reservoir and aquifer operating schedules for one year planning horizon, and hydropower generation. Rao et al. (1992) have developed a two-stage policy for real-time irrigation scheduling under limited water supply with the aim of maximizing crop yield. In the first stage, irrigation is planned for the entire season at weekly intervals using historical data while in 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 for the new conditions.

Yamashita and Walker (1994) have presented a model that can simulate aggregate water demands by command areas and generate inputs for the operation of irrigation delivery systems. Radhey Shyam et al. (1994) have developed a linear programming model to find water allocation plan for different canals in a system. Kalu et al. (1995) have suggested a water distribution policy in irrigation projects considering the objectives of equity and efficiency. Garg et al. (1998) have developed a two-level optimization 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 given canal and groundwater capacities. 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 while 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 first level are then taken as those obtained from the second level and the process is repeated till it converges. Wardlaw (1999) has suggested an 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 and scarce water resources. Khepar et al. (2000) have described a model for the distribution of water under an equitable delivery schedule. Nixon et al. (2001) have applied a genetic algorithm for optimizing irrigation scheduling.

The main objective of implementing a decision support tool in an irrigation system is to improve the system performance in terms of crop yield, water use efficiency, environmental sustainability or any other criterion decided by the management. Several canal automation and control algorithms have been developed (Clemmens & Replogle 1989; Loof et al. 1991a; Malaterre, 1995). Several decision support systems for planning irrigation projects have been reported (Chavez-Morales et al., 1992; Prajamwong et al., 1997; Kuo et al., 2000). Smith (1992) has presented a comprehensive computer program (CROPWAT) for irrigation planning and management based on estimating crop water requirements using climatological procedures. Van der Krogt (1994) reports the development of a model package (OMIS) to plan water deliveries for irrigation system management. Mateos et al. (2002) have reported the development of FAO decision support system for irrigation scheme management (SIMIS). Some other models for irrigation water delivery include INCA (Makin & Skutsch, 1993), IOS (Singh et al., 1999), CAMSIS (Burton, 1994), MIOS (Kipkorir et al., 2001), RIWAP (Sriramany and Murty, 1996), IMSOP (Malano et al., 1993) etc. Some main system level models related to irrigation delivery/scheduling are briefly described below:

a) CROPWAT

CROPWAT is used to calculate crop water requirements and irrigation demands from climatic and crop data. The program allows development of irrigation schedules for different management conditions and calculation of water supply for varying cropping patterns. Procedures for calculation of crop water requirements and irrigation demands are mainly based on methodologies presented in FAO Irrigation and Drainage Papers No. 24, 33, and 56. The program is meant as a practical tool to help the Irrigation Engineer and Irrigation Agronomist to carry out standard calculations for design and management of irrigation schemes. It also helps in the development of recommendations for improved irrigation practices and planning of irrigation schedules under varying water supply conditions.

CROPWAT version 5.7 facilitates the linkage to the CLIMWAT program, a climatic data base of 3261 stations of 144 countries worldwide in Asia, Africa, Near East, South Europe, Middle and South America. CROPWAT version 7 has been converted to WINDOWS platform for easy data entry and analysis. Presently, CROPWAT 4 WINDOWS 4.2 version is available.

b) OMIS

The Delft Hydraulics has developed a computer model package [Operational Management of Irrigation Systems (OMIS)] for irrigation system management (Krogt, 1993). OMIS can be used for simulating a canal network with reservoir or run-of-river supply for pre-season planning, in-season operation or post-season evaluation.

Under planning component, model calculates the overall and sub-area water demands for selected cropping patterns using historical rainfall for assessing the adequacy of water supply for simulating the canal/reservoir operation. Water allocation for in-season operation is carried out in three steps: demand inventory step (demands in each command are computed and traced upwards through the network), balancing demand and supply step (if supply is insufficient, then first curtail unauthorized crops and then distribute water proportionately), and allocation step (flow of water is traced downwards). Irrigation demands are decided based on the field water balance and the flows in the network are calculated. Post-season evaluation issues seasonal reports including areas of under-supply, irrigation efficiency, overall water balance and actual versus required supply.

Input to the model includes system geometry, cropping pattern, crop details, soils characteristics, hydrological data including rainfall, river flows, canal flows, reservoir level, reference evapo-transpiration, institutional data, and monitoring data. Some of the input data are in form of GIS maps while other data can be interactively entered on screen. Results related to schedules, schematics, summaries are presented in graphical and report form. GIS maps are also produced as output.

c) IMSOP

Irrigation Main System OPeration model (IMSOP) (Malano et al. 1993) is developed to simulate the operation of canal networks that assist in day-to-day operation of an irrigation system. The model has the capability to simulate the operation of branching canal networks and is structured in three integrated modules: (a) evapo-transpiration (ETM) module; (b) irrigation requirement (IRM) module; and (c) system operation (SOM) module. ETM calculates the crop evapo-transpiration based on climatic data. IRM calculates the weekly irrigation requirements of each tertiary irrigation unit in the system based on rate of evapo-transpiration, effective rainfall, canal seepage and application losses. SOM accumulates the irrigation demands in the canal network and determines the canal flow rates required to meet crop demand, conveyance losses and reservoir losses. While accumulating the demands in upstream direction, capacity constraint is satisfied by assuming proportionate reduction.

Input data to the model include meteorological data, probable and actual rainfall, crop areas and crop details, soil details, field moisture content, canal network geometry, reservoir inflows and operation rules. Output of the model provides the day-to-day operation details such as discharge required at various points in the canal network, gate opening at selected measuring points, and reservoir levels and volumes.

d) INCA

The aim of Irrigation Network Control and Analysis (INCA) package is to provide assistance to the irrigation manager to plan and allocate resources prior to, or within season, schedule water effectively and equitably through a command area, monitor system performance and incorporate feedback into operations, provide a knowledge base of system characteristics and operational procedures, and function as a decision support system by giving access to information in a timely and easily understood form. The software includes a high degree of flexibility to enable the representation of a wide range of irrigation schemes.

INCA provides information in graphical form to simplify data quality control and interpretation. The menu-driven program is designed on a modular basis and can be used for pre-season planning, water allocation, performance evaluation, and monitoring general management data. The planning module combines a resource operations model with the results of a pre-season run of water allocation model using seven probable levels of rainfall. In the water allocation module, water demands are aggregated through the system, checked against capacity, and if required, automatically modified. Depending upon demand and supply, full or partial irrigation can be applied.

Input to the model includes irrigation system details such as water sources, canal network, regulation structures etc. Agricultural data include cropping pattern and characteristics of various crops such as maximum root depth, time to reach maximum root depth, crop coefficient, special water demand etc. Hydrological data include actual and probable inflows, actual and expected rainfall, actual and long-term mean evaporation. Output of the model includes graphs and reports on water distribution and performance and general management information. The output is also linked to a GIS for improved presentation of spatially distributed information and model results.

e) IOS

Irrigation Optimisation System (IOS), developed by the Danish Hydraulic Institute, is a decision support tool and modelling system for optimising the canal releases to meet the crop water demands within existing infrastructure. Besides the MIKE 11 and MIKE SHE modelling systems for hydraulic and hydrological simulations respectively, it has an optimisation module to govern the canal releases. IOS acts as a short-term planning tool with decision time steps of two weeks.

IOS has various modules such as controller module, hydraulic module, hydrologic module, crop growth module, and irrigation scheduling module. The core of IOS system is the controller module, which controls and steers data flow among various modules. The transport of water through the canal system is modelled through the hydrodynamic module using one-dimensional unsteady river flow simulation. It can be used to simulate the operation of gates or regulators in canals. The water movement in irrigation command is modelled using a distributed physically based system. The irrigation scheduling module is based on the water balance technique and uses either the soil water balance approach or the water level approach. In the soil water balance approach, irrigation demand is governed by user specified maximum allowable depletion while in the water level approach (used exclusively for paddy), irrigation demand is governed by the water levels defined as a function of crop growth stage. Modelling of crop growth and crop yield is used to assess the effect of water stress on crop production. Daily potential and actual yields, leaf area index and yield loss due to moisture stress are the main outputs from this module.

The optimisation module employs deterministic hydraulic, hydrological and crop growth modules, embedded into a non-linear optimisation framework, for the gradient based search leading to improved irrigation system operation. To capture basic operational objective of optimal use of available water for maximizing crop production, a specific objective function is devised in IOS. The objective function is introduced through the evaluation of hydrodynamic states at certain locations in the canal system and crop states on individual fields. For the hydrodynamic condition, non-linear functional relationships of relevant system variables and penalties at certain locations in the system are established. The evaluation of crop yields on individual fields is based on the results from the crop growth module such that deviations from the potential crop yield due to water stress results in penalty. The overall objective function includes these two non-linear penalty functions. Detailed description of various modules of IOS is given by Singh et al. (1997).

Different modules in IOS interact with one another, providing useful information on various aspects of irrigation command including canal losses, irrigation water utilisation, moisture status in the unsaturated zone and crop growth.

f) CAMSIS

The simulation package (CAMSIS - Computer Aided Management and Simulation of Irrigation Systems) is developed as an aid in the management of irrigation systems (Burton and Farrier, 1986). CAMSIS is designed to process data for planning, operation, monitoring and evaluation of an irrigation system and is useful for day-to-day management of an irrigation system. The package can be used for simulation, either at the design stage, the pre-season stage, or in-season stage.

The package accepts data entry at intervals during the crop season such that plans can be made for the coming time period (of usual1y 7, 10 or 15 days duration) based on the irrigation demand at control points and the available water supply. The components of the package include various programs. The system is initialised through three programs to describe the scheme layout, physical components, crop and soil characteristics and hydrologic data. These programs are not required on a regular basis and may be accessed periodically (once a year) to update the basic system database. The remaining programs are used on a regular basis each time period to:

- enter data for the last period's discharges, rainfall and climate (using CLIMAT).
- enter data on the next period's cropping (using REGAT).
- estimate next time period's available discharge and rainfall (using WATSUP).
- calculate the irrigation water requirements (using PRODAT).
- update each field's soil moisture status (WBUPDATE).
- monitor the performance of last period's actual water allocation against that planned for the same period (using MONITOR).
- allocate water according to selected water allocation policy (using DECIDE).
- print out instructions on water allocations at each control point, together with general management summaries (using WRITEO).

Water allocation policy subroutines are located in the DECIDE program. This program takes the available water supply from WATSUP, demand from PRODAT and soil moisture status from WBUPDATE and allocates the water according to some selected water allocation policy. Various policies available in the package for allocation of available water include: i) equal division on the basis of calculated crop water demand, ii) division based on the gross area of each tertiary unit, iii) based on a ranking which depends on growth stage of crop and its sensitivity to water shortage, iv) ranking based on the crop value, v) water supply to most water use efficient areas, vi) ranking based on the crop water use efficiency, vii) ranking based on the potential loss if not watered, viii) water supply to most water deficient crops, and ix) water supply in proportion to crop area. There is a facility within the program for the operator to override a given water allocation policy and manually change allocations. Burton (1994) has demonstrated the use of CAMSIS for an irrigation system in East Africa to study the consequences of various allocation policies during water shortage.

g) SIMIS

Scheme Irrigation Management Information System (SIMIS) is a decision support system developed by FAO for managing irrigation schemes. The SIMIS approach is based on simple water balance with capacity constraints. This simplification is used for modelling the root zone water balance and in the distribution model. The root zone water balance is done by daily time-steps while the time-step in the distribution model varies from minutes to a day. The water-distribution modelling approach is simpler than that of non-steady and steady state hydraulic models.

Development of SIMIS began in 1993 as a DOS based information system (Sagardoy et al., 1994) designed to help irrigation managers and staff in their daily tasks by providing a comprehensive database application. It was soon developed into a MS Windows-based decision support system and in its current form, SIMIS is a decision support system to help in the management of irrigation schemes (Mateos et al., 2002). In contrast to other decision support systems, it is intended to be valid for most of the common planning, water delivery, maintenance, administrative, and performance assessment activities in an irrigation scheme.

SIMIS allows the simulation of different cropping patterns, irrigation network design, water-distribution modalities, and water-distribution schedules. It also provides a module for assessing irrigation planning scenarios and management alternatives. The user can approach optimum alternatives by simulating and assessing options, implementing them in the field if feasible, and reassessing them. In contrast to other decision supports designed to assist in planning (Kuo et al., 2000) and operation (Khepar et al., 2000; Nixon et al., 2001), SIMIS does not attempt to identify optimal parameters, but acts as a tool in the learning process towards satisfactory irrigation management (Skogerboe and Merkley, 1996).

The database related to a project is organized in five main sets, related to meteorological, cropping, irrigation layout, plot, and maintenance aspects. Climatic variables include daily, decadal, or monthly values of reference evapo-transpiration and effective rainfall. The soil related information is stored in soil database while crop details are entered in crop database. The method of setting up irrigation layout involves defining parent-child relationship. In plot database, information for each plot such as crop present, their planted area and date of planting are entered. In maintenance database, the user can define a series of maintenance activities with their unit cost. Water management module in SIMIS deals with four key issues: crop water requirements, seasonal irrigation planning, water delivery scheduling, and recording water consumption. The crop water requirements sub-module follows the approach of CROPWAT (FAO, 1992). Irrigation plan sub-module calculates net irrigation requirements for different cropping patterns with staggered planting dates. Water delivery scheduling sub-module can handle three main water delivery modes: fixed rotation, arranged rotation, and proportional supply.

SIMIS is a user-friendly software with modular structure (FAO, 2001). Many inputs and outputs can be graphically displayed and printed. All the geo-referenced information can be visualized through GIS contained within SIMIS.

h) Other Software

Sriramany and Murty (1996) developed a simulation model (Real-time Irrigation Water Allocation Program, RIWAP) for real-time irrigation scheduling of water deliveries (at weekly time step) at the tertiary and secondary canal levels of a large irrigation system. Scheduling for a subsequent week is found out at the end of each week by updating the system status with real-time data up to that week and by solving the model for new conditions. Soil moisture balance approach is used for irrigation demands estimation. The model application is presented for a large irrigation system in Thailand.

Kipkorir et al. (2001) presented a Multicrop Irrigation Optimization System (MIOS) for optimal allocation of short-term irrigation supply under deficit conditions. Optimization is based on dynamic programming. Different strategies, such as maximum benefit, equitable benefit, equitable yield, and maintaining system equity are provided and the user can find the optimized supply corresponding to any strategy.

2.4 THE DEVELOPED GEO-SIMULATION MODEL

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. 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, possible to develop suitable criteria for the regulation of canal systems and make substantial improvement in the existing water delivery system.

To help in the scientific and rational conjunctive management of irrigation water, a spatially distributed simulation model has been developed that can integrate various process of irrigation management from micro-scale (field level) to macro-scale (overall command) and provide a comprehensive analysis of the total system. Objective of the developed geo-simulation (GIS based simulation) model is to integrate the spatial information on different variables related to irrigation water demand and supply for real-time conjunctive operation of a canal network. The model uses the remote sensing observations for ascertaining the prevailing cropping pattern in the command and is linked to GIS database for utilizing the spatially distributed data of different variables. GIS is also used to depict the model results in map form for easy comprehension and visualization. The model is briefly described below.

2.4.1 Purpose of development

Large amount of information about various processes is involved in irrigation management of a command area. The variables, parameters and processes involved in task of irrigation management, such as cropping pattern, soil properties, rainfall, topography, groundwater depth, canal system characteristics, water use efficiencies etc. vary spatially as well as temporally. The decision-making process for irrigation management in developing countries has been handicapped with the non-availability of geographic information on real-time basis and the inability to process and analyze vast quantity of geographic data. With the advancement of remote sensing satellites, it is now possible to gather and update information of large areas at regular intervals. Using a Geographic Information System (GIS), the spatial information can be efficiently stored, analyzed and retrieved. There was a need to develop a geo-simulation model that can integrate real-time information coming from remote sensing observations and the spatial details provided by GIS to help irrigation managers in analyzing the system operation under prevailing conditions of water demands and availability.

2.4.2 Modeling Strategy

The model uses spatially distributed data of various features of a command, attribute data related to crops and soils and the dynamic data related to rainfall, evapo-transpiration and canal network operation in the command. The study area is divided into square grids of uniform size. The spatial data includes maps related to crops, soils, Thiessen polygons of rainfall stations, DEM, flow direction, canal layout, canal irrigable area, and groundwater depth in the command. Flow chart of the model is presented in Figure – 2.1.

After developing the database for a command, the model run is started for a specified week. If it is the starting week of model execution, then suitable initial soil moisture conditions in the command are assumed. Otherwise, the moisture content in the crop root zone in various grids at the end of previous week becomes the initial water content for the present week. Next, the probable rainfall and evapo-transpiration estimates in the command at various stations are obtained (either from forecast information or statistical analysis) and the soil water balance model (SWBM) is run to find the grid-wise irrigation demands.

After calculating the spatial demands, canal network operation is simulated to find the best configuration of canal water delivery depending on the canal water availability during the week and the prevailing groundwater conditions in the command. At the end of week,

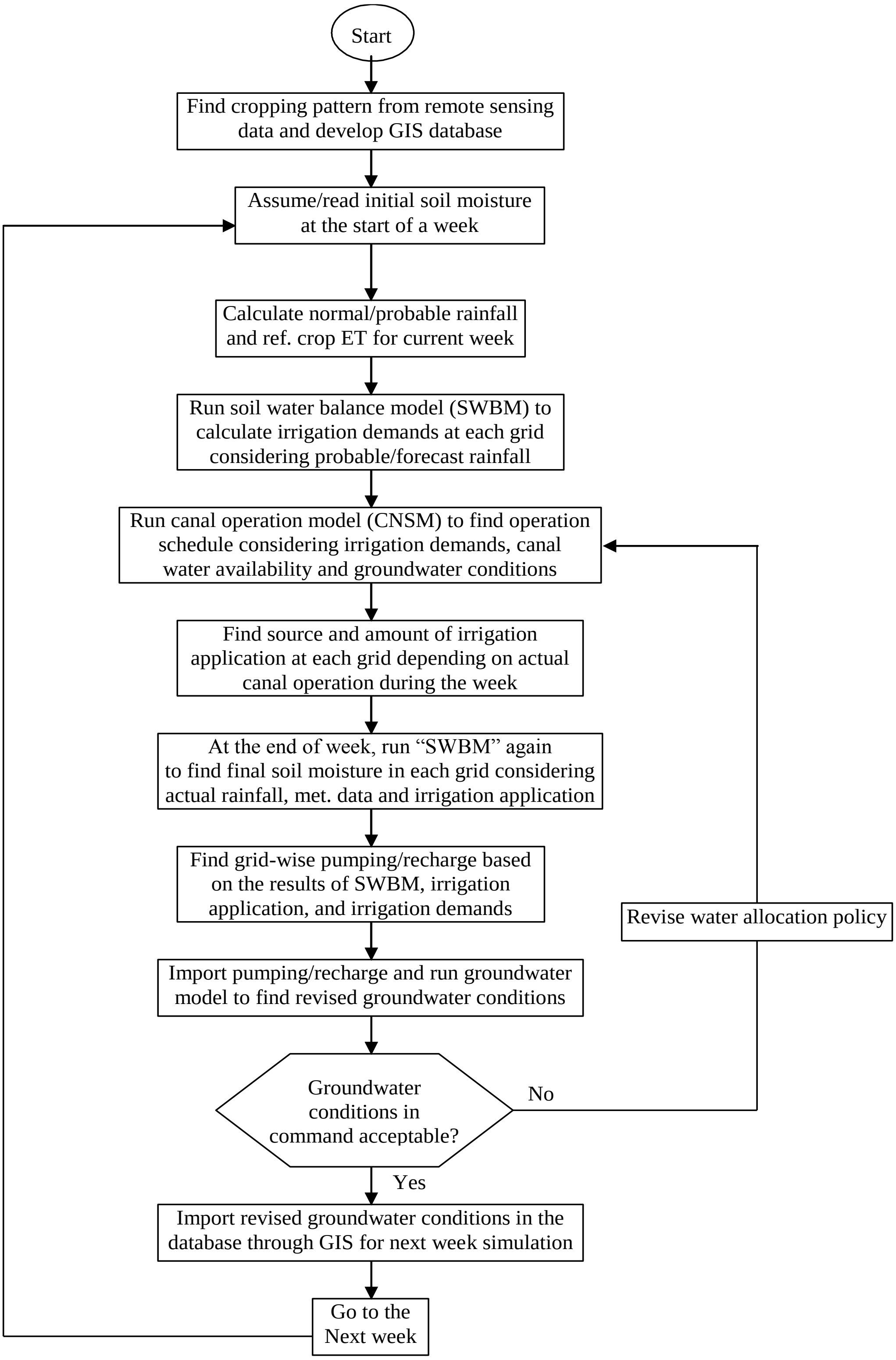


Figure – 2.1: Flow chart of geo-simulation model

knowing the actual meteorological conditions and actual canal network operation, SWBM is run again to estimate the spatial distribution of final water content and groundwater recharge in the command and the extent of groundwater pumping requirement. Spatial estimates of pumping and recharge are then linked with a groundwater simulation model to find the groundwater table for subsequent week. The model can be used to examine the consequences of a canal operation policy. If, as a result of the particular policy, the developed groundwater conditions are unacceptable, the canal operation policy can be revised and model runs can be taken again. The model is run for each week of crop season to manage the available surface water and groundwater conjunctively in real-time.

The model operates at weekly time step and consists of two major distributed models [Soil Water Balance Model (SWBM) and Canal Network Simulation Model (CNSM)] and a number of sub-models for database generation and linkage of various models. The purpose of SWBM is to simulate the moisture variation in root zone of crops for finding spatially distributed irrigation demands, groundwater recharge, water stress conditions in crops, and soil moisture content at the end of each week. CNSM is used to analyze various scenarios of canal network operation on the basis of water demands, supply, and system characteristics. For generating revised groundwater conditions corresponding to different canal operation scenarios, an existing groundwater simulation model (Visual MODFLOW) has been linked with the scheme. Various aspects of the modeling approach and brief description of the SWBM and CNSM modules of *SINCHAI* are presented in the following:

2.4.2.1 Use of remote sensing observations

Remote sensing implies sensing from a distance. These systems are used to observe the earth's surface and analyze the information about the resources. Vastness of the agricultural areas, time and manpower constraints in data collection and yearly changes in the information require fast inventory of situations. In all these circumstances, remote sensing can be looked upon as an aid in planning and decision-making. Remote sensing can be used to map the actual cropping pattern in a command area and such information can be used to find the actual crop water demand for irrigation management. With the availability of high-resolution sensors, it is now possible to delineate the exact layout of the canal system from remote sensing observations. This information, in combination with field records, can provide the spatial extent of the area that can be irrigated with different segments of the canal system. Cropping pattern derived from remote sensing data is used in the demand module (SWBM) for calculating irrigation requirements.

2.4.2.2 Linkage of model with GIS database

Irrigation management requires huge volume of data pertaining to hydrological, hydro-geological, hydro-meteorological, soil, agronomic, and cropping pattern parameters in command areas. These data need to be efficiently stored, analyzed, and retrieved in a user-friendly environment, such as a GIS. Various spatial data layers (crop map, soil map, Thiessen polygon map of rainfall stations, digital elevation map, flow direction map, canal layout map, canal irrigable area map, and groundwater depth map) are developed in GIS. Spatial data layers are imported in the model and used for formulating water distribution plans in a specified week.

2.4.2.3 Rainfall forecasting

One week ahead daily/weekly rainfall forecast is required for evaluating the irrigation water demands in the command area. A few options are available: i) forecasts available from IMD for the region, ii) evaluation of rainfall corresponding to some specified dependability (say 75%) using historical data, iii) use of statistical techniques such as transition probability matrix to find probable rainfall based on rainfall in the recent past.

2.4.2.4 Determination of potential evapo-transpiration

In this step, potential evapo-transpiration in the command based on the weather conditions (temperature, humidity, sunshine, and wind speed) is determined. This information is used to find crop water demands in the command based on the crop type, crop growth, and moisture availability in the root zone.

2.4.2.5 Soil water balance model (SWBM)

Soil water balance of cropped area is a dynamic process influenced by crop and soil properties, climatological variables and topography. Knowledge of water content in soil is crucial for several agricultural applications, such as prediction of irrigation demands, crop water stress, irrigation schedules, crop yields and groundwater recharge. In the present model, moisture variation in the root zone is simulated to find the irrigation demands in the command. Once the irrigation demands are worked out, it remains a management decision to finalize the source of water and to see how it is arranged.

The developed SWBM incorporates spatial variability of crop, soil, rainfall, and topography in the dynamics of soil- water-plant interaction for irrigation management. The module makes grid-wise computations using the raster as well as attribute data of different variables and calculates the final water content at the end of a week. Raster information includes crop type, soil type, Thiessen polygon of rainfall stations, surface elevation, flow direction, groundwater depth, and actual irrigation application. Attribute information includes properties of crops (such as maximum root depth, time to reach the maximum root depth, starting week of the crop, total time period, weekly crop coefficients etc.) and properties of soils (such as specific gravity, porosity, field capacity, permanent wilting point, and saturated hydraulic conductivity). In addition, dynamic information needs to be provided every day/week such as rainfall at different gauging stations, reference crop evapo-transpiration demand of the weather, and the irrigation application in command.

Two time steps are possible in the program: daily or weekly. In weekly time step, the various inputs and outputs of the system are assumed to be lumped over the whole week. In the daily time step, the water balance computation is performed for each day of the week considering daily rainfall and daily reference crop evapo-transpiration. The calculations are performed for all the days of the week and the soil moisture status at the end of the last day of the week is given as output (final water content at the end of the week). This model is developed and presented in detail in a NIH report entitled “*Optimum Water Management in a Command Area*”.

Four output files are generated by SWBM: a) final water depth at the end of the week, b) irrigation water demand, c) stress condition, and d) deep percolation. The result files can be converted into maps or pictures and can be displayed in a GIS system. The projection of the results in the map form makes the interpretation and decision making much easier as compared to the conventional record form or tabular form.

In the operation strategy of the present model, SWBM is utilized in two steps per week. First, it is used to forecast the irrigation demands for the forthcoming week, given the normal/probable rainfall and evapo-transpiration for the forthcoming week. Based on the forecast demands, the operation of the canal system is simulated. After the week has passed and the actual rainfall, evapo-transpiration, and actual canal operation during the week become known, the SWBM is run again to find the final water content at the end of the week based on the actual input to the system. The final water content map becomes the input for the subsequent week.

2.4.2.6 Canal network simulation model (CNSM)

The objective of this module is to simulate the weekly operation of the canal system for satisfying crop water demands by optimizing the use of canal water and groundwater. Using the simulation model, one can analyze different operation scenarios and evaluate system performance. The proposed operation in CNSM is governed by the prevailing irrigation demands, availability of surface water at canal head and prevailing groundwater conditions in the command area during a week.

For optimizing the use of surface and groundwater, the approach utilizes the surface water to the extent possible provided that groundwater conditions permit. This results in least power requirement for extracting groundwater and simultaneous recharging of the underground aquifer. However, if the surface water availability is less than the demand during a week, then the approach utilizes the groundwater in the region of least depth of pumping. Thus, this approach tries to equalize the groundwater regime in the command area in head and tail reaches at each time step [extraction in the area of shallow groundwater table and recharge (in the form of canal water seepage) in the area of higher groundwater depth]. Further, pumping from the shallow water table region in the command results in less consumption of power for pumping groundwater.

Another objective of developing CNSM is to account for the spatial variation of characteristics of the canal system and other important variables. Spatially distributed information used by CNSM include: crop type, layout of different canal segments, layout of command areas of individual canal segments, irrigation demands, and depth of groundwater table. Attribute information used by CNSM relates to the characteristics of different canal segments (discharge capacity, section details, irrigable area, conveyance efficiency, application efficiency in the local command, field channel efficiency, canal seepage rate). Model also requires information about those canal segments, which are running at the end of the previous week for calculating fill-time of different segments.

The irrigation demands (obtained from the SWBM) at all grids that lie within the irrigable command of each canal segment (from canal irrigable area map) are accumulated after accounting for the water application efficiency and the field channel efficiency and the total irrigation demands in different canal segments of the entire canal network are worked out. Next, calculations are started from the tail end of the system in the upstream direction. Knowing the discharge capacity of canal segments, the required run-time and seepage loss in each segment is worked out. Canal seepage is then added to the water demands of a segment and the final run-time is computed iteratively. The water requirements are accumulated in the upstream direction after giving due consideration to canal capacity. If the canal capacity at a segment is not sufficient, then the amount of groundwater required (because of capacity constraint) in the segment is found out. The groundwater demands of intermediate segments are settled first by curtailing irrigation demands of some downstream canal segments. Calculations are carried up to the head of the canal system by satisfying the capacity constraint of all intermediate segments and the total water requirement at the head is estimated. This is the canal water requirement in the command (including seepage losses) that can be satisfied from the existing canal system. Now, this requirement is compared with the available water at the system head. If the water availability is more than or equal to the required demand, then the system is operated according to the discharge requirement as calculated earlier for different segments. However, if the availability is less than the demands, then, some allocation criteria needs to be evolved to find the segments of canal water supply and groundwater supply.

Five different distribution/allocation policies have been included in the model and the operator can select any one policy for the operation of the canal system. The results of different policies can be analyzed before the implementation of any particular approach. For finding the water allocation to different canal segments, calculations proceed from the head of canal system towards the tail end. Different allocation policies that have been included in the CNSM are briefly described below:

Policy 1:Head-reach priority

Under this policy, the segments in the head reach are given priority and their demands are met in full. The remaining water left at a system node is sent to the downstream segments. This policy is mainly applicable to a system with no control on the canal flow and the canal water is utilized as far as and as long as it is available.

Policy 2: Based on conjunctive use of water

Under this policy, curtailing the irrigation demands of some downstream canal segments compensates the deficit at the head of the canal system. The demands of such affected canal segments are met through groundwater withdrawal. The groundwater depth under each canal segment governs the identification of affected segments. The segment of least depth of groundwater is selected iteratively and the calculations are repeated for finding revised water requirement at head under changed demand scenario till the water demands match with the water availability.

Policy 3: Proportionate supply

Under this policy, water available at a system node is distributed proportionately among different segments (bifurcating from a node) in proportion to their total demands. Thus, this policy tries to equitably distribute the deficit among different canal segments.

Policy 4: Tail-reach priority

Under this policy, the allocation is started from the tail end of the system and it advances in the upstream direction as the demands of the tail-end canals are satisfied. Using this policy, the operator can visualize the total extent of the downstream canal system that can be satisfied for the available water. Since the groundwater depth in the tail-end is generally high as compared to the head reaches and canal water is given priority in tail-end, this policy also tries to equalize the groundwater regime in the command area.

Policy 5: Conjunctive use with minimum energy demand

Under this policy, the canal-run configuration corresponding to the least energy requirement in the irrigation system for pumping groundwater is identified. After finding the canal-run configuration corresponding to Policy-2, the canal-run segments are moved in the upstream direction and corresponding energy requirement for pumping groundwater is calculated. The configuration that results in least energy requirement is recommended.

Option is included in the model to select any one of the available allocation policies and simulate the operation of the canal system. The output of simulation analysis indicates the discharge, run-time, and seepage loss of various canal segments for the week under consideration. Output results of the simulation model are presented in the form of maps and table. Different results are presented as attributes of canal segments and can be instantly visualized in a GIS. Various maps that can be generated include: whether a canal segment is supplied water or not, cause of not running the canal segment, required discharge, run-time, seepage loss, groundwater usage etc.

Of the five policies mentioned above, Policy 1, Policy 2, and Policy 5 have been developed and discussed in a NIH report entitled “GIS Based Efficient Distribution System for a Command”. Policy of proportionate supply (Policy 3) and policy of tail-reach priority (Policy 4) have been included to make the model more generalized for assessing various scenarios. In addition, concept of priority has been added to introduce user-defined specific instructions in the modeling strategy. Further, concept of augmentation supply has been introduced to make the model more versatile for testing various combinations of surface water and groundwater use in a command. These will be discussed in the following sections.

2.4.2.7 Linkage of model with Visual MODFLO

Various models of the geo-simulation model are linked to each other through various sub-modules. The modeling scheme is also linked to a groundwater simulation model (Visual MODFLOW) for analyzing the effect of operating the canal system on the groundwater system.

Generally, groundwater table observations are taken at specific periods in a year (pre-monsoon and post-monsoon) at selected observation wells. The groundwater simulation model can help in predicting the groundwater conditions at each grid in the intermediate periods also. Further, the groundwater model can also be used to visualize the long-term impact of adopting a particular operation policy on the irrigation system.

2.4.3 Concept of Priority in CNSM

The concept of priority has been introduced in the simulation model to order to incorporate user-defined specific instructions in the modeling strategy. Priority of a canal segment refers to the importance of a particular segment with regard to supply of canal water. In actual field situation, it is possible that some area in the command needs to be given canal water urgently either because of crop stress (to avoid crop failure) or various socio-political reasons. In such cases, higher priority can be assigned to the canal segments of the area. Under such conditions, canal water is first allocated to the high priority segments over-riding all the policies of water allocation.

In the simulation model, two levels of segment priorities are considered – normal and high. First, the demands of all high priority segments are satisfied with canal water and the water left thereafter in the canal system (if any) is distributed among other normal priority segments in accordance with the specified criteria. This concept provides a lot of flexibility to the irrigation manager in analyzing the network operation. The canal segments with higher priority are specified (0 – normal, 1 – high) while defining the canal characteristic attributes.

2.4.4 Concept of Augmentation Supply in CNSM

Water is supplied at the head of a canal system either from a storage reservoir or through a diversion in a river/canal. Sometimes, augmentation wells are also installed within the command area for pumping groundwater from the area of shallow water table or waterlogged area and discharge it in the canal network for downstream use. A few examples are quoted here.

One of the planned conjunctive use development in India that can be cited as an example is the construction of augmentation tube wells in Western Yamuna canal command in the State of Haryana. In the 1950s, it was observed that while the command of lower reaches of Western Yamuna Canal was facing scarcity of canal supply, water logging was developing in the upper reaches. The Irrigation Department of Haryana chalked out a scheme for the installation of deep tube-wells in the year 1969. A total of 1643 augmentation tube wells with 1 to 7 cusec capacity were installed (Tanwar, 1997). This management technology resulted in the subsidence of water table in the region. Further, in the Gandak Canal Project of U.P., about 150 augmentation tube wells have been installed to supplement canal water supplies. In Chambal irrigation system, 175 augmentation tube wells with an installed capacity of about 13 cumec have been constructed for conjunctive use of canal water and groundwater. The wells discharge into various parts of the canal conveyance system including distributaries, minors and sub-minors.

To incorporate such scenarios in the modeling procedure, a provision is made in the model to account for the additional availability of water at intermediate locations in the canal network by augmentation supply. Using this option, the operator can visualize the effect of augmentation supply on the performance of canal system and the effect of augmentation withdrawal on the groundwater conditions.

2.4.5 Computational Steps of CNSM

The spatial irrigation demands in the command area corresponding to the prevailing cropping pattern, rainfall, and meteorological conditions are worked out by the SWBM (also specified earlier as *DEMAND* model). Using these irrigation demands, water availability at canal head, and the prevailing groundwater conditions in the command during a week, CNSM (also specified earlier as *ALLOCATION* model) is used to allocate the canal water and groundwater to satisfy irrigation demands. Various steps of computation of CNSM have been specified in the NIH report entitled "GIS Based Efficient Distribution System for a Command". However, incorporation of concepts of priority and augmentation supply has modified the computational steps. Revised steps of CNSM calculation are presented below:

a) Reading of input data & analysis options

Model reads all the spatial as well as attribute data of the command area. In addition, some analysis options need to be specified at the time of simulation run. These include: available discharge at system head, method of satisfying capacity constraint (1-head-reach priority, 2-conjunctive use, 3-tail-reach priority), water allocation policy (1-head-reach priority, 2-conjunctive use, 3-proportionate supply, 4-tail-reach priority, and 5-conjunctive use with minimum energy demand), number of segments with augmentation supply and their identity and augmented discharge.

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.

$$WR_{ij} = SWR(i,j) * 24 * 24 / 1000 \qquad \ldots(2.1)$$

$$(WDG_{ij})_{id} = \frac{WR_{ij}}{AEFF_{id} * FCEFF_{id}} \qquad \ldots(2.2)$$

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:

$$WD_{id} = \sum(WDG_{ij})_{id} \qquad \ldots(2.3)$$

$$TWRCN_{id} = WD_{id} \qquad \ldots(2.4)$$

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.

$$AGW_{id} = {TGW_{id}}\big/{NGCA_{id}} \qquad \ldots(2.5)$$

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 pumpage 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:

$$GCAP_{id} = \frac{2.7 * PPP_{id} * NOP_{id} * POWS_{id} * EFF}{AGW_{id}} \qquad \ldots(2.6)$$

d) Identification of waterlogging and revision of demand

Based on the type of crops present in canal segment and their root depth, critical water logging 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:

$$TWRCN_{id} = 0 \qquad \ldots(2.7)$$

$$TWGCN_{id} = \text{Minimum of } [WD_{id}, GCAP_{id}] \qquad \ldots(2.8)$$

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

$$NOPR_{id} = \frac{[WD_{id} - TWGCN_{id}] * AGW_{id}}{2.7 * PPP_{id} * POWS_{id} * EFF} \qquad \ldots(2.9)$$

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}) and the number of free high priority segments ($NFSP_{id}$) below each segment are calculated. The intermediate segments of normal priority ($IPRIO_{id} = 0$) that supply water to the high priority segments ($IPRIO_{id} = 1$) are assigned secondary priority ($IPRIO_{id} = 2$). 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, the model also calculates the distance ($DIST_{id}$) of each segment head from the 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:

$$VEL_{id} = \frac{CAP_{id}}{\left[(BEDW_{id} + SL_{id} * WDEPT_{id}) * WDEPT_{id}\right]} \quad \text{…(2.10)}$$

$$FIL_{id} = {ALEN_{id}}\big/{VEL_{id}} \quad \text{…(2.11)}$$

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)

The operation is started when the DDI exceeds the specified value. If ‘AL’ is the length of all segments having 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:

$$DDI = AL/BL \quad \text{…(2.12)}$$

h) Subroutine (COPR) for calculating run-time, discharge, and canal seepage

After finding the system linkages and irrigation demands (corresponding to spatial irrigation demands) in all 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:

$$RUNTIM_{id} = \frac{(TWRCN_{id} + CANSEP + WRSN(IDS)_{id})}{CAP_{id}} \quad \text{…(2.13)}$$

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:

$$REQDIS_{id} = \frac{(TWRCN_{id} + CANSEP + WRSN(IDS_{id}))}{RUNTIM_{id}} \qquad \ldots(2.14)$$

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

iv) The discharge flowing in a segment affects the wetted perimeter and the water depth. If the canal seepage uses either of these observations and the $REQDIS_{id}$ is not equal to the CAP_{id}, then actual value of wetted perimeter and water depth is calculated before computing canal seepage. It is assumed that Manning's formula holds good for flow calculation in a canal section. As shown in Figure – 2.2, 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,

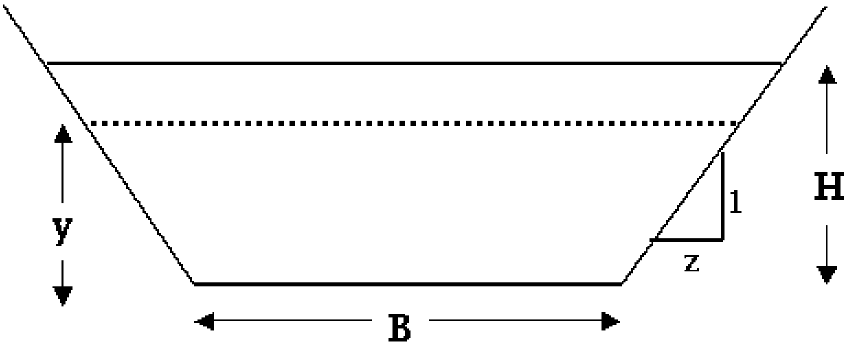


Figure – 2.2: Representation of variables in a canal section

$$REQDIS_{id} = CAP_{id} * \frac{(B+zy)*y*\left[\dfrac{(B+zy)*y}{B+2y\sqrt{1+z^2}}\right]^{2/3}}{(B+zH)*H*\left[\dfrac{(B+zH)*H}{B+2H\sqrt{1+z^2}}\right]^{2/3}} \qquad \ldots(2.15)$$

Knowing the $REQDIS_{id}$, CAP_{id}, B, z, and H, the water depth 'y' is found out 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,

$$CSEEP_{id} = REQDIS_{id} * (1 - CEFF_{id}) * RUNTIM_{id} \qquad \ldots(2.16)$$

If ISCOD = 2,

$$CSEEP_{id} = \frac{(BEDW_{id} + y)^{0.667}}{200} * \frac{ALEN_{id}}{1000} * RUNTIM_{id} \qquad \ldots(2.17)$$

If ISCOD = 3,

$$CSEEP_{id} = (BEDW_{id} + 2 * y * \sqrt{1+z^2}) * ALEN_{id} * SEEPR_{id} * RUNTIM_{id} \qquad \ldots(2.18)$$

Eq. (2.17) is the empirical formula for seepage calculation used in the Lakhaoti command, which is the study area for application of proposed scheme.

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:

$$TWSCN_{id} = REQDIS_{id} * RUNTIM_{id} \qquad \ldots(2.19)$$

$$TWGCN_{id} = TWRCN_{id} + CSEEP_{id} + WRSN(IDS_{id}) - TWSCN_{id} \qquad \ldots(2.20)$$

$WRSN(IDS_{id})$ in a segment 'id' is computed by adding the canal water demand of all segments bifurcating from its downstream node.
viii) If there is some augmentation supply ($AWAV_{id}$) in a segment, canal water demand of the segment (which is accumulated in the upstream direction) is reduced:

$$TWSCN_{id} = TWSCN_{id} – AWAV_{id} \qquad \ldots(2.21)$$

ix) $TWSCN_{id}$ 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.
x) Calculations are made separately for satisfying high priority demands in canal network. The procedure is similar to the one explained in steps (i) through (ix). Irrigation demands of only high priority segments ($IPRIO_{id} = 1$) are considered and irrigation demands of all other segments are assumed to be zero. For each segment with higher priority ($IPRIO_{id} = 1$ or 2), calculations are made to find run-time ($RUNTIMP_{id}$), required discharge ($REQDISP_{id}$), canal water demand ($TWSCNP_{id}$), canal seepage ($CSEEPP_{id}$), and total canal water demand at each node ($WRSNP_{id}$) because of priority demands.

i) Incorporating canal capacity constraint

Using the subroutine COPR, $TWSCN_{id}$ and $TWGCN_{id}$ for each canal segment in the network are found out. Groundwater demand in an intermediate segment occurs when canal water demand exceeds the conveyance capacity of segment. To settle groundwater demands in intermediate segments, demands in downstream network need to be curtailed. Calculations proceed in upstream direction from the tail end. Three methods have been provided in present model for selecting the segments for canal water supply curtailment. For an intermediate segment 'id' with groundwater demand, the computations are performed as follows:

Method of head-reach priority

In this method, the free segment lying downstream and farthest of segment 'id' 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 farthest of 'id' is identified and its canal water demands are curtailed. This process is repeated till the groundwater demand at segment ‘id’ reduces to zero. If the full curtailment of demands of a segment reduces the flow in segment ‘id’ below its discharge capacity, then its demands are curtailed partially so that canal water demand at segment ‘id’ becomes equal to its discharge capacity.

Method of tail-reach priority

This method is similar to the method of head-reach priority except that in this method, free segments lying downstream and nearest to the segment ‘id’ are selected iteratively for curtailing canal water demands.

Method based on groundwater depth

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 the full curtailment of demands of a segment reduces the flow in segment ‘id’ below its discharge capacity, then the demands of the last identified segment are curtailed partially so that the 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 in the previous section 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. Five 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 five allocation policies is described below:

Policy - 1: Head-reach priority

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. However, at every node, water for meeting priority demands is kept reserved. The computational steps are as follows:

i) Initially, the water availability at the canal head is compared with the priority demand at head. If available water is less than the priority demand, then allocation is made only among the priority segments starting from the head of the system.

ii) If the water available at head is more than priority demands, the segment having greatest distance from the head, having normal priority, and having canal water demands is selected and its canal water demands are curtailed (provide it has sufficient groundwater potential).

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

iv) If the demands still exceed supply, then step (ii) and (iii) are repeated iteratively till the supply exceeds 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 matches with the supply.

Policy – 2: Based on least depth of pumping

In this policy, the identification of segments for demand curtailment is governed by groundwater depth under various canal segments. Computations are performed as follows:

i) Calculate the water deficit at head.

ii) The priority of canal segments is defined in three levels: normal (IPRIO=0), high [specified in canal characteristics (IPRIO=1)], and secondary [calculated by the model and refers to that segment which takes water from head to a high priority segment (IPRIO=2)]. Selection of segments for curtailment of canal water demands is carried out in phases: First, segments with normal priority are considered for canal water demand curtailment. After all such segments are exhausted, segments with secondary priority are selected. If deficit still persists at the head, then segments with higher priority are picked up for demand curtailment.

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: Proportionate Supply

In this policy, available water at a node is distributed proportionately among different segments (bifurcating from the node) in proportion to their canal water demands after keeping reserve water for the high priority demands. Computations proceed from the head node towards the tail end. The steps are mentioned below for two cases – node with priority demand and without priority demand. For a node (M) with no priority demand:

i) Observe the number of segments bifurcating from node M and their identity.

ii) Find ratio of water availability (WAV_M) to total canal water demand ($WRSN_M$) at a node:

$$RATIO = \frac{WAV_M}{WRSN_M} \qquad \ldots(2.22)$$

iii) Take each bifurcating segment at the node 'is' and calculate its share ($WAVS_{is}$) of available water at the node as:

$$WAVS_{is} = TWSCN_{is} * RATIO + AWAV_{is} \qquad \ldots(2.23)$$

where $TWSCN_{is}$ is the total canal water demand [canal water demands of irrigable command area of the segment ($TWRCN_{is}$) plus its canal seepage plus canal water demands of downstream network] and $AWAV_{is}$ is the additional water supply to the segment 'is' through augmentation supply, if any.

iv) Revised canal water demands ($TWRCNN_{is}$) in segment 'is' and the water available at downstream node (IDS_{is}) are calculated as:

$$TWRCNN_{is} = RATIO * TWRCN_{is} \quad \text{…(2.24)}$$

$$WAV(IDS_{is}) = WAVS_{is} - TWRCNN_{is} - CSEEP_{is} \quad \text{…(2.25)}$$

For a node (M) with some high priority demand:

i) Number of bifurcating segments and their identity is observed.

ii) If available water at node (WAV_M) exceeds the total high priority demand at node ($WRSNP_M$), then available free water ($WAVF_M$), free demand ($WRSNF_M$), and their ratio is found as:

$$WAVF_M = WAV_M - WRSNP_M \quad \text{…(2.26)}$$

$$WRSNF_M = WRSN_M - WRSNP_M \quad \text{…(2.27)}$$

$$RATIO = \frac{WAVF_M}{WRSNF_M} \quad \text{…(2.28)}$$

Take each bifurcating segment one-by-one. If segment priority is greater than 0, then free canal water demand ($TWSCNF_{is}$), water allocation of segment ($WAVS_{is}$), revised canal irrigation demand of local irrigable command ($TWRCNN_{is}$), and water availability at the downstream node of the segment [$WAV(IDS_{is})$] are given by:

If IPRIOis > 0, then

$$TWSCNF_{is} = TWSCN_{is} - TWSCNP_{is} \quad \text{…(2.29)}$$

$$WAVS_{is} = RATIO * TWSCNF_{is} + AWAV_{is} + TWSCNP_{is} \quad \text{…(2.30)}$$

If $WAVS_{is} < TWSCN_{is}$ & $IPRIO_{is} = 1$, $\quad TWRCNN_{is} = TWRCN_{is}$ …(2.31)

If $WAVS_{is} < TWSCN_{is}$ & $IPRIO_{is} = 2$, $\quad TWRCNN_{is} = RATIO * TWRCN_{is}$ …(2.32)

If $WAVS_{is} > TWSCN_{is}$, then

$$TWRCNN_{is} = TWRCN_{is} \quad \text{…(2.33)}$$

$$WAV(IDS_{is}) = \text{Min.of } [WAVS_{is} - TWRCN_{is} * RATIO - CSEEP_{is}, WRSNP(IDS_{is})] \quad \text{…(2.34)}$$

If $WAV(IDS_{is}) < WRSNP(IDS_{is})$, then

$$WAV(IDS_{is}) = WRSNP(IDS_{is}) \quad \text{…(2.35)}$$

$$TWRCNN_{is} = WAVS_{is} - CSEEP_{is} - WAV(IDS_{is}) \quad \text{…(2.36)}$$

If priority of selected segment is normal, then the revised canal water demand in local irrigable area and available water at downstream is calculated using Eq. 2.25 to Eq. 2.27.

iii) If WAV_M is < $WRSNP_M$, then water is allotted among the higher priority segments only in the ratio of the higher priority demand of each bifurcating segment. In this case, the priority demands (IPRIO = 1) are proportionately reduced.

iv) After completing the computations for all segments at a node, the calculations proceed for the next downstream node. This way, all the nodes and segments are covered and the revised canal water demands and water availability at each node is worked out. After covering all segments, subroutine COPR is run again to get the final scenario of run-time, discharge, and canal seepage for the revised canal irrigation demands of different segments.

Policy – 4:Tail-reach priority

In this policy, the allocation is started from the tail end of the system and it advances in the upstream direction as the demands of the tail-end canals are satisfied. The computational steps are as follows:

i) Initially, the water availability at canal head is compared with the priority demand at head. If available water is less than the priority demand, only allocation is made among the priority segments starting from the tail end of the system.

ii) If the water available is more than the priority demands, the segment having greatest distance from the head and having normal priority is selected.

iii) Leaving the priority segments and the segment of greatest distance as selected in step (ii), the canal water demands of all other segments are considered to be met from groundwater.

iv) Assuming the canal irrigation demands (TWRCN) of the selected segment and the priority demands of the canal system, subroutine COPR is run to find the total water requirements at the system head.

v) If the water available at canal head is more than the requirement, then the next segment of greatest distance is selected in addition to the earlier selected segments and COPR is run again. The process is continued till the water availability at the head is completely exhausted.

Policy-5: Conjunctive use with minimum energy demand

In 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 amount of canal seepage and hence, larger withdrawal of groundwater. 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 the 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) Now 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-5.

2.4.6 Output of CNSM & Proposed Usage

The output results of the simulation model are presented in the form of maps and table. Maps are the means of easy visualization and understanding of model results but one map cannot represent the analysis in great detail. For detailed representation of results, a table is generated by the model.

In the operation strategy adopted in the present study, the CNSM is used to analyze the alternate policies of canal operation for different conditions of water use. The model makes detailed calculations of different operation variables using the real-time demand and water availability data and considering the spatial variation of canal system characteristics and groundwater scenario in the command area. Using the simulation model, the operator can visualize the extent of demands that can be satisfied from the available canal water during a week and the groundwater requirement in different canal segments of the command. Different scenarios of prioritization of canal segments and augmentation supply can be simulated and their impact on the performance of the system can be evaluated. Using the model, the operator can find the operation schedule of the canal system.

The developed model calculates the canal seepage loss in different canal segments for a given policy of operation. Canal seepage in an irrigation command is a major source of groundwater recharge. By running the model continuously for a longer time step (say for the complete rainy season) and combining it with the soil water balance model and the groundwater behavior model, the long-term impact of adopting of a particular operation policy in the command area can be evaluated. Different policies of operation can be tried and the policy which makes best utilization of the resources and also keeps the system in balance can be adopted for the region. The results of the model are presented in the form of maps for easy visualization by the decision-maker or those who are affected by the canal operation.

The application of the complete geo-simulation modeling scheme, consisting of database generation, application of SWBM and CNSM, and groundwater simulation model, is cited for the Lakhaoti branch canal command area for one Kharif crop season of the year 1998. The database development and model results are presented in the following chapters.

* * *

CHAPTER – 3
STUDY AREA AND DATABASE GENERATION

3.1 GENERAL

The geo-simulation conjunctive use model has been applied to a study area to analyze its performance and utilisation. The selected study area is representative of: a) underdeveloped agricultural region traditionally irrigated from shallow and deep wells where, a canal system was introduced in the year 1988, b) experiencing sub-optimal utilisation of available water resources, c) gradual depletion of water table before the introduction of canal system, and d) gradual built-up of water table after the introduction of canal system such that some area in the head reach has become waterlogged. In this chapter, description of physical characteristics of area and methods adopted for generation of spatially distributed database has been discussed. Basic data have been obtained from literature, from various Government agencies working in the study area, from field observations, and from satellite imageries.

3.2 GANGA CANAL SYSTEM

The agricultural land in western part of Uttar Pradesh (U.P.) State, India, is served by major river diversion schemes on the Ganga and Yamuna rivers. The area comprising of Ganga-Yamuna Doab is primarily served by the Upper Ganga Canal (UGC), Lower Ganga Canal (LGC), and Eastern Yamuna Canal systems. With the objective of raising paddy production in the command of UGC system, Madhya Ganga Canal Project (MGCP) was framed, which envisaged diversion of surplus monsoon water of Ganga River in the dry pockets [178000 hectare (ha)] of UGC command. The area for investigation in the present study is the Lakhaoti branch system, taking off from left of MGC at 82.4 km with a design discharge of about 64 cumec. Location map and schematic diagram of Ganga Canal System is given in Figure – 3.1.

3.3 LAKHAOTI BRANCH SYSTEM

The command area of Lakhaoti branch lies between latitude 27°45′ N to 28°45′ N and longitude 77°45′ E to 78°35′ E and covers an area of 205.6 thousand ha in the districts of Ghaziabad (3.8%), Bulandshahr (71.4%) and Aligarh (24.8%) in the U.P. State. Command area is bounded by the two main drainage of the area, Kali river in the west and Nim river in the east. Lakhaoti branch supplies water to the area during monsoon period (June – October) for irrigation of Kharif (monsoon season) crops. An index map of the area showing boundary rivers and the MGC is shown in Figure – 3.2.

Lakhaoti branch canal (64 cumec design discharge) commands an area of 193 thousand ha and the design paddy irrigation is around 48 thousand ha. The length of branch canal is 72.4 km while the length of distribution system of various capacities is 1,030 km. In the head reach, Lakhaoti branch has a bed width of 35 m, water depth 2.25 m, and bed slope 15 cm/km. At the tail end, discharge is 20 cumec, bed width reduces to 14 m and water depth reduces to 1.56 m.. All main canals and distribution systems are unlined earthen canals.

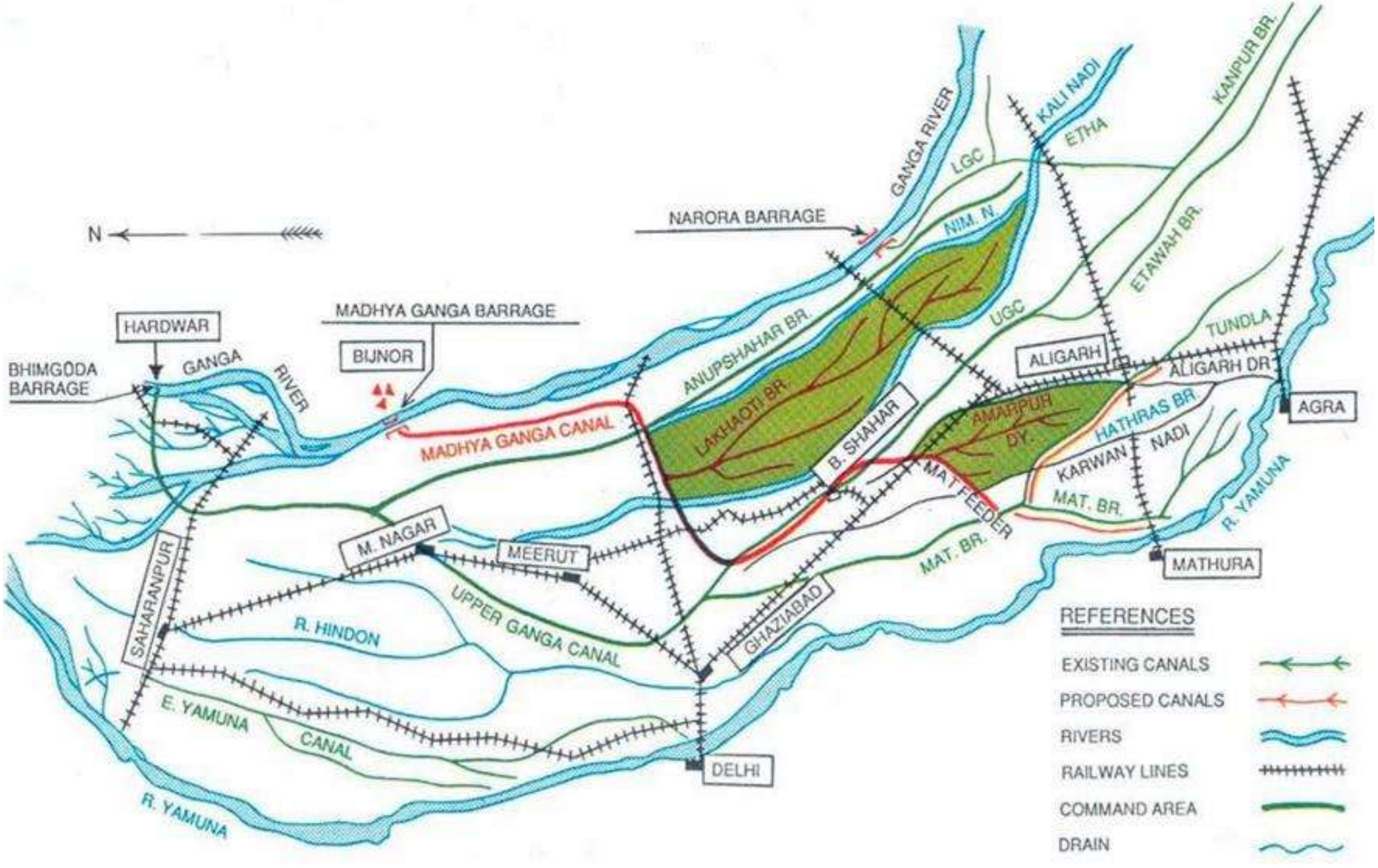


Figure – 3.1: Schematic diagram showing UGC, MGC, and Lakhaoti command

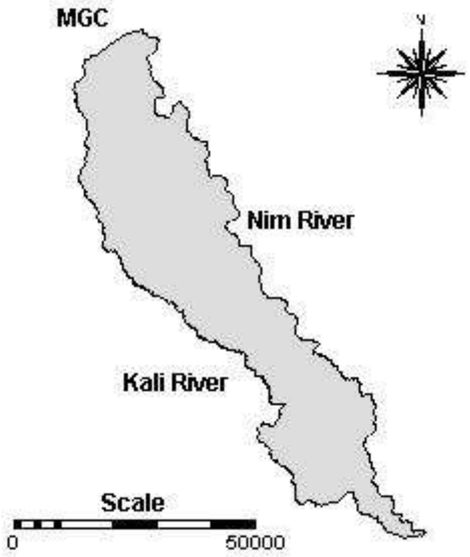


Figure – 3.2: Boundary of the Lakhaoti branch command

In the absence of surface water supplies till 1987, irrigation water requirements were being met by pumpage from groundwater reservoir. Groundwater was pumped through state tube wells, private tube wells, and Persian wheels in dug wells. Excessive pumping of groundwater in the area led to gradual depletion of water table thereby increasing the cost of pumping and causing loss of natural vegetation. Introduction of canal irrigation in the year 1988 has led to greater recharge to the ground water with gradual built-up of water table.

3.3.1 Climate and rainfall

The area experiences moderate type of sub-tropical and monsoon climate. May is generally the hottest month with the mean daily maximum temperature of about 41°C. January is generally the coldest month with the mean daily maximum temperature of about 21°C. During monsoon, humidity is relatively high, often exceeding 70 percent while it becomes less than 20 percent during summer. 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 worked out by the U.P. Groundwater Department is 653.7 mm.

Daily rainfall data of five rain gauge stations (Siyana, Bulandshahr, Anupshahr, Khurja, and Atrauli) have been available from the year 1994 to year 2000. Layout of various rain gauge stations in/around the Lakhaoti command is shown in Figure – 3.3. Thiessen polygon map is prepared and the weights of various stations are: Siyana-1 (0.198), Bulandshahr-2 (0.210), Anupshahr-3 (0.168), Khurja-4 (0.078), and Atrauli-5 (0.346). The areal average rainfall, worked out using Thiessen weights in Lakhaoti command in the monsoon season (June to October) for various years is presented in Table – 3.1.

Table – 3.1

Areal average monsoon rainfall in Lakhaoti command

Year	1994	1995	1996	1997	1998	1999	2000
Rainfall (mm)	438.64	615.32	570.74	592.39	776.25	635.77	660.05

During the period of seven years, 1998 has been relatively wet year while 1994 has been relatively dry year. As discussed later, data of year 1998 has been used in this study for the application of simulation scheme. July, August, and September are the months that receive maximum proportion of the monsoon rainfall.

3.3.2 Topography, physiography & soil characteristics

The average ground slope of the area is 0.375% in longitudinal direction from North to South. The surface elevation varies from 210 m in the north to 168 m in the south. The area is made up of recent unconsolidated fluvial formation comprising sand, silt, clay and kankar with occasional beds of gravel deposited by Ganges and its tributaries. Geologically, sediments are favourably embedded in the sub-surface strata for occurrence of groundwater.

The study area has soils of sandy loam and silt loam type in texture and granular in structure. Thickness of the fertile soil is more than two meters. Average infiltration rate is about 2.6 cm/hour. The dry bulk density is 1.53 gm/cm^3. Average hydraulic conductivity of the soils is 0.7 m/day. In the present study, soil map of Lakhaoti command is derived from the soil map of U.P. State at a scale of 1:500,000 from the National Bureau of Soil Survey and Land Use Planning (NBSSLUP), New Delhi. This map is presented in Figure – 3.4. The soils in the command have been broadly classified in nine categories by NBSSLUP and named as: Soil 088, Soil 099, Soil 086, Soil 134, Soil 197, Soil 112, Soil 102, Soil 159, and Soil 203. The input of soil map in GIS is described under Section 3.4.2. Soil properties of interest in this study have been determined in laboratory and are mentioned in Table – 3.2.

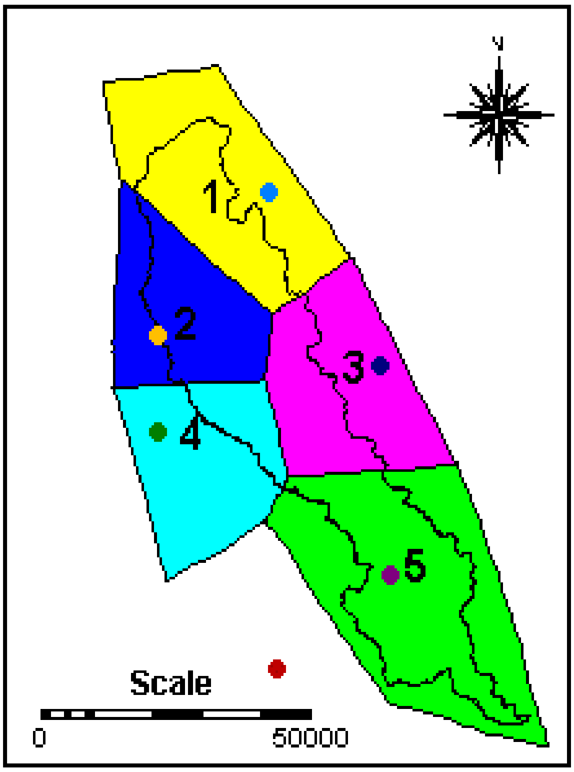
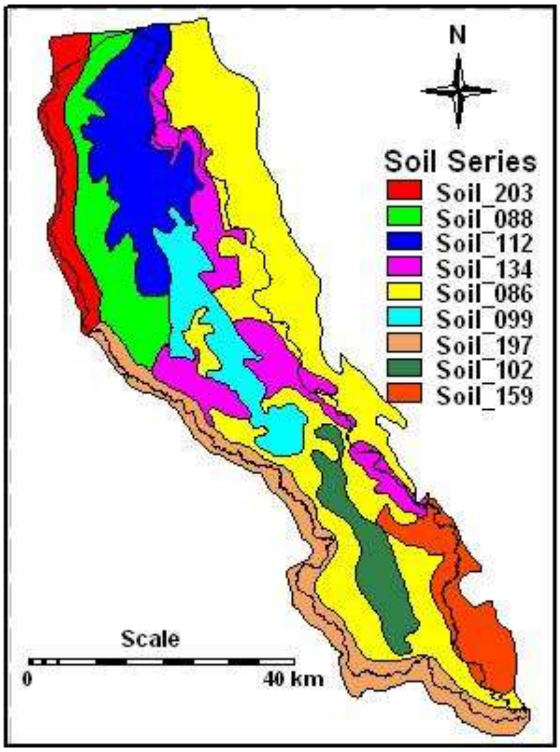


Figure-3.3 Thiessen polygon of rainfall stations



Figure–3.4 Soil map in Lakhaoti command

Table – 3.2
Soil properties used in the study

Soil type	Field capacity	Permanent wilting point	Specific gravity
Soil 088	18.92	10.45	2.70
Soil 099	20.38	07.92	2.58
Soil 086	22.87	14.45	2.57
Soil 134	14.08	04.16	2.60
Soil 197	08.84	03.12	2.65
Soil 112	17.56	07.50	2.67
Soil 102	24.68	14.33	2.63
Soil 159	18.18	10.12	2.62
Soil 203	19.22	05.50	2.67

3.3.3 Groundwater conditions

Exploratory drilling in the Lakhaoti command indicates that the thickness of the alluvium varies between 379 m and 700 m. 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 below ground level in the command. A perusal of 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 and has built up a lot since the canal introduction. The quality of ground water in the area is generally good and water is non-corrosive and non-incrusting.

There are a number of deep and shallow wells in the area with discharges of shallow wells (depth < 50 m) ranging between 6 to 15 litres per second (lps) whereas discharges of deep wells range between 25 and 45 lps. Pumping tests indicate that the deeper aquifers are leaky and confined with coefficient of transmissibility varying between 484 and 683 m^2/day. The coefficient of storage varies between 0.0009 and 0.004. The shallow aquifers have coefficient of transmissibility ranging between 167 and 1,1917 m^2/day. The value of specific yield varies between 0.05 and 0.27.

3.3.4 Crops & cropping pattern

Before the introduction of canal system, principal crops in the area were wheat, sugarcane and maize and the area under paddy was very small. However, after introduction of canals, major Kharif crops of the area are maize, sugarcane, rice, oil seed, pulses, fodder, and other crops. During Rabi season (winter-season), major crops are wheat, mustard, potato, gram, and barley. The average area under various crops for the conditions prior to introduction of canal system and as proposed by the project authority after the introduction of canal system are shown in Table - 3.3.

The crop calendar that is broadly followed in the Lakhaoti command is presented in Table – 3.4. Sowing and harvesting dates for various crops have been collected from the Agriculture Department, Bulandshahr. In the simulation model, each crop is assumed to be sown and harvested at fixed times (calendar weeks) throughout the command.

Table – 3.3
Cropping pattern in Lakhaoti command before & after canal introduction

S. No.	Name of crop	Crop area before canal		Crop area after canal		Yield (quintal/ha)
		(in ha)	(as %)	(in ha)	(as %)	
1.	Sugarcane	21426	11.1	21426	11.1	463
2.	Rice	3455	1.8	48254	25.0	35
3.	Maize	37551	19.5	0	0	25
4.	Arhar (pulse)	10950	5.7	10950	5.7	10
5.	Guar (fodder)	9694	5.0	9694	5.0	10
6.	Gram	1191	0.6	1191	0.6	10
7.	Mustard	6436	3.3	6436	3.3	8
8.	Potato	2615	1.4	2615	1.4	200
9.	Wheat	98063	50.8	98063	50.8	35

Table – 3.4
Crop calendar of major crops in Lakhaoti command

S. No.	Name of crop	Months											
		J	F	M	A	M	J	J	A	S	O	N	D
	Perennial Crop												
1.	Sugarcane	─	►		◄	─	─	─	─	─	─	─	─
	Hot-weather crops												
2.	Moong (Pulse)		◄	─	─	►							
3.	Urad (Pulse)				◄	─	►						
	Kharif crops												
4.	Rice							◄	─	─	►		
5.	Maize						◄	─	─	►			
6.	Arhar (Pulse)						◄	─	─	─	─	►	
7.	Guar (Fodder)							◄	─	►			
	Rabi crops												
8.	Gram	─	►								◄	─	─
9.	Mustard	─	►								◄	─	─
10.	Potato	─	►									◄	─
11.	Wheat	─	─	►								◄	─
12.	Barley	─	►									◄	─

3.3.4.1 Characteristics of crops

Different crops have different characteristics, such as crop factors at different growth stages, maximum root depth, time to reach maximum root depth, starting week of crop, crop duration, standing water requirement (if any), and the fraction of the available water without affecting the yield of the crop.

Crop factors as applicable to crops in the region at different growth stages have been obtained from Irrigation Department. Root depth characteristics and the fraction of available water for different crops have been obtained from the FAO – IDP 24 (1977). In between the period from starting of crop to the time of maximum root depth, root depth was assumed to follow sinusoidal function as stated by Borg and Grims (1986). Starting week of a crop, crop period, water depth required for land preparation and time of land preparation are obtained from the Agriculture Department. Bund height of 150 mm for rice fields is assumed. Various characteristics of crops, as used in this study, are presented in Table – 3.5.

Table – 3.5

Crop characteristics of major crops in Lakhaoti command

Crop characteristic	Sugarcane	Maize	Rice	Arhar	Guar	Gram	Mustard	Potato	Barley	Wheat
Fraction of available soil water	0.65	0.60	1.00	0.50	0.50	0.50	0.50	0.25	0.55	0.50
Maximum root depth (mm)	1000	900	500	900	1000	1000	1000	500	1000	1000
Time to maximum root depth (weeks)	15	9	9	9	6	9	9	9	9	9
Starting week (calendar week)	51	25	27	25	27	42	42	44	45	47
Period of crop (weeks)	52	15	17	20	13	20	18	17	17	18
Standing water depth required (mm)	0	0	100	0	0	0	0	0	0	0
Time of standing water requirement (weeks)	0	0	15	0	0	0	0	0	0	0
Required water depth for initial land preparation (mm)	50	50	150	50	50	50	50	50	50	50
Time of initial land preparation (weeks)	1	1	1	1	1	1	1	1	1	1
Fortnightly Crop Coefficients										
January (I)	1.10					0.89	1.10	1.15	1.10	1.08
January (II)	1.06					0.63	1.09	1.15	1.07	1.10
February (I)	1.02					0.41	0.93	1.11	0.87	1.10
February (II)	1.00					0.41	0.52	0.86	0.50	1.07
March (I)	0.98					0.40		0.86	0.50	0.87
March (II)	0.51									0.50
April (I)	0.53									
April (II)	0.57									
May (I)	0.59									
May (II)	0.61									
June (I)	0.64									
June (II)	0.66	0.49		0.40						
July (I)	0.70	0.59	1.06	0.47	0.48					
July (II)	0.7	0.91	1.10	0.65	0.54					
August (I)	0.81	1.10	1.10	0.99	0.77					
August (II)	0.87	1.10	1.12	1.03	0.99					
September (I)	0.92	1.01	1.15	1.05	1.05					
September (II)	0.96	1.01	1.15	1.05	1.04					
October (I)	1.00	0.71	1.04	1.03	0.98					
October (II)	1.05	0.71	0.98	0.83		0.23	0.31			
November (I)	1.09		0.98	0.48		0.29	0.48	0.34	0.31	
November (II)	1.10					0.83	0.50	0.42	0.42	0.31
December (I)	1.10					1.05	1.09	0.72	0.80	0.42
December (II)	1.10					1.04	1.10	1.00	1.08	0.80

3.3.5 Surface water availability

Lakhaoti canal is the only source of surface water to Lakhaoti command. Water is released in this canal only during the months from June to October at varying rates. Table – 3.6 shows the supply discharge and volume of canal water available during different periods.

Table – 3.6

Proposed canal releases in different time periods

S. No.	Period		Discharge (cumec)	% of Full Supply Discharge
	Month	Dates		
1.	June	08-15	12.8	020
		16-23	12.8	020
		24-30	12.8	020
2.	July	01-07	64.0	100
		08-15	64.0	100
		16-23	64.0	100
		24-31	64.0	100
3.	August	01-07	64.0	100
		08-15	64.0	100
		16-23	64.0	100
		24-31	64.0	100
4.	September	01-07	64.0	100
		08-15	64.0	100
		16-23	64.0	100
		24-30	32.0	050
5.	October	01-07	32.0	050
		08-15	16.0	025

3.3.6 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). These have been used in deciding the capacities of different segments and in calculating canal seepage. These are presented in Table – 3.7.

In addition to this, detailed information about various minors and distributaries in the canal network are collected from Irrigation Department in Bulandshahr and Aligarh. In this study, 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 under section 3.4.2.

3.4 GENERATION OF DATABASE FOR LAKHAOTI COMMAND IN GIS

An objective of this study is to integrate the irrigation system simulation model with spatial database. The spatial database is generated, stored, manipulated, and retrieved in a GIS. The GIS system used is ILWIS (Integrated Land and Water Information System) developed by ITC, The Netherlands. ILWIS is a user-friendly PC-based GIS and image processing package designed for WINDOWS environment. It provides a tool for collection,

Table – 3.7
Characteristics of Lakhaoti distribution system

Reduced distance	Discharge (cumec)	Wetted perimeter (m)	Length (m)	Wetted area (Mm^2)	Losses (cumec)	Reach efficiency
1. Lakhaoti Branch						
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	--	--	--	--	--	--
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	--	--	--	--	--	--
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	--	--	--	--	--	--
6. Chharra Distributary						
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	--	--	--	--	--	--
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	--	--	--	--	--	--

storage, analysis, transformation and presentation of spatial data (ILWIS 3.0 Academic User's Guide, 2001). Various data layers (boundary, contours, spot levels, drainage, cities, villages, forests, plantations, roads, and water bodies) were digitized from 1:25,000 scale SOI toposheets. Boundary layer is used to separate the area of interest from remote sensing image and other spatial data. Contour and spot level data are used to generate the DEM for the area. Forest/plantation layer is used to separate forests/plantations from agricultural area. Village map is used to identify the location of groundwater observation wells. Roads and railways are used to provide control points for georeferencing remote sensing images.

The crop map of the area for the Kharif season of year 1998 is obtained from the multi-temporal remote sensing data of IRS-1C/1D satellite. The DEM of the area is prepared from contours and spot levels. These are discussed in detail in the NIH report on “Optimum Water Management in a Command Area”. The DEM of Lakhaoti command and crop map of Kharif season for the year 1998 are presented in Figure – 3.5 and Figure - 3.6 respectively.

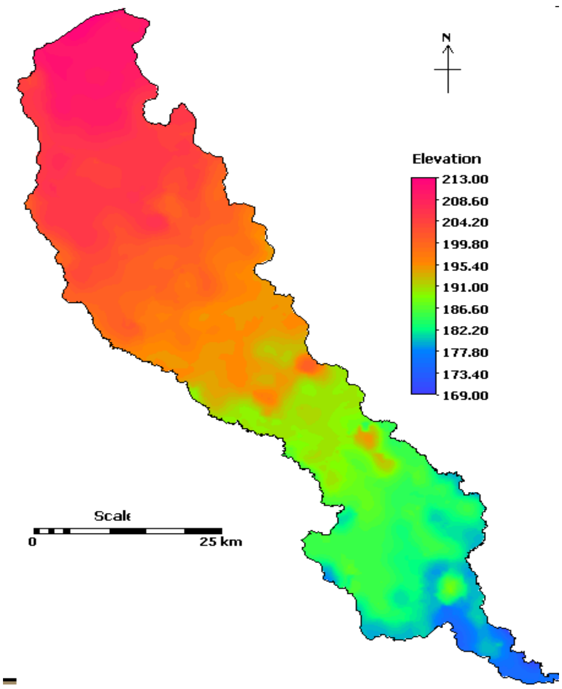
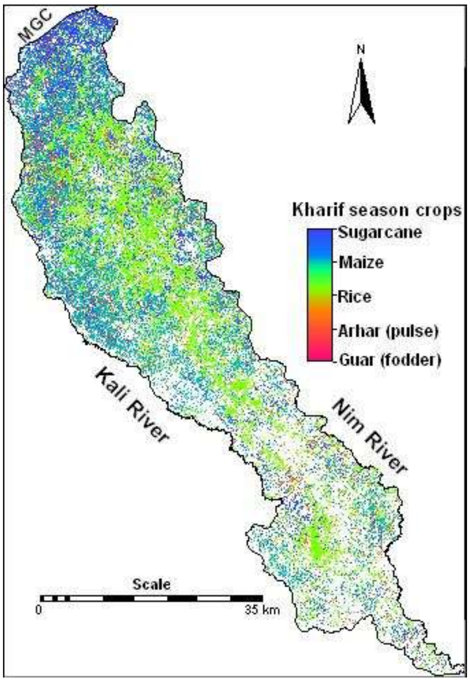


Figure-3.5 DEM of Lakhaoti command



Figure–3.6 Kharif crop map in year 1998

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 using the moving-surface method of point interpolation. The groundwater surface for October 1998 is shown in Figure – 3.7 (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 – 3.7 (b).

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 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 (PAN sensor) has been used to delineate the canal network up to minor level. After obtaining the canal network layout, irrigable areas of different canal segments has been delineated using various ancillary information. The details are given in the NIH report entitled “GIS Based Efficient Distribution System for a Command”. The canal network layout map and the irrigable command area map are given in Figure – 3.8 and Figure - 3.9 respectively.

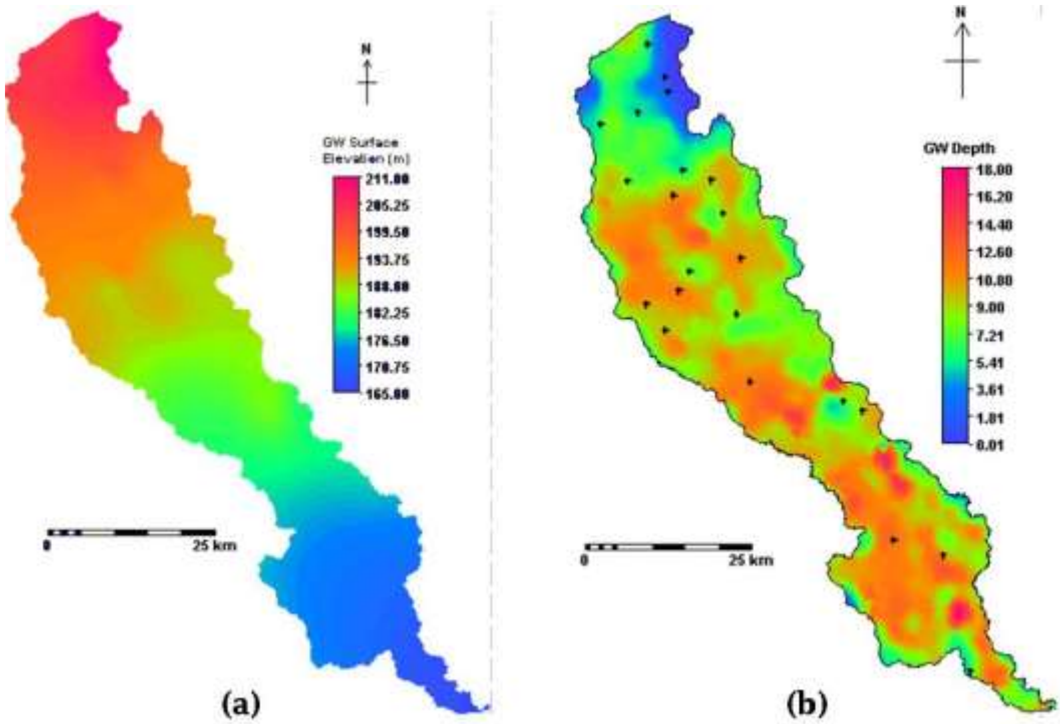


Figure – 3.7: (a) GW surface map for October, 1998, (b) GW depth map and location of wells

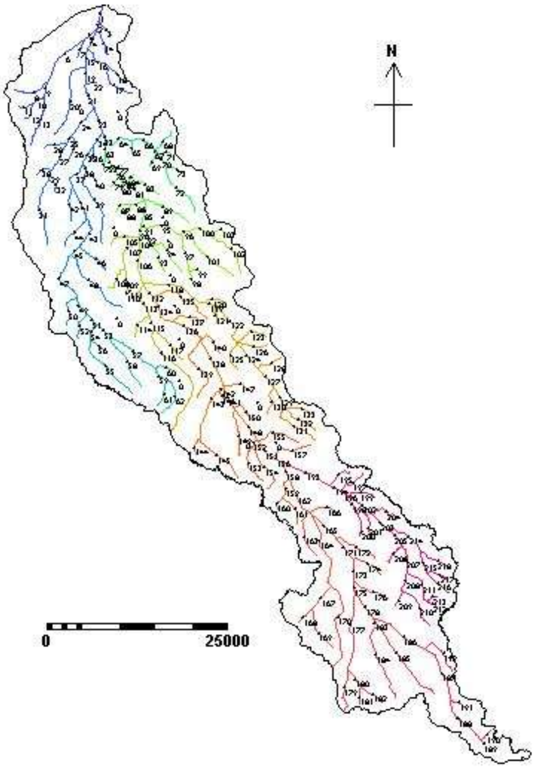


Figure – 3.8: Canal network in Lakhaoti command

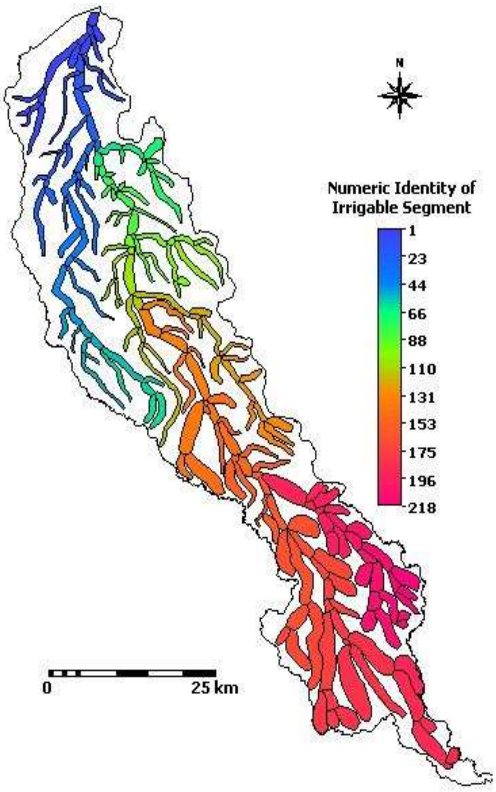


Figure – 3.9: Irrigable command areas

3.5 CHARACTERIZATION OF DIFFERENT CANAL SEGMENTS

In the simulation scheme, each canal segment represents a link in the network and various links are connected at nodes. Various canal characteristics are required in the scheme 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:

$$\text{Canal Seepage} = [(\text{Bed width}+\text{Water depth})^{2/3}/200] * \text{Segment length} * \text{Run-time} \qquad \ldots(3.3)$$

Here, the bed width and water depth are in m while the length of segment is in km. 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, irrigation in command was fully dependent on the groundwater. Further, during the non-monsoon season, the canal water supply is not planned and therefore, groundwater continues to be the only source of irrigation water supply during Rabi season. Characteristics of various canal segments are presented in Table – 3.8.

Table – 3.8
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	-	-
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	-	-	-	-

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
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	-	-	-	-
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	-	-	-	-

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_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	-	-	-	-
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	-	-

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_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/ 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 name of corresponding branch or distributary to differentiate the names of different canal segments of a branch or distributary. 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.

3.6 DATABASE GENERATION FOR GROUNDWATER FLOW MODEL

A groundwater behavior model (Visual MODFLOW) is used in the present geo-simulation scheme to find the groundwater surface in the command at different time steps corresponding to the external stresses of pumping and recharge under various policies of canal network operation. Input module of the package allows user to graphically assign all necessary input parameters for building database for the groundwater model. Various input data prepared for groundwater model are discussed below.

3.6.1 Base map of Lakhaoti command

Groundwater levels do not vary considerably over very short distances. For groundwater model study, the grid size of 24 m * 24 m, as used in developing spatial database in GIS, is considered too fine. Thus, spatial data of 10 x 10 grids have been aggregated and grid size of 240 m * 240 m is used for groundwater model studies. With this grid size, the number of rows and columns of the data set are calculated to be 437 and 302 respectively which lie within the maximum range of VMOD limitations (500 x 500). The base map of Lakhaoti command (rasterized boundary layer) is available in ILWIS system. The same is aggregated to 240 m grid size and imported in VMOD as a BMP file. The area outside of the command is marked inactive, thus defining the irregular boundary of command (Kali river, Nim river, and MGC).

3.6.2 Surface elevation map of Lakhaoti command

The DEM of command area has been generated in ILWIS. The same is aggregated to

240 m grid size using the “Average” function in ILWIS and imported in VMOD using the “Import Elevation” utility.

3.6.3 Initial groundwater surface maps of Lakhaoti command

Groundwater surface maps for Lakhaoti command are generated in ILWIS for the months of June and October. Groundwater surfaces for June and October, as generated in ILWIS, have been aggregated to 240 m grid size using the “Average” function in ILWIS and then imported in VMOD using the “Import Initial Heads” utility.

3.6.4 Boundary conditions of Lakhaoti command

As the Lakhaoti command is bounded by the Kali and Nim rivers and the MGC, the boundary conditions along the Kali and Nim rivers are assigned to be “Rivers”. Since the MGC is an unlined canal with higher water surface elevation, it was considered as a “Recharge” boundary.

For the river boundary, information about river stage elevation at each time step, river bottom elevation, and the conductance of river-bed (representing resistance to flow between surface water body and groundwater) is required. Daily river stage levels for the two rivers have been collected from the State Department. Daily data were converted to weekly average values and then specified in VMOD. The conductance of the river-bed is calculated as:

$$C = K.L.W/M \qquad \ldots(3.4)$$

where “L” is the length of reach, “K” is hydraulic conductivity of river bed material, “W” is width of river bed, and “M” is the thickness of river bed. Bed material has been classified as sand and therefore, the hydraulic conductivity of 25 m/day (obtained from Todd, 1987) is used. Each river (Kali and Nim) is divided in 11 segments from head (intersection with MGC) to tail (confluence of Kali and Nim). The river-bed elevations and the river stage elevations for the eleven segments have been linearly interpolated and specified in VMOD. River widths in head and tail reaches for the Kali and Nim Rivers have been obtained from PAN sensor data. The same have been linearly interpolated for intermediate segments.

For recharge boundary (MGC), the method for estimation of seepage loss from a ridge canal when the water table is at large depth (given by Harr, 1962) is:

$$q = k\ (B + A\,H) \qquad \ldots(3.5)$$

in which, B = the width of the canal at the water surface, H = the maximum depth of water in the canal; and A = a parameter, derived rigorously for a trapezoidal straight canal in a homogeneous isotropic porous medium of infinite depth and the water table lies at large depth below the canal bed, and is equal to two. At the location in MGC where Lakhaoti branch takes off, the MGC has discharge capacity of 139 cumec, bed width of 42 m, bed slope of 11 cm/km and side slope of 1.5:1. The bed level is at RL 207.80 m while full supply level is at RL 211.10 m. Using water stage data and section details, seepage loss from the MGC is calculated and specified in VMOD. Since the water table below MGC generally remains at 10-15 m deep, so level remains, the canal is assumed to be hydraulically connected to the aquifer and unsteady seepage would take place. Interaction of a partially penetrating river and aquifer for varying river stage has been analyzed by Morel-Seytoux and Daly (1977) and the same analysis is used to find the seepage from MGC.

3.6.5 Wells in Lakhaoti Command

Two kinds of wells have been defined for the Lakhaoti command. External stresses of pumping and recharge are introduced through the pumping wells in the command. A pumping well is assigned to each grid of size 480 m * 480 m. Total pumping or recharge calculated in the command at weekly time step (by SWBM) at each 24 m * 24 m grid is aggregated to 480 m * 480 m grid, converted to m^3/day, and then assigned to each well through the module (WELL). The well data so generated is imported in VMOD using “Import Pumping wells” utility. Each well is given a separate identity. Layout of wells in a part of the command is shown in Figure – 3.10 and representation of data for a well in VMOD are presented in Figure – 3.11.

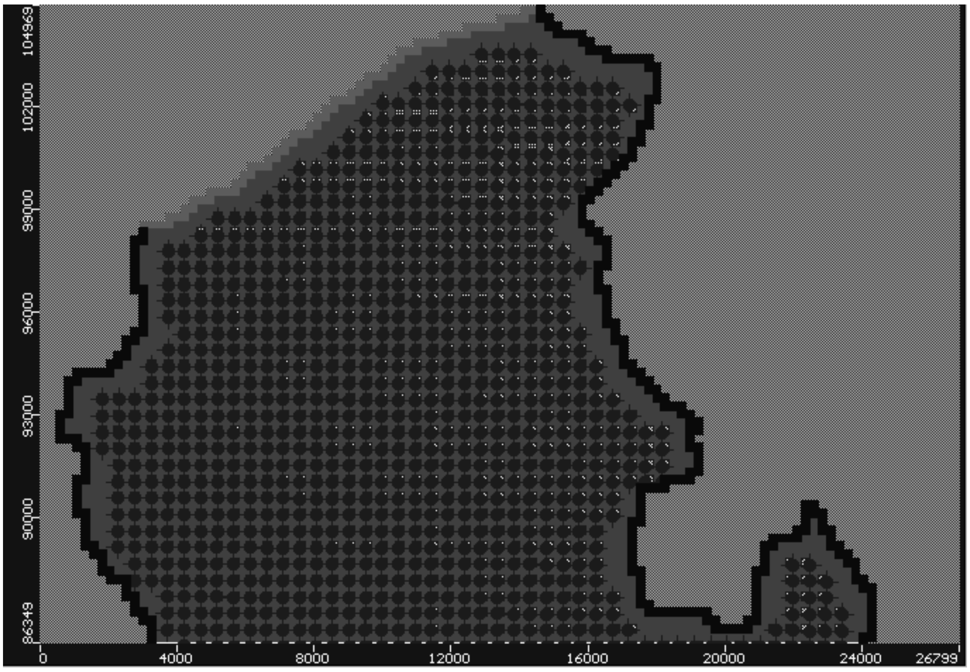
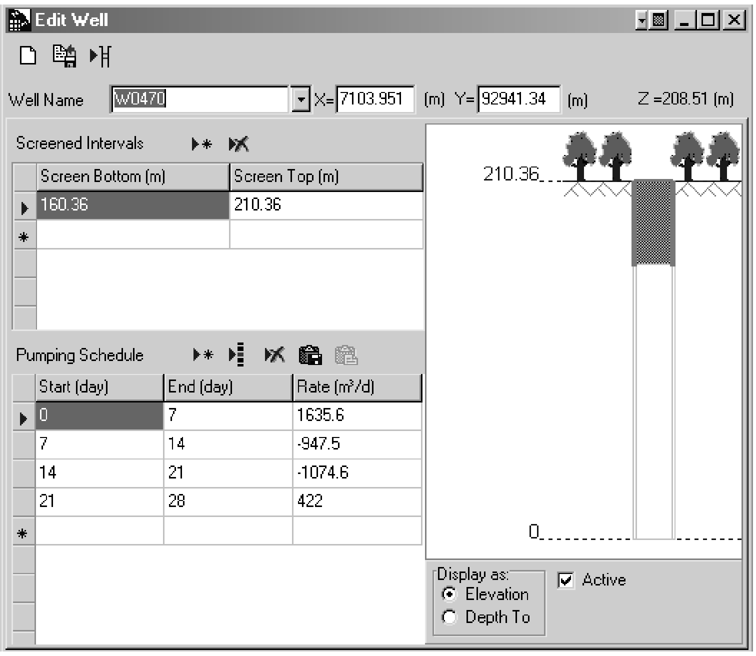


Figure – 3.10: Layout of pumping wells in a part of Lakhaoti command

Another kind of wells defined for the command are Head Observation Wells which are used as calibration and validation points by comparing the observed and simulated heads. Data of 19 observations wells at different time steps are imported in VMOD. The layout of head observation wells in Lakhaoti command is shown in Figure – 3.12.

3.6.6 Aquifer characteristics in Lakhaoti command

Simulation of groundwater flow requires the definition of hydro-geological properties of the aquifer. Two hydro-geological properties have been defined for the Lakhaoti aquifer system: conductivity and storage. Groundwater modeling of Lakhaoti branch command was studied by Nayak et al. (1990). In this study, the command was divided in 35 polygons with



Well Name W0470 X= 7103.951 (m) Y= 92941.34 (m) Z =208.51 (m)

Screened Intervals

	Screen Bottom (m)	Screen Top (m)
▶	160.36	210.36
*		

Pumping Schedule

	Start (day)	End (day)	Rate (m³/d)
▶	0	7	1635.6
	7	14	-947.5
	14	21	-1074.6
	21	28	422
*			

Display as: ● Elevation ○ Depth To

☑ Active

Figure – 3.11: Representation of pumping well data in VMOD

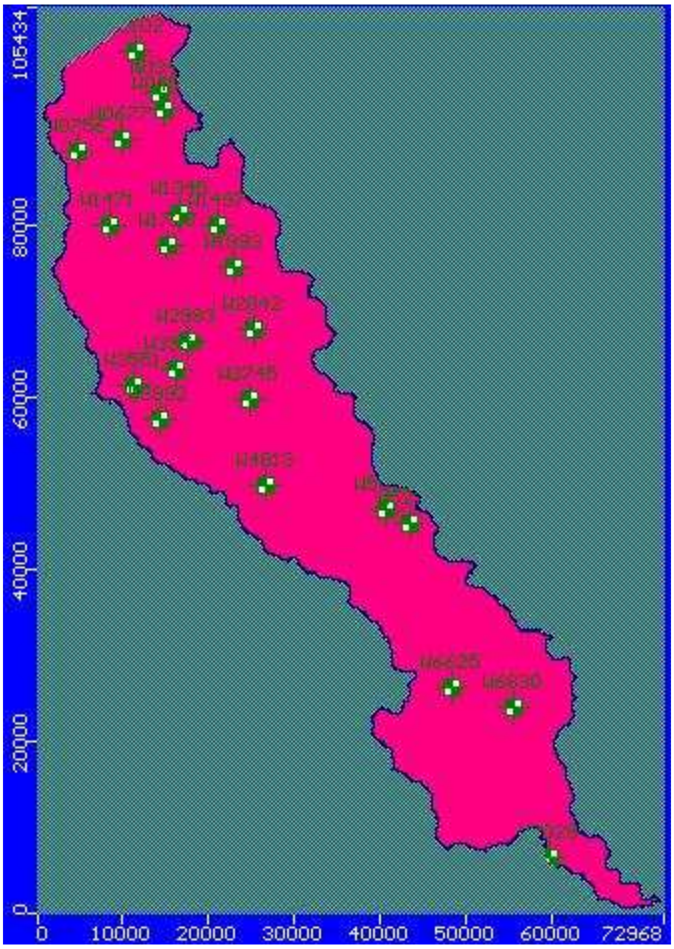


Figure – 3.12: Location of observation wells in Lakhaoti command an average area of 5700 ha. Integrated finite difference method was used and the model was calibrated with 4 years of data (1984-87) using two time steps: 4 monthly for the monsoon season and 8 monthly for the non-monsoon season. The specific yield of the aquifer was found to vary from 0.05 to 0.25 while the transmissivity was found to vary from 2.5 to 5.5 ha/month. Conductivity and storage characteristics of the aquifer system have been taken from this study. Specific yield map of the Lakhaoti aquifer system is shown in Figure - 3.13.

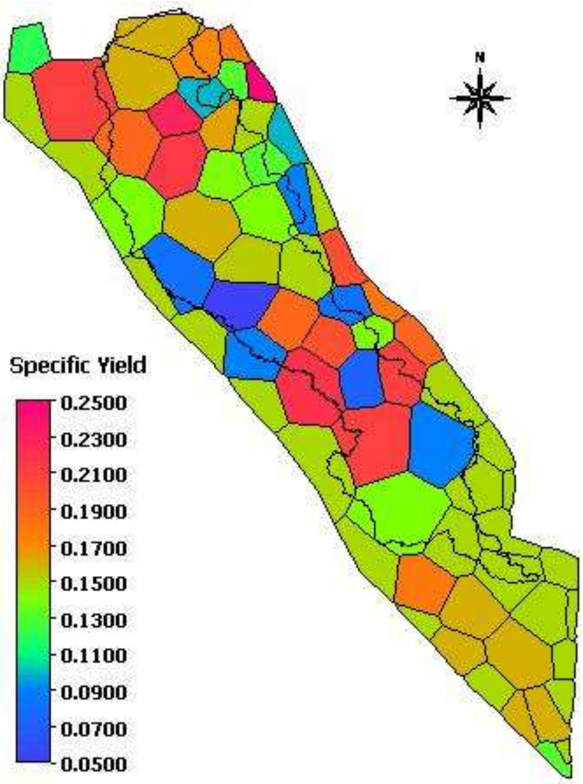


Figure – 3.13: Specific yield map of aquifer in Lakhaoti command

3.7 ESTIMATION OF EVAPO-TRANSPIRATION

The meteorological factors that are useful in the soil water balance computation include rainfall and reference crop evapo-transpiration (RET). Daily RET depends on several factors such as max. and min. temperature, max. and min. relative humidity, solar radiation, average wind speed, time of year, the latitude and altitude of place. The water consumption by the plants is computed on the basis of daily/weekly RET. Various methods are available in the literature for the estimation of RET. These include Modified Penman's method, Penman-Monteith (PM) method, Hargreave's method, Blaney Criddle method etc. PM method is the most advanced resistance based method recommended by FAO-56 (1998) for estimation of ET_{ref}. The application of Penman or PM methods requires data on temperature, humidity, wind, and radiation. The basic equation governing the estimation of ET_{ref} is stated as:

$$RET = \frac{0.408.\Delta.(R_n - G) + \gamma \dfrac{900}{T+273}.u_2.(e_s - e_a)}{\Delta + \gamma(1 + 0.34.u_2)} \qquad \ldots(3.5)$$

where RET is in mm/day, R_n is the net radiation at the crop surface in MJ per m^2 per day, G is the soil heat flux density in MJ per m^2 per day, T is the mean daily air temperature at 2 m height in °C, u_2 is the wind speed at 2 m height in m/s, e_s is the saturation vapour pressure in kPa, e_a is the actual vapour pressure in kPa, $(e_s - e_a)$ is the saturation vapour pressure deficit in kPa, Δ is the slope of vapour pressure curve in kPa per °C, and γ is the psychrometric constant in kPa per °C. FAO-56 [Allen et al. (1998)] describes the procedure in detail for estimation of various parameters of the Penman-Monteith method.

For this study, the Penman-Monteith method is used. The meteorological data of Bulandshahr station at daily time step are available and the same have been collected from the Agriculture Department. Average monthly wind velocity values have been obtained from Sakthivadivel and Chawla (2002). Daily radiation data are not available for the station. However, the FAO-56 manual recommends the following equation for estimation of approximate value of radiation from the temperature data:

$$R_s = k_{rs}.\sqrt{(T_{max} - T_{min})}.R_a \qquad \ldots(3.6)$$

where R_a is the extraterrestrial radiation in MJ per m^2 per day, T_{max} is the maximum air temperature in °C, T_{min} is the minimum air temperature in °C, k_{rs} is the adjustment coefficient (varying between 0.16 to 0.19 for interior to coastal areas). In the present case, since the study area was located in-between the Ganga and Yamuna river systems with well-distributed canal network, k_{rs} value of 0.17 was used. A computer program is written to estimate the daily value of RET for the Lakhaoti command. RET values for 12 years of data (1989-2000) have been estimated and average values for different days are found out. Since the operation scheme in this study is demonstrated with the data of year 1998, actual RET values for the year 1998 have been used in the analysis. A plot showing variation of average values of daily RET and the actual values of RET in the year 1998 is presented in Figure – 3.14. Rainfall of the year 1998 are also plotted to show the effect of weather change on the daily RET values.

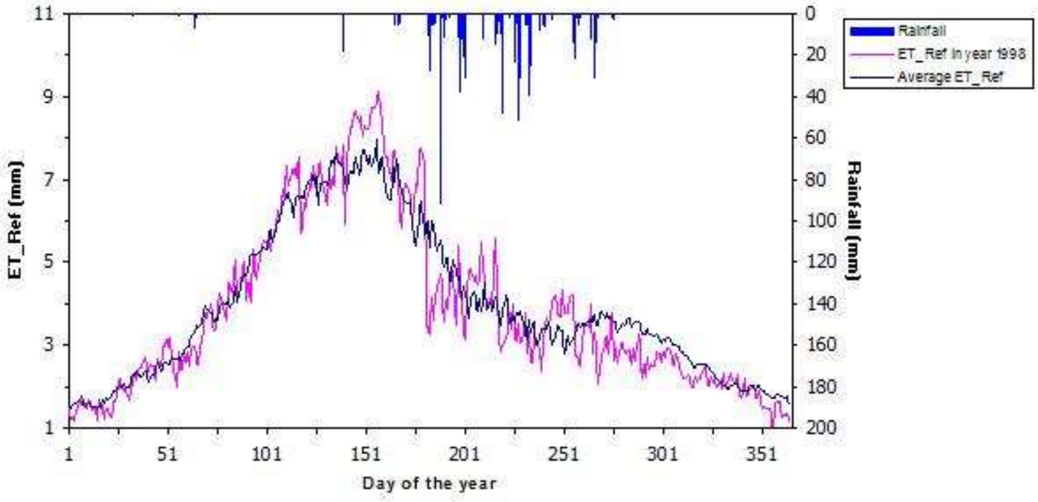


Figure – 3.14: Reference crop evapo-transpiration in Lakhaoti command

* * *

CHAPTER – 4
MODEL APPLICATION & DISCUSSION OF RESULTS

4.1 GENERAL

The geo-simulation scheme is applied to a canal command area for a specific year and its performance is analyzed. Application of the scheme required generation of extensive database for the command area, which is explained in Chapter – 3. This chapter explores the potential use of scheme through a case study and elaborates the results of model application. First, the application of two major modules of the scheme [soil water balance model (SWBM) and canal network simulation model (CNSM)] for one week duration are discussed illustrating the effect of various options on the model output. Then, the scheme is validated by comparing observed and simulated groundwater levels at the end of Kharif season. Various operation policies under the canal network simulation model can be adopted when the canal water demand in the system exceeds the canal water availability. Therefore, as a third step, potential use of the scheme is evaluated for a simulated condition of deficit canal water supply. The scheme is run for an entire crop season (June to October) during which the Lakhaoti canal network is planned to be operated and the relative performance of different policies of canal operation are analyzed.

4.2 APPLICATION OF SOIL WATER BALANCE MODEL

The objective of soil water balance model is to simulate the dynamics of soil moisture within the crop root zone at weekly time step giving particular focus to the spatial variation of crop, soil, rainfall, topography, and groundwater condition in the command area. Output of the model provides spatial information about the moisture content in the crop root zone at the end of the week, irrigation water demand during the week, water stress conditions in the crop root zone, and the recharge to the groundwater table for each grid in the command area. The output of SWBM is presented in the map form for easy visualization and comprehension. This spatial information is integrated with canal operation model for computer-based rational management of irrigation water. SWBM, its inputs and outputs have been described at length in the NIH report entitled “Optimum water management in a command area”. However, the four maps generated by SWBM for the calendar week number 32 (July 23 – 29, 1998), i.e. final water content map, irrigation demand map, groundwater pumping/recharge map, and crop stress map have been presented in Figure – 4.1 to Figure – 4.4 respectively.

4.3 APPLICATION OF CANAL NETWORK SIMULATION MODEL

The objective of CNSM 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 simulation model, different policies of canal water allocation can be visualized. Various scenarios of prioritization of canal segments and augmentation supply in different canal segments can be simulated and their impact on the system performance can be evaluated. Results of CNSM can be generated in the form of maps and table. The tabular

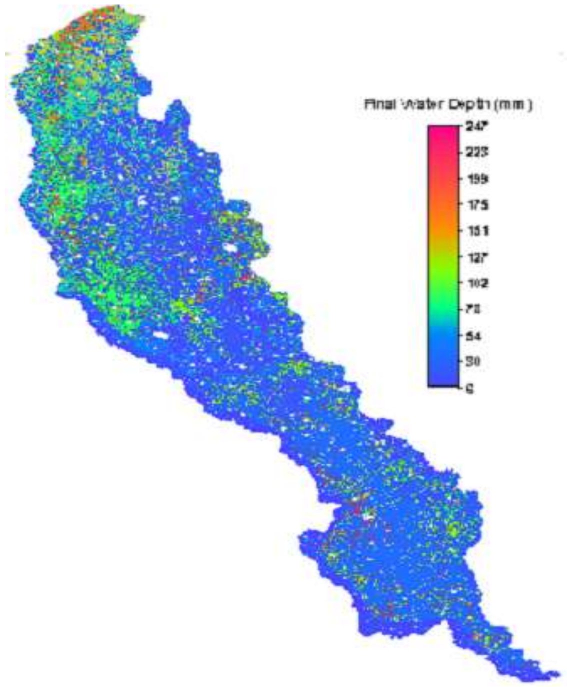


Figure-4.1 Final water content map at end of week derived from SWBM

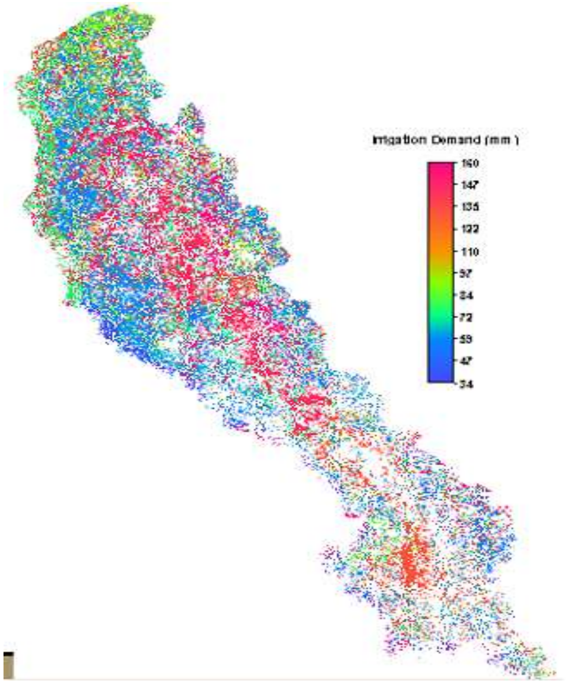
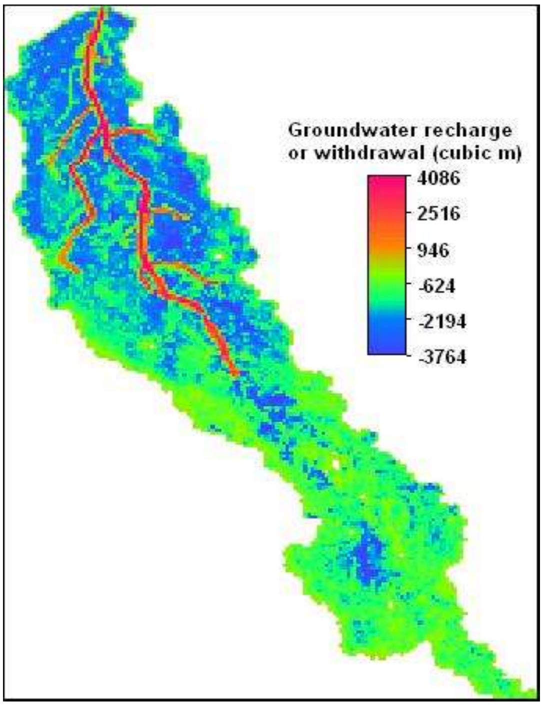


Figure-4.2 Irrigation demand map in a week as derived from SWBM



Figure–4.3 Groundwater recharge/pumping map in a week as derived from *SWBM*

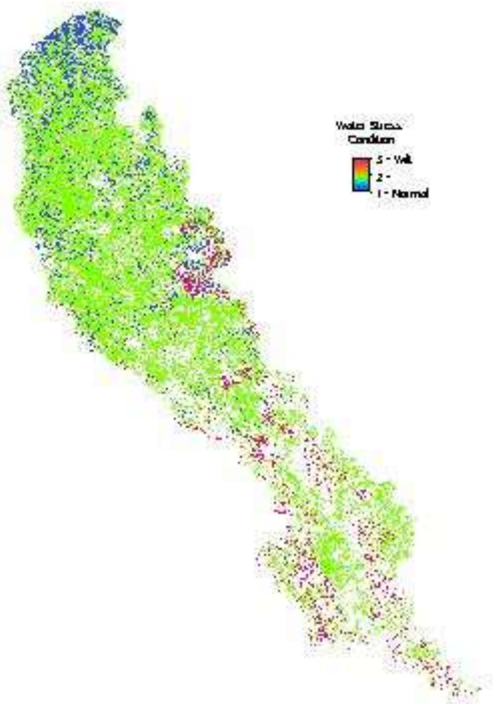


Figure-4.4 Crop stress map in a week as obtained from SWBM

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. The CNSM, its input data, and outputs for three policies of canal operation, i.e. head-reach priority, policy of conjunctive use, and policy of conjunctive use with minimum energy demand have been described in detail in the NIH report entitled “GIS based efficient distribution system for a command”. However, two more policies of canal operation under deficit conditions, namely policy of proportionate supply and policy of tail-reach priority have been included in the modeling scheme. In addition, the concepts of priority and augmentation supply have also been incorporated to make the model more generalized. These are discussed in the following.

4.3.1 Analysis of priority assignment to some canals

To present the computations with priority assignment, first the operation scenario generated while adopting the policy of head-reach priority (Policy-1) without any priority considerations is presented in Table – 4.1. 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. It is assumed that 40 cumec of water is available at canal head (against the demand of 62.54 cumec). Operation results with Policy-1 are depicted in map form in Figure – 4.5.

Table – 4.1

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

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)
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
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

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)
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
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

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	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

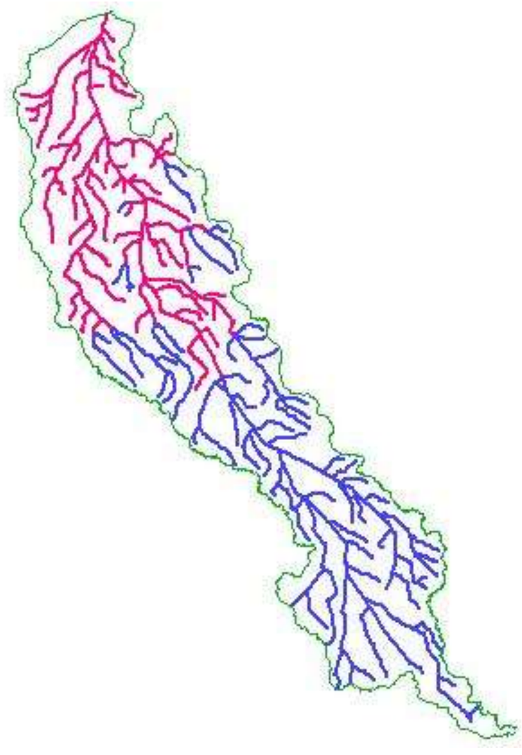


Figure – 4.5: Operation plan of Lakhaoti canal network with policy of head-reach priority with available head Q of 40 cumec (Red – running, Blue – non-running canals)

These are the results of CNSM assuming normal priority of all canal segments. However, it is possible in CNSM to assign higher priority to some canal segments. Separate calculations are made for the priority demands in various segments and these demands are satisfied first from the available canal water. Water in excess of priority demands is then distributed as per the adopted allocation policy. As an illustration, the results of canal network operation, assuming higher priority of segment 203 and all its downstream segments and adopting Policy-1, are presented in Table – 4.2. The results in map form are presented in Figure – 4.6.

Table – 4.2
Operation scenario for canal system having priority demands 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)	For Priority Segments			
												Total D/s Demand (Ham)	Canal Seepage Loss (Ham)	Canal Water Demand (Ham)	Required Discharg (Cumec)
1	0	4.75	4.75	2402.15	11.85	2418.75	39.99	2.25	0.00	168.00	0.00	324.12	5.36	1.59	322.53
2	1	4.30	4.30	2376.71	11.72	2392.74	39.76	2.24	0.83	167.17	0.00	322.53	5.36	1.58	320.95
3F	1	8.42	8.42	0.00	0.99	9.42	0.18	0.50	0.83	145.46	0.00	0.00	0.00	0.00	0.00
4	2	2.10	2.10	2229.42	18.00	2249.52	37.47	2.22	1.24	166.76	0.00	320.95	5.35	2.57	318.38
5	2	3.80	3.80	112.09	2.58	118.47	2.01	0.78	1.24	164.05	0.00	0.00	0.00	0.00	0.00
6	5	34.44	34.44	56.52	8.36	99.32	1.70	0.75	2.93	162.37	0.00	0.00	0.00	0.00	0.00
7F	5	11.79	11.79	0.00	0.98	12.77	0.30	0.55	2.93	119.30	0.00	0.00	0.00	0.00	0.00
8F	6	11.58	11.58	0.00	2.16	13.74	0.25	0.55	9.06	152.59	0.00	0.00	0.00	0.00	0.00
9	6	7.42	7.42	33.69	1.67	42.78	0.76	0.48	9.06	156.23	0.00	0.00	0.00	0.00	0.00
10	9	11.31	11.31	3.39	0.89	15.59	0.28	0.55	10.63	154.66	0.00	0.00	0.00	0.00	0.00
11F	10	0.62	0.62	0.00	0.08	0.70	0.10	0.43	12.56	19.80	0.00	0.00	0.00	0.00	0.00
12F	10	2.18	2.18	0.00	0.51	2.70	0.09	0.35	12.56	83.14	0.00	0.00	0.00	0.00	0.00
13F	9	15.27	15.27	0.00	2.83	18.10	0.50	0.48	10.63	100.87	0.00	0.00	0.00	0.00	0.00
14F	2	7.43	7.43	0.00	1.29	8.72	0.22	0.50	1.24	110.12	0.00	0.00	0.00	0.00	0.00
15	4	14.15	14.15	2161.28	24.20	2199.62	36.87	2.19	2.29	165.71	0.00	318.38	5.34	3.50	314.88
16	4	12.69	12.69	14.82	2.30	29.80	0.50	0.60	2.29	165.64	0.00	0.00	0.00	0.00	0.00
17F	16	11.47	11.41	0.00	2.11	13.52	0.25	0.50	5.30	150.17	0.06	0.00	0.00	0.00	0.00
18F	16	1.12	1.12	0.00	0.18	1.30	0.10	0.42	5.30	36.21	0.00	0.00	0.00	0.00	0.00
19	15	8.04	8.04	2116.99	23.64	2148.67	36.21	2.16	3.17	164.83	0.00	314.88	5.31	3.46	311.42
20F	15	9.96	9.96	0.00	2.65	12.61	0.50	0.60	3.17	70.08	0.00	0.00	0.00	0.00	0.00
21	19	29.53	29.53	2058.28	23.22	2111.03	35.74	2.15	3.90	164.10	0.00	311.42	5.27	3.43	307.99
22F	19	5.30	5.30	0.00	0.66	5.96	0.12	0.37	3.90	137.92	0.00	0.00	0.00	0.00	0.00
23	21	36.87	36.87	1858.44	17.79	1913.10	32.66	2.11	5.29	162.71	0.00	307.99	5.26	2.86	305.13
24	21	26.45	26.45	114.16	4.57	145.18	2.48	0.98	5.29	162.71	0.00	0.00	0.00	0.00	0.00
25	24	7.96	7.96	93.25	0.88	102.08	1.77	0.79	7.90	160.10	0.00	0.00	0.00	0.00	0.00
26F	24	26.29	10.55	0.00	1.52	12.08	0.21	0.40	7.90	160.10	15.74	0.00	0.00	0.00	0.00
27	25	28.56	28.56	55.87	3.31	87.73	1.53	0.72	8.45	159.55	0.00	0.00	0.00	0.00	0.00
28F	25	7.53	4.36	0.00	1.15	5.51	0.10	0.38	8.45	159.55	3.16	0.00	0.00	0.00	0.00
29	27	7.25	7.25	41.11	0.99	49.35	0.87	0.50	10.63	157.37	0.00	0.00	0.00	0.00	0.00
30F	27	5.65	5.65	0.00	0.86	6.51	0.14	0.32	10.63	129.36	0.00	0.00	0.00	0.00	0.00
31F	29	23.93	23.93	0.00	3.10	27.03	0.90	0.62	11.38	83.87	0.00	0.00	0.00	0.00	0.00
32F	29	14.47	12.78	0.00	1.30	14.08	0.25	0.50	11.38	156.62	1.69	0.00	0.00	0.00	0.00
33	23	9.59	9.59	1349.81	20.84	1380.24	23.75	2.07	6.56	161.44	0.00	305.13	5.25	4.61	300.52
34	23	23.78	23.78	428.40	26.01	478.20	8.23	1.55	6.56	161.44	0.00	0.00	0.00	0.00	0.00
35	34	37.17	37.17	364.27	23.09	424.54	7.34	1.50	7.38	160.62	0.00	0.00	0.00	0.00	0.00
36F	34	10.98	3.17	0.00	0.70	3.86	0.07	0.35	7.38	160.62	7.82	0.00	0.00	0.00	0.00
37	35	29.05	29.05	279.48	17.75	326.28	5.68	1.42	8.48	159.51	0.00	0.00	0.00	0.00	0.00
38	35	11.38	11.38	25.87	0.75	37.99	0.66	0.67	8.48	159.51	0.00	0.00	0.00	0.00	0.00
39F	38	46.72	13.87	0.00	3.44	17.31	0.49	0.63	9.37	97.48	32.85	0.00	0.00	0.00	0.00
40F	38	20.68	7.34	0.00	1.21	8.55	0.15	0.42	9.37	158.63	13.33	0.00	0.00	0.00	0.00
41	37	44.51	44.51	209.56	14.62	268.69	4.72	1.32	10.00	158.00	0.00	0.00	0.00	0.00	0.00
42F	37	14.55	8.41	0.00	2.38	10.79	0.19	0.38	10.00	157.99	6.14	0.00	0.00	0.00	0.00
43	41	42.31	42.31	136.74	10.30	189.35	3.37	1.19	11.86	156.14	0.00	0.00	0.00	0.00	0.00
44F	41	32.53	17.65	0.00	2.56	20.21	0.36	0.55	11.86	156.14	14.88	0.00	0.00	0.00	0.00
45	43	10.07	10.07	113.62	0.27	123.97	2.39	1.08	13.54	143.94	0.00	0.00	0.00	0.00	0.00
46F	43	23.70	10.44	0.00	2.33	12.77	0.23	0.46	13.54	154.46	13.25	0.00	0.00	0.00	0.00
47	45	32.88	32.88	34.20	0.15	67.22	1.41	1.04	14.12	132.08	0.00	0.00	0.00	0.00	0.00
48F	45	38.32	38.32	0.00	8.08	46.40	0.90	0.66	14.12	143.36	0.00	0.00	0.00	0.00	0.00
49	47	8.95	8.95	11.42	0.04	20.42	0.65	0.85	16.89	87.30	0.00	0.00	0.00	0.00	0.00
50F	47	11.54	11.54	0.00	2.23	13.78	0.30	0.52	16.89	129.31	0.00	0.00	0.00	0.00	0.00
51	49	7.61	7.61	0.00	0.02	7.62	2.88	0.78	17.94	7.36	0.00	0.00	0.00	0.00	0.00
52F	49	2.80	2.80	0.00	1.00	3.80	0.12	0.36	17.94	86.25	0.00	0.00	0.00	0.00	0.00
53	51	7.69	0.00	0.00	0.00	0.00	0.00	0.00	18.77	0.00	7.69	0.00	0.00	0.00	0.00
54	51	3.69	0.00	0.00	0.00	0.00	0.00	0.00	18.77	0.00	3.69	0.00	0.00	0.00	0.00
55F	54	14.00	0.00	0.00	0.00	0.00	0.00	0.00	22.00	0.00	14.00	0.00	0.00	0.00	0.00
56F	54	2.85	0.00	0.00	0.00	0.00	0.00	0.00	22.00	0.00	2.85	0.00	0.00	0.00	0.00
57	53	43.65	0.00	0.00	0.00	0.00	0.00	0.00	19.58	0.00	43.65	0.00	0.00	0.00	0.00

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)	For Priority Segments			
												Total D/s Demand (Ham)	Canal Seepage Loss (Ham)	Canal Water Demand (Ham)	Required Discharg (Cumec)
58F	53	18.11	0.00	0.00	0.00	0.00	0.00	0.00	19.58	0.00	18.11	0.00	0.00	0.00	0.00
59	57	15.01	0.00	0.00	0.00	0.00	0.00	0.00	22.48	0.00	15.01	0.00	0.00	0.00	0.00
60F	57	11.31	0.00	0.00	0.00	0.00	0.00	0.00	22.48	0.00	11.31	0.00	0.00	0.00	0.00
61F	59	34.22	0.00	0.00	0.00	0.00	0.00	0.00	23.41	0.00	34.22	0.00	0.00	0.00	0.00
62F	59	34.10	0.00	0.00	0.00	0.00	0.00	0.00	23.41	0.00	34.10	0.00	0.00	0.00	0.00
63	33	20.24	20.24	1201.10	18.72	1240.06	21.40	2.06	7.05	160.95	0.00	300.52	5.19	4.54	295.98
64	33	48.94	48.94	57.85	2.96	109.75	1.89	1.05	7.05	160.95	0.00	0.00	0.00	0.00	0.00
65F	64	11.28	4.22	0.00	0.62	4.84	0.08	0.40	9.21	158.79	7.06	0.00	0.00	0.00	0.00
66	64	23.84	23.84	26.72	2.45	53.01	0.93	0.58	9.21	158.79	0.00	0.00	0.00	0.00	0.00
67	66	1.57	1.57	12.53	0.55	14.65	0.26	0.19	11.14	156.85	0.00	0.00	0.00	0.00	0.00
68F	66	20.04	10.54	0.00	1.53	12.07	0.21	0.60	11.14	156.86	9.50	0.00	0.00	0.00	0.00
69F	67	10.33	0.40	0.00	0.04	0.44	0.17	0.45	11.60	7.27	9.93	0.00	0.00	0.00	0.00
70	67	8.00	8.00	0.00	0.15	8.15	0.82	0.57	11.60	27.70	0.00	0.00	0.00	0.00	0.00
71F	67	4.03	3.37	0.00	0.56	3.94	0.07	0.40	11.60	156.40	0.66	0.00	0.00	0.00	0.00
72F	70	69.13	0.00	0.00	0.00	0.00	0.00	0.00	12.35	0.00	69.13	0.00	0.00	0.00	0.00
73F	70	17.41	0.00	0.00	0.00	0.00	0.00	0.00	12.35	0.00	17.41	0.00	0.00	0.00	0.00
74	63	17.29	17.29	1153.82	17.95	1189.07	20.62	2.04	7.79	160.21	0.00	295.98	5.13	4.47	291.51
75F	63	11.43	11.43	0.00	0.60	12.03	0.23	0.35	7.79	143.21	0.00	0.00	0.00	0.00	0.00
76	74	23.52	23.52	1109.47	17.37	1150.37	20.01	2.03	8.33	159.67	0.00	291.51	5.07	4.40	287.11
77F	74	10.92	3.01	0.00	0.44	3.45	0.06	0.35	8.33	159.66	7.90	0.00	0.00	0.00	0.00
78	76	9.83	9.83	1078.56	16.69	1105.07	19.32	2.01	9.15	158.85	0.00	287.11	5.02	4.34	282.78
79F	76	8.73	3.75	0.00	0.66	4.40	0.08	0.35	9.15	158.85	4.98	0.00	0.00	0.00	0.00
80F	78	12.10	5.05	0.00	0.59	5.64	0.10	0.40	9.53	158.47	7.05	0.00	0.00	0.00	0.00
81	78	24.22	24.22	1016.81	15.96	1056.99	18.53	2.00	9.53	158.47	0.00	282.78	4.96	4.27	278.51
82	78	1.99	1.99	13.73	0.21	15.93	0.28	0.50	9.53	158.47	0.00	0.00	0.00	0.00	0.00
83F	82	22.38	8.39	0.00	1.76	10.15	0.20	0.45	9.93	140.24	13.99	0.00	0.00	0.00	0.00
84F	82	6.75	3.20	0.00	0.38	3.58	0.06	0.35	9.93	158.06	3.55	0.00	0.00	0.00	0.00
85	81	56.02	56.02	928.78	10.55	995.34	17.61	1.97	10.98	157.02	0.00	278.51	4.93	2.95	275.55
86	81	8.53	8.53	0.26	0.67	9.46	0.18	0.53	10.98	149.68	0.00	0.00	0.00	0.00	0.00
87F	86	3.74	0.00	0.00	0.00	0.00	0.00	0.00	12.89	0.00	3.74	0.00	0.00	0.00	0.00
88F	86	5.80	0.22	0.00	0.04	0.26	0.05	0.30	12.89	14.07	5.59	0.00	0.00	0.00	0.00
89F	81	20.97	9.07	0.00	2.93	12.00	0.21	0.40	10.98	157.02	11.90	0.00	0.00	0.00	0.00
90	85	26.37	26.37	747.30	8.29	781.96	13.94	1.94	12.22	155.78	0.00	275.55	4.91	2.92	272.63
91	85	4.12	4.12	137.27	5.43	146.82	2.62	1.02	12.22	155.78	0.00	0.00	0.00	0.00	0.00
92	91	13.16	13.16	14.17	1.21	28.55	0.51	0.58	12.58	155.41	0.00	0.00	0.00	0.00	0.00
93F	92	19.69	8.90	0.00	1.56	10.46	0.19	0.49	14.17	153.83	10.80	0.00	0.00	0.00	0.00
94F	92	43.82	2.99	0.00	0.73	3.71	0.27	0.50	14.17	38.34	40.83	0.00	0.00	0.00	0.00
95	91	49.01	49.01	55.69	4.02	108.72	1.94	1.00	12.58	155.42	0.00	0.00	0.00	0.00	0.00
96	95	11.42	11.42	5.23	0.64	17.29	1.11	0.78	15.50	43.08	0.00	0.00	0.00	0.00	0.00
97	95	39.35	35.24	0.00	3.16	38.40	0.70	0.65	15.50	152.50	4.11	0.00	0.00	0.00	0.00
98F	97	14.32	0.00	0.00	0.00	0.00	0.00	0.00	19.35	0.00	14.32	0.00	0.00	0.00	0.00
99F	97	16.03	0.00	0.00	0.00	0.00	0.00	0.00	19.35	0.00	16.03	0.00	0.00	0.00	0.00
100	96	14.09	5.11	0.00	0.12	5.23	0.60	0.73	16.35	24.29	8.97	0.00	0.00	0.00	0.00
101F	96	42.10	0.00	0.00	0.00	0.00	0.00	0.00	16.35	0.00	42.10	0.00	0.00	0.00	0.00
102F	100	15.90	0.00	0.00	0.00	0.00	0.00	0.00	18.60	0.00	15.90	0.00	0.00	0.00	0.00
103F	100	5.11	0.00	0.00	0.00	0.00	0.00	0.00	18.60	0.00	5.11	0.00	0.00	0.00	0.00
104	90	7.74	7.74	720.05	7.80	735.59	13.17	1.92	12.82	155.18	0.00	272.63	4.88	2.89	269.74
105F	90	22.85	9.69	0.00	2.02	11.71	0.21	0.43	12.82	155.18	13.16	0.00	0.00	0.00	0.00
106	104	73.96	73.96	606.17	12.61	692.74	12.42	1.91	13.13	154.87	0.00	269.74	4.84	4.91	264.83
107	104	29.37	29.37	0.00	2.72	27.31	0.49	0.58	13.13	154.87	0.00	0.00	0.00	0.00	0.00
108F	107	10.81	0.00	0.00	0.00	0.00	0.00	0.00	17.21	0.00	10.81	0.00	0.00	0.00	0.00
109	107	13.30	0.00	0.00	0.00	0.00	0.00	0.00	17.21	0.00	13.30	0.00	0.00	0.00	0.00
110F	109	4.43	0.00	0.00	0.00	0.00	0.00	0.00	19.83	0.00	4.43	0.00	0.00	0.00	0.00
111F	109	2.06	0.00	0.00	0.00	0.00	0.00	0.00	19.83	0.00	2.06	0.00	0.00	0.00	0.00
112	106	27.61	27.61	408.72	8.09	444.42	8.07	1.86	15.12	152.88	0.00	264.83	4.81	4.82	260.01
113	106	56.60	56.60	21.99	3.59	82.18	1.50	0.77	15.12	152.39	0.00	0.00	0.00	0.00	0.00
114F	113	15.03	6.10	0.00	1.02	7.12	0.16	0.55	17.87	120.49	8.94	0.00	0.00	0.00	0.00
115	113	14.53	14.53	0.00	0.34	14.87	1.10	0.67	17.87	37.44	0.00	0.00	0.00	0.00	0.00
116F	115	59.46	0.00	0.00	0.00	0.00	0.00	0.00	19.06	0.00	59.46	0.00	0.00	0.00	0.00
117F	115	14.85	0.00	0.00	0.00	0.00	0.00	0.00	19.06	0.00	14.85	0.00	0.00	0.00	0.00
118	106	76.28	76.28	0.00	3.29	79.57	3.60	1.08	15.12	61.46	0.00	0.00	0.00	0.00	0.00
119	118	14.16	0.00	0.00	0.00	0.00	0.00	0.00	19.74	0.00	14.16	0.00	0.00	0.00	0.00
120F	118	24.71	0.00	0.00	0.00	0.00	0.00	0.00	19.74	0.00	24.71	0.00	0.00	0.00	0.00
121F	119	12.08	0.00	0.00	0.00	0.00	0.00	0.00	20.56	0.00	12.08	0.00	0.00	0.00	0.00
122	119	43.08	0.00	0.00	0.00	0.00	0.00	0.00	20.56	0.00	43.08	0.00	0.00	0.00	0.00
123F	122	9.06	0.00	0.00	0.00	0.00	0.00	0.00	23.67	0.00	9.06	0.00	0.00	0.00	0.00
124	122	36.48	0.00	0.00	0.00	0.00	0.00	0.00	23.67	0.00	36.48	0.00	0.00	0.00	0.00
125F	122	42.06	0.00	0.00	0.00	0.00	0.00	0.00	23.67	0.00	42.06	0.00	0.00	0.00	0.00
126F	122	10.53	0.00	0.00	0.00	0.00	0.00	0.00	23.67	0.00	10.53	0.00	0.00	0.00	0.00
127	124	22.57	0.00	0.00	0.00	0.00	0.00	0.00	26.01	0.00	22.57	0.00	0.00	0.00	0.00
128F	124	8.91	0.00	0.00	0.00	0.00	0.00	0.00	26.01	0.00	8.91	0.00	0.00	0.00	0.00
129	127	6.04	0.00	0.00	0.00	0.00	0.00	0.00	27.74	0.00	6.04	0.00	0.00	0.00	0.00
130F	127	9.31	0.00	0.00	0.00	0.00	0.00	0.00	27.74	0.00	9.31	0.00	0.00	0.00	0.00

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)	For Priority Segments			
												Total D/s Demand (Ham)	Canal Seepage Loss (Ham)	Canal Water Demand (Ham)	Required Discharg (Cumec)
131F	129	8.28	0.00	0.00	0.00	0.00	0.00	0.00	29.27	0.00	8.28	0.00	0.00	0.00	0.00
132F	129	8.41	0.00	0.00	0.00	0.00	0.00	0.00	29.27	0.00	8.41	0.00	0.00	0.00	0.00
133F	129	4.95	0.00	0.00	0.00	0.00	0.00	0.00	29.27	0.00	4.95	0.00	0.00	0.00	0.00
134	112	74.99	74.99	299.52	6.94	381.45	6.97	1.84	15.98	152.02	0.00	260.01	4.75	4.73	255.28
135F	112	56.50	21.75	0.00	5.52	27.27	0.50	0.52	15.98	152.02	34.74	0.00	0.00	0.00	0.00
136	134	54.26	42.56	245.61	11.35	299.52	5.54	1.79	17.70	150.30	11.70	255.28	4.72	9.68	245.61
137F	134	23.76	0.00	0.00	0.00	0.00	0.00	0.00	17.70	0.00	23.76	0.00	0.00	0.00	0.00
138	136	110.92	0.00	236.30	9.31	245.61	4.59	1.75	19.37	148.63	110.92	245.61	4.59	9.31	236.30
139F	136	44.48	0.00	0.00	0.00	0.00	0.00	0.00	19.37	0.00	44.48	0.00	0.00	0.00	0.00
140F	136	23.81	0.00	0.00	0.00	0.00	0.00	0.00	19.37	0.00	23.81	0.00	0.00	0.00	0.00
141	138	34.62	0.00	227.34	8.96	236.30	4.50	1.68	22.05	145.95	34.62	236.30	4.50	8.96	227.34
142	138	7.10	0.00	0.00	0.00	0.00	0.00	0.00	22.05	0.00	7.10	0.00	0.00	0.00	0.00
143	142	31.62	0.00	0.00	0.00	0.00	0.00	0.00	22.49	0.00	31.62	0.00	0.00	0.00	0.00
144F	143	4.12	0.00	0.00	0.00	0.00	0.00	0.00	26.41	0.00	4.12	0.00	0.00	0.00	0.00
145F	143	18.02	0.00	0.00	0.00	0.00	0.00	0.00	26.41	0.00	18.02	0.00	0.00	0.00	0.00
146F	142	9.23	0.00	0.00	0.00	0.00	0.00	0.00	22.49	0.00	9.23	0.00	0.00	0.00	0.00
147F	138	29.76	0.00	0.00	0.00	0.00	0.00	0.00	22.05	0.00	29.76	0.00	0.00	0.00	0.00
148	141	52.70	0.00	218.73	8.62	227.34	4.36	1.64	23.21	144.79	52.70	227.34	4.36	8.62	218.73
149F	141	24.25	0.00	0.00	0.00	0.00	0.00	0.00	23.21	0.00	24.25	0.00	0.00	0.00	0.00
150F	141	24.29	0.00	0.00	0.00	0.00	0.00	0.00	23.21	0.00	24.29	0.00	0.00	0.00	0.00
151	148	34.69	0.00	210.44	8.29	218.73	4.25	1.60	25.06	142.94	34.69	218.73	4.25	8.29	210.44
152	148	3.40	0.00	0.00	0.00	0.00	0.00	0.00	25.06	0.00	3.40	0.00	0.00	0.00	0.00
153F	152	18.62	0.00	0.00	0.00	0.00	0.00	0.00	25.94	0.00	18.62	0.00	0.00	0.00	0.00
154F	152	48.90	0.00	0.00	0.00	0.00	0.00	0.00	25.94	0.00	48.90	0.00	0.00	0.00	0.00
155F	148	45.48	0.00	0.00	0.00	0.00	0.00	0.00	25.06	0.00	45.48	0.00	0.00	0.00	0.00
156	151	6.90	0.00	202.46	7.98	210.44	4.12	1.56	26.23	141.77	6.90	210.44	4.12	7.98	202.46
157F	151	43.53	0.00	0.00	0.00	0.00	0.00	0.00	26.23	0.00	43.53	0.00	0.00	0.00	0.00
158	156	8.80	0.00	0.00	0.00	0.00	0.00	0.00	26.73	0.00	8.80	0.00	0.00	0.00	0.00
159	158	22.80	0.00	0.00	0.00	0.00	0.00	0.00	27.85	0.00	22.80	0.00	0.00	0.00	0.00
160F	159	1.92	0.00	0.00	0.00	0.00	0.00	0.00	30.46	0.00	1.92	0.00	0.00	0.00	0.00
161F	159	14.70	0.00	0.00	0.00	0.00	0.00	0.00	30.46	0.00	14.70	0.00	0.00	0.00	0.00
162	158	34.21	0.00	0.00	0.00	0.00	0.00	0.00	27.85	0.00	34.21	0.00	0.00	0.00	0.00
163F	162	25.72	0.00	0.00	0.00	0.00	0.00	0.00	29.93	0.00	25.72	0.00	0.00	0.00	0.00
164	162	42.03	0.00	0.00	0.00	0.00	0.00	0.00	29.93	0.00	42.03	0.00	0.00	0.00	0.00
165	162	35.37	0.00	0.00	0.00	0.00	0.00	0.00	29.93	0.00	35.37	0.00	0.00	0.00	0.00
166F	162	25.13	0.00	0.00	0.00	0.00	0.00	0.00	29.93	0.00	25.13	0.00	0.00	0.00	0.00
167	164	23.49	0.00	0.00	0.00	0.00	0.00	0.00	38.48	0.00	23.49	0.00	0.00	0.00	0.00
168F	167	6.34	0.00	0.00	0.00	0.00	0.00	0.00	41.20	0.00	6.34	0.00	0.00	0.00	0.00
169F	167	28.10	0.00	0.00	0.00	0.00	0.00	0.00	41.20	0.00	28.10	0.00	0.00	0.00	0.00
170F	164	114.63	0.00	0.00	0.00	0.00	0.00	0.00	38.48	0.00	114.63	0.00	0.00	0.00	0.00
171	165	8.97	0.00	0.00	0.00	0.00	0.00	0.00	32.13	0.00	8.97	0.00	0.00	0.00	0.00
172F	165	43.04	0.00	0.00	0.00	0.00	0.00	0.00	32.13	0.00	43.04	0.00	0.00	0.00	0.00
173	171	21.59	0.00	0.00	0.00	0.00	0.00	0.00	33.66	0.00	21.59	0.00	0.00	0.00	0.00
174F	171	28.22	0.00	0.00	0.00	0.00	0.00	0.00	33.66	0.00	28.22	0.00	0.00	0.00	0.00
175	173	9.11	0.00	0.00	0.00	0.00	0.00	0.00	34.82	0.00	9.11	0.00	0.00	0.00	0.00
176F	173	44.45	0.00	0.00	0.00	0.00	0.00	0.00	34.82	0.00	44.45	0.00	0.00	0.00	0.00
177	175	157.04	0.00	0.00	0.00	0.00	0.00	0.00	35.42	0.00	157.04	0.00	0.00	0.00	0.00
178	175	72.53	0.00	0.00	0.00	0.00	0.00	0.00	35.42	0.00	72.53	0.00	0.00	0.00	0.00
179F	177	41.30	0.00	0.00	0.00	0.00	0.00	0.00	46.32	0.00	41.30	0.00	0.00	0.00	0.00
180	177	18.06	0.00	0.00	0.00	0.00	0.00	0.00	46.32	0.00	18.06	0.00	0.00	0.00	0.00
181F	180	22.72	0.00	0.00	0.00	0.00	0.00	0.00	49.31	0.00	22.72	0.00	0.00	0.00	0.00
182F	180	18.40	0.00	0.00	0.00	0.00	0.00	0.00	49.31	0.00	18.40	0.00	0.00	0.00	0.00
183	178	9.77	0.00	0.00	0.00	0.00	0.00	0.00	37.32	0.00	9.77	0.00	0.00	0.00	0.00
184F	183	85.81	0.00	0.00	0.00	0.00	0.00	0.00	38.16	0.00	85.81	0.00	0.00	0.00	0.00
185F	183	58.01	0.00	0.00	0.00	0.00	0.00	0.00	38.16	0.00	58.01	0.00	0.00	0.00	0.00
186	178	80.92	0.00	0.00	0.00	0.00	0.00	0.00	37.32	0.00	80.92	0.00	0.00	0.00	0.00
187	186	41.05	0.00	0.00	0.00	0.00	0.00	0.00	41.91	0.00	41.05	0.00	0.00	0.00	0.00
188	187	32.79	0.00	0.00	0.00	0.00	0.00	0.00	44.93	0.00	32.79	0.00	0.00	0.00	0.00
189F	188	2.92	0.00	0.00	0.00	0.00	0.00	0.00	46.27	0.00	2.92	0.00	0.00	0.00	0.00
190F	188	10.69	0.00	0.00	0.00	0.00	0.00	0.00	46.27	0.00	10.69	0.00	0.00	0.00	0.00
191F	187	13.85	0.00	0.00	0.00	0.00	0.00	0.00	44.93	0.00	13.85	0.00	0.00	0.00	0.00
192F	186	25.69	0.00	0.00	0.00	0.00	0.00	0.00	41.91	0.00	25.69	0.00	0.00	0.00	0.00
193	156	74.30	0.00	198.94	3.52	202.46	3.98	1.28	26.73	141.27	74.30	202.46	3.98	3.52	198.94
194	193	6.87	0.00	194.64	4.30	198.94	4.01	1.23	30.10	137.90	6.87	198.94	4.01	4.30	194.64
195F	193	13.63	0.00	0.00	0.00	0.00	0.00	0.00	30.10	0.00	13.63	0.00	0.00	0.00	0.00
196	194	4.14	0.00	189.35	5.29	194.64	3.94	1.10	30.79	137.21	4.14	194.64	3.94	5.29	189.35
197F	194	27.61	0.00	0.00	0.00	0.00	0.00	0.00	30.79	0.00	27.61	0.00	0.00	0.00	0.00
198	196	17.79	0.00	0.00	0.00	0.00	0.00	0.00	31.33	0.00	17.79	0.00	0.00	0.00	0.00
199F	196	14.54	0.00	0.00	0.00	0.00	0.00	0.00	31.33	0.00	14.54	0.00	0.00	0.00	0.00
200F	198	12.76	0.00	0.00	0.00	0.00	0.00	0.00	33.26	0.00	12.76	0.00	0.00	0.00	0.00
201F	198	14.24	0.00	0.00	0.00	0.00	0.00	0.00	33.26	0.00	14.24	0.00	0.00	0.00	0.00
202	196	16.46	0.00	181.72	7.63	189.35	3.85	0.96	31.33	136.67	16.46	189.35	3.85	7.63	181.72
203	202	9.28	9.28	165.11	7.32	181.72	3.73	0.82	32.74	135.26	0.00	181.72	3.73	7.32	165.11

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)	For Priority Segments			
												Total D/s Demand (Ham)	Canal Seepage Loss (Ham)	Canal Water Demand (Ham)	Required Discharg (Cumec)
204F	202	21.93	0.00	0.00	0.00	0.00	0.00	0.00	32.74	0.00	21.93	0.00	0.00	0.00	0.00
205	203	15.60	15.60	81.11	3.99	100.70	2.08	0.80	33.59	134.41	0.00	100.70	2.08	3.99	81.11
206F	205	21.86	14.30	0.00	1.34	15.64	0.33	0.55	34.57	133.43	7.56	15.64	0.33	1.34	0.00
207	205	34.73	34.73	27.74	3.00	65.47	1.68	0.70	34.57	108.37	0.00	65.47	1.68	3.00	27.74
208	207	15.81	15.81	0.00	1.10	16.91	0.93	0.55	35.94	50.33	0.00	16.91	0.93	1.10	0.00
209F	208	9.41	0.00	0.00	0.00	0.00	0.00	0.00	36.91	0.00	9.41	0.00	0.00	0.00	0.00
210F	208	17.78	0.00	0.00	0.00	0.00	0.00	0.00	36.91	0.00	17.78	0.00	0.00	0.00	0.00
211	207	19.33	9.50	0.00	1.32	10.83	0.48	0.55	35.94	62.47	9.83	10.83	0.48	1.32	0.00
212F	211	3.51	0.00	0.00	0.00	0.00	0.00	0.00	40.82	0.00	3.51	0.00	0.00	0.00	0.00
213F	211	5.76	0.00	0.00	0.00	0.00	0.00	0.00	40.82	0.00	5.76	0.00	0.00	0.00	0.00
214	203	41.17	41.17	19.26	3.98	64.41	1.36	0.67	33.59	131.64	0.00	64.41	1.36	3.98	19.26
215	214	12.97	12.97	0.00	0.52	13.49	0.62	0.46	37.15	60.64	0.00	13.49	0.62	0.52	0.00
216F	215	18.84	0.00	0.00	0.00	0.00	0.00	0.00	38.24	0.00	18.84	0.00	0.00	0.00	0.00
217F	215	12.98	0.00	0.00	0.00	0.00	0.00	0.00	38.24	0.00	12.98	0.00	0.00	0.00	0.00
218F	214	26.17	5.10	0.00	0.67	5.77	0.35	0.52	37.15	45.28	21.08	5.77	0.35	0.67	0.00

It is seen from the table that even after assigning higher priority, segments 209, 210, 212, 213, 216, and 217 could not be allocated canal water because of capacity constraint of upstream segments (for example, demands of segment 209 are curtailed for satisfying capacity constraint of segments 205 and 207). It is also observed from Figure – 4.6 and Figure – 4.5 that because of priority demands, a few segments of normal priority could not be allocated canal water in the head reaches.

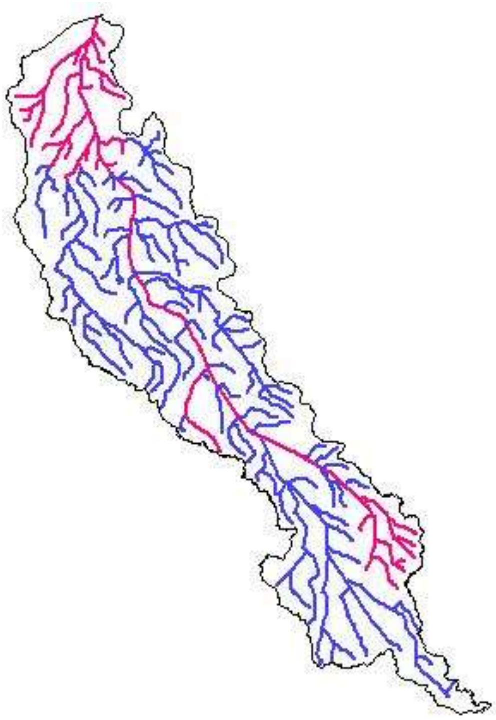


Figure – 4.6: Operation plan of Lakhaoti canal network with priority demands under deficit conditions with policy of head-reach priority

4.3.2 Analysis of augmentation supply in the canal network

The canal network simulation model takes into account the augmentation supply in canal network at any intermediate location. From Table – 4.1, it is observed that with the water availability of 40 cumec at canal head and with the adoption of Policy-1, discharge of 32.57 cumec is required at segment 23 while its discharge capacity is 54.79 cumec. Let augmentation supply of 10 cumec is made in segment 23. The resulting operation scenario is tabulated in Table – 4.3 and depicted in map form in Figure – 4.7.

Table – 4.3
Operation scenario for canal system having augmentation supply 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	2402.13	11.85	2418.73	39.99	2.25	0.00	168.00	0.00
2	1	4.30	4.30	2376.69	11.72	2392.71	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	2229.40	18.00	2249.49	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	2161.26	24.20	2199.60	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	2116.97	23.64	2148.65	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	2058.25	23.22	2111.01	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	2457.59	23.42	1913.07	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	1924.65	29.65	1963.90	33.79	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	1767.26	27.41	1814.90	31.32	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

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)
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
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	1711.43	26.50	1755.23	30.43	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	1658.67	25.79	1707.98	29.71	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	1619.46	24.98	1654.26	28.93	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	1549.54	24.13	1597.89	28.01	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	1455.86	16.20	1528.07	27.03	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	1268.80	13.88	1309.04	23.34	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	1236.02	13.33	1257.09	22.50	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	1112.75	22.00	1208.71	21.68	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	798.26	15.31	841.18	15.28	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	105.28	7.82	189.39	3.44	1.08	15.12	152.88	0.00
119	118	14.16	14.16	69.83	6.94	90.93	1.70	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	15.60	4.85	63.52	1.20	0.83	20.56	147.44	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	13.85	0.00	1.75	15.60	0.30	0.52	23.67	144.33	28.22
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	681.97	14.03	770.99	14.09	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	591.55	25.44	671.24	12.41	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	425.26	21.12	557.30	10.42	1.75	19.37	148.63	0.00

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)
139F	136	44.48	21.14	0.00	5.53	26.67	0.50	0.53	19.37	148.63	23.34
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	34.62	291.40	12.84	338.87	6.45	1.68	22.05	145.95	0.00
142	138	7.10	7.10	63.77	0.64	71.51	1.36	0.58	22.05	145.95	0.00
143	142	31.62	31.62	24.74	3.71	60.06	1.74	0.72	22.49	96.11	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	18.02	0.00	2.05	20.06	0.94	0.51	26.41	59.57	0.00
146F	142	9.23	3.31	0.00	0.40	3.71	0.07	0.40	22.49	145.51	5.92
147F	138	29.76	12.98	0.00	1.90	14.88	0.28	0.55	22.05	145.95	16.78
148	141	52.70	52.70	207.21	10.24	270.15	5.18	1.64	23.21	144.79	0.00
149F	141	24.25	10.76	0.00	3.26	14.02	0.27	0.46	23.21	144.78	13.49
150F	141	24.29	5.46	0.00	1.78	7.23	0.14	0.38	23.21	144.78	18.83
151	148	34.69	34.69	115.82	5.93	156.44	3.04	1.60	25.06	142.94	0.00
152	148	3.40	3.40	29.22	0.66	33.28	0.65	0.60	25.06	142.94	0.00
153F	152	18.62	13.36	0.00	2.35	15.71	0.31	0.55	25.94	142.06	5.25
154F	152	48.90	10.33	0.00	3.17	13.51	0.28	0.50	25.94	132.49	38.57
155F	148	45.48	14.35	0.00	3.14	17.49	0.34	0.50	25.06	142.94	31.13
156	151	6.90	6.90	89.23	3.79	99.92	6.79	1.56	26.23	40.87	0.00
157F	151	43.53	13.06	0.00	2.84	15.90	0.31	0.45	26.23	141.77	30.47
158	156	8.80	8.80	4.60	0.21	13.61	0.94	1.54	26.73	40.37	0.00
159	158	22.80	4.25	0.00	0.35	4.60	0.33	0.55	27.85	39.24	18.56
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	74.30	0.00	1.32	75.62	6.23	1.28	26.73	33.72	0.00
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

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)
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

In the table, it is observed that though the required discharge in segment 23 remains 32.54 cumec (this column represents the discharge requirement from the upstream segment), the discharge requirement of segments 33 and 34, which lie immediately downstream of segment 23, amounts to a total of 42.16 cumec, indicating the augmentation supply in segment 23.

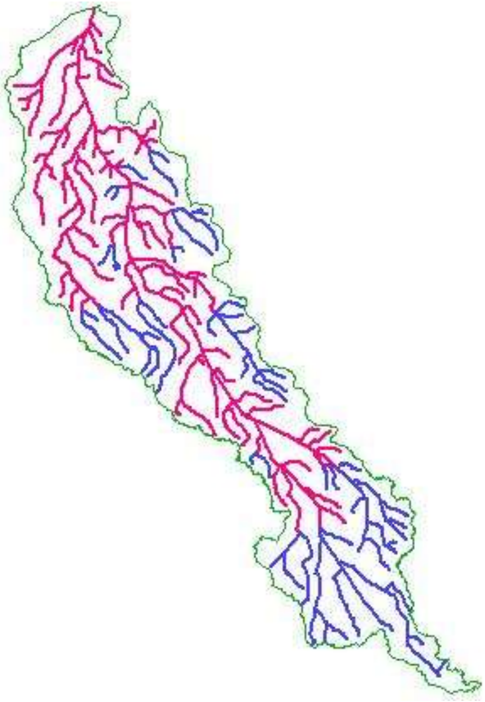


Figure – 4.7: Operation plan of Lakhaoti canal network with augmentation supply and under deficit conditions with policy of head-reach priority

It is seen from Figure – 4.7 that with intermediate augmentation supply, it is possible to meet the demands of a larger downstream network.

4.3.3 Policy of proportionate supply

Under the proportionate supply policy, water deficit at a node is equally distributed among various segments bifurcating from the node. Thus, reduced demands of a large number of segments can be met with canal water using this policy. Though operation tables can be generated for proportionate supply policy (Policy-3), the results with these policies are presented in map form in Figure – 4.8 assuming availability of 40 cumec of head discharge against the total requirement of 62.50 cumec.

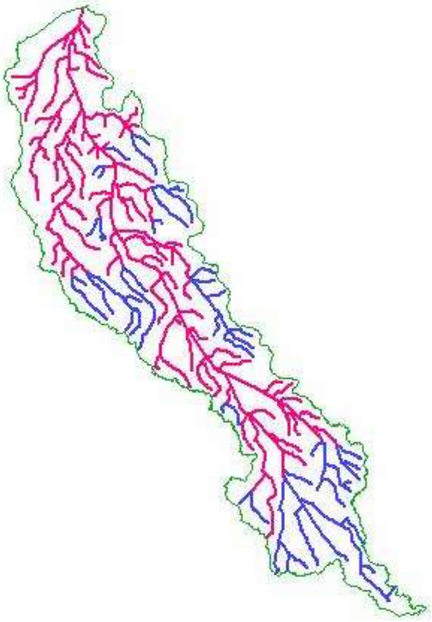


Figure – 4.8: Operation plan of Lakhaoti canal network with policy of proportionate supply with available head Q of 1500 cusec (Red – Running canals, Blue – Non-running canals)

4.3.4 Policy of tail-reach priority

Under the tail-reach priority policy (Policy-4), canal water distribution is started from the tail-end of the system and it moves upwards towards the head of command depending on water availability at head as can be seen from Figure – 4.9. Though operation tables can be generated for tail-reach priority policy, the results with this policy are presented in map form in Figure – 4.9 assuming availability of 1500 cumec of head discharge against the total requirement of 62.50 cumec.

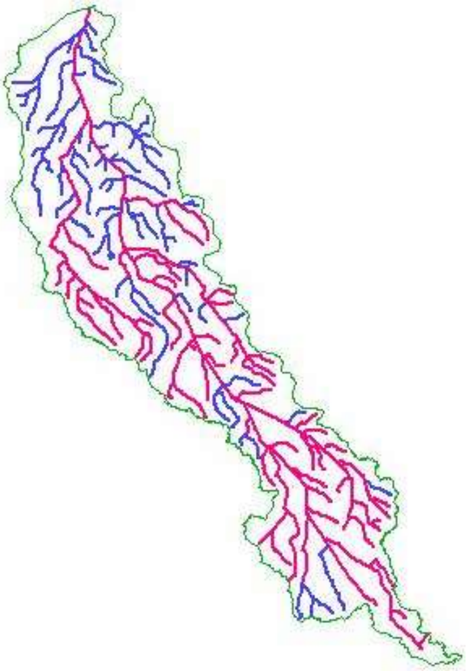


Figure – 4.9: Operation plan of Lakhaoti canal network with policy of tail-reach priority with available head Q of 1500 cusec (Red – Running canals, Blue – Non-running canals)

Graphical comparison of all the five policies is depicted in Figure – 4.10.

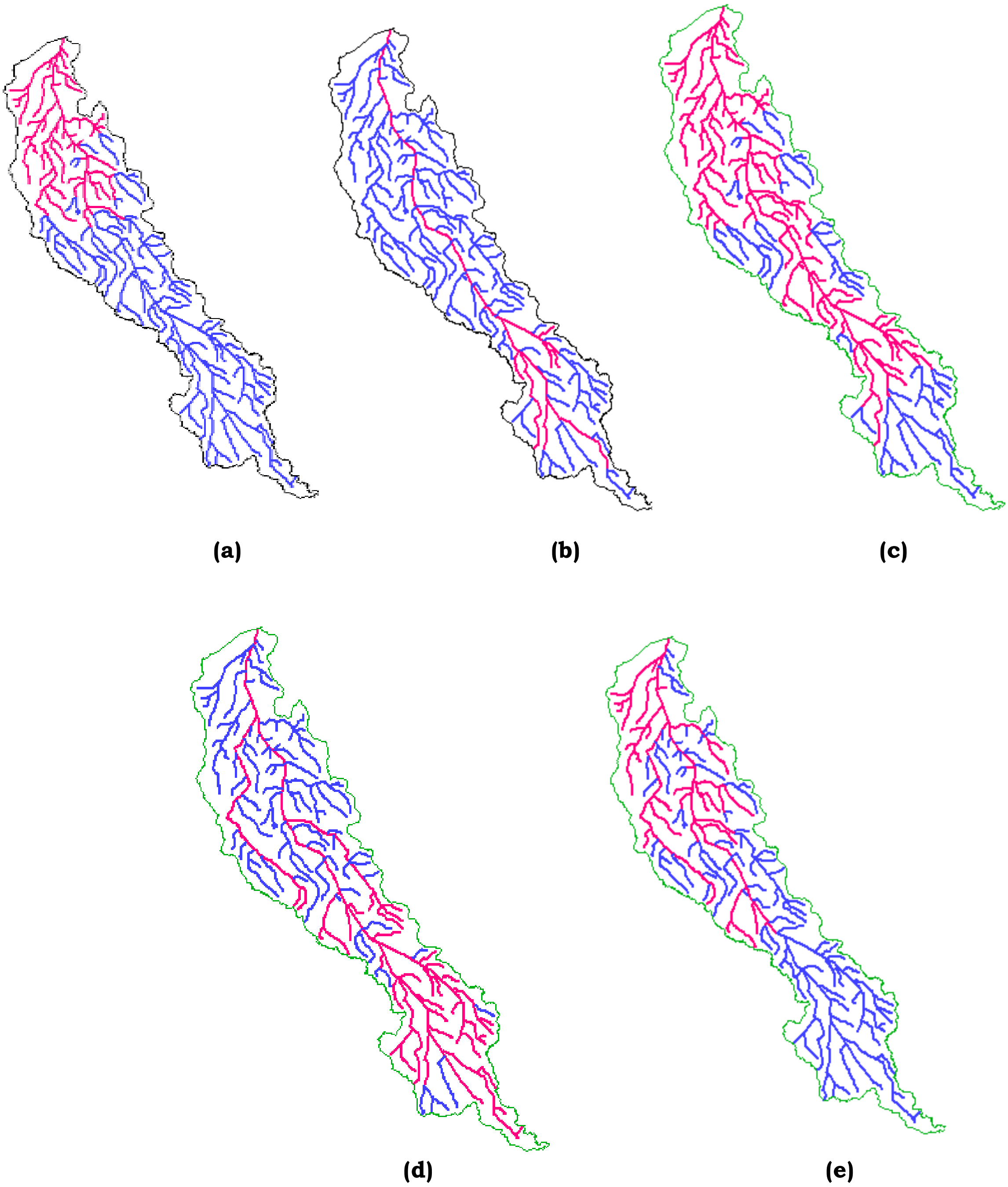


Figure-4.10 Canal operation for a week with five policies: (a) Policy of head-reach priority, (b) Policy of conjunctive use, (c) Policy of proportionate supply, (d) Policy of tail-reach priority, (e) Policy of conjunctive use with minimum energy demand

Summary results of the five operation policies are presented in Table – 4.4. Of the available water at canal head, maximum water is used under Policy-1 with minimum loss through canal seepage. However, Policy-1 does not take the groundwater conditions into

Table – 4.4
Summary results of five allocation policies

Performance Measure	Policy-1	Policy-2	Policy-3	Policy-4	Policy-5
Surface Water Available at Canal Head (Mm3)	24.19	24.19	24.19	24.19	24.19
Irrigation Demand at Head (Mm3)	50.75	50.75	50.75	50.75	50.75
Surface Water Utilized for Irrigation (Mm3)	18.84	16.50	17.36	14.40	18.57
Canal Seepage Loss (Mm3)	5.35	7.69	6.83	9.79	5.62
Groundwater Use in Command (Mm3)	31.91	34.37	33.39	36.25	32.18
Energy Demand in Canal-irrigable Area (MKwh)	1.2942	1.3269	1.3329	1.3706	1.286

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. Similarly, Policy-3 and Policy-4 also do not take the groundwater position in the command into consideration and adoption of these policies result in higher canal seepage loss and higher energy demand. Policy-2 takes into account the groundwater conditions in the command while allocating canal water and groundwater.

Comparison of results of Policy-5 with all other policies shows that Policy-5 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-5 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.

4.4 VALIDATION OF GEO-SIMULATION MODEL FOR LAKHAOTI COMMAND

To check the validity of the geo-simulation model, the scheme is run with the database of Lakhaoti command area for the Kharif season during the year 1998. The validity of the scheme is checked by comparing the computed and observed groundwater levels in different observation wells spread over the command at the end of Kharif season. The groundwater well data were available for the months of June 1998 and October 1998. Using the observation well data of June 1998, the groundwater surface has been generated which defines the initial groundwater conditions in the command. Two main reasons for selecting the entire Lakhaoti command, instead of a part of it, for validating the scheme are: a) the Lakhaoti command has well-defined boundaries which are required for modeling the groundwater behaviour, and b) utility of some policies (Policy-2 and Policy-5) can be visualized only when there is significant variation of groundwater depth across the command which may not occur over small distances.

The model is run for Lakhaoti command at weekly time step starting from June 11, 1998 (calendar week 24). The Kharif season is assumed to start from this week (with the sowing of Arhar and Maize crops) and the proposed releases in the Lakhaoti branch canal from this week. For running the scheme, following assumptions have been made:

a) Since the groundwater conditions in a command do not vary appreciably over short span of time (week), it is assumed that the groundwater surface (observed/generated) in a month holds good for the various weeks during the month. So, revised groundwater surface is generated at monthly time step rather than at weekly time step. For example, for the calendar weeks 24 to 28 (June 11 to July 15), the groundwater surface of June is considered representative. Various other calendar weeks and corresponding month of representative groundwater surface are given below:

Calendar weeks	Month of representative groundwater surface
29 – 32	July
33 – 37	August
38 – 41	September

b) Irrigation demands at a grid in each week have been worked out considering that moisture content in an agricultural grid is brought to the field capacity.

c) Though the available discharge at canal head changes within a week, average values have been worked out and used for simulating the network operation. In year 1998, Lakhaoti canal was planned to start from 26th calendar week (June 25) but due to the breach in the canal system, the canal was actually run from July 16, 1998.

d) For simulating canal operation scenario corresponding to the year 1998, the policy of head-reach priority (Policy-1) has been adopted, as the actual water distribution plan of the canal network is not available. The supply in Lakhaoti canal in 1998 actually starts from July 16 (calendar week 29). It is observed that out of the 13 weeks (calendar week 29 to 41) of Lakhaoti canal operation during the year 1998 in the study period (calendar week 24 to 41), the water deficit at head occurs only in 3 weeks (36, 40, and 41) for which the allocation policy becomes applicable.

e) Higher priority is assigned to Atrauli distributary system (segment 158 and its downstream) and Dharampur distributary system (segment 193 and its downstream) in case of deficiency of canal water as specified by the officials.

The application of the scheme is carried out as per the flow chart (Figure-2.1). If the scheme is implemented in real-time, then actual rainfall and evapo-transpiration at the beginning of a week will not be known and one needs to use probable/forecast values. In the present case, since actual rainfall and evapo-transpiration data are known at the begining of a week, SWBM is run considering actual rainfall and evapo-transpiration data and spatial irrigation demands are worked out. Using the irrigation demands and actual availability of canal water at the network head, the CNSM is run to find the areas of canal water application and the amount of canal water use. Grid-wise canal water seepage is also worked out. The canal-run configuration at the end of a week is saved in a file, which is used in the next week to find the fill-time and run-time of various canal segments. Knowing the grid-wise irrigation demands (from SWBM) and canal water supply (from CNSM), grids of groundwater use and required amount of groundwater pumping are worked out. Now, the soil water balance model is run again incorporating the grid-wise information about the canal water use and groundwater use (in addition to the actual rainfall and evapo-transpiration) and the grid-wise moisture content at the end of the week are worked out which becomes the initial moisture content for the next week. Knowing grid-wise recharge and the amount of groundwater pumping, net groundwater recharge/pumping at each grid is worked out. Using the depth of groundwater table at each grid, the energy required to pump the required groundwater is calculated. For use in groundwater model, pumping/recharge values are aggregated from a grid-size of 24 m to a grid-size of 480 m. Every 480 m grid is assumed to have a well in the command and the calculated spatial pumping/recharge information is attached to the corresponding wells. The pumping/recharge wells are imported in the groundwater model (VMOD) and the model is run to find the new groundwater surface for the next time step corresponding to the applied stresses of pumping and recharge. The new groundwater surface generated by groundwater behaviour model is imported in the scheme for subsequent runs.

The scheme is run from calendar week 24 to 41. For the period from week 24 to 28, groundwater surface of June is considered representative. The scheme is run for each week and corresponding spatial distribution of pumping/recharge are obtained. After running the scheme up to 28th week, the spatial pumping/recharge information of five weeks is imported in groundwater model and the model run is taken. The output of the model provides the revised groundwater surface which is imported in the scheme to represent the groundwater conditions for the period from 29 to 32nd week. Now, the scheme is run from calendar week 29 to 32. This procedure is repeated for different time steps and groundwater surface at the end of week 41 is estimated. For the month of October, the water levels in various observation wells are available and the same are compared with simulated water levels in corresponding wells. The graph depicting the simulated and observed levels in the month of October is shown in Figure – 4.11.

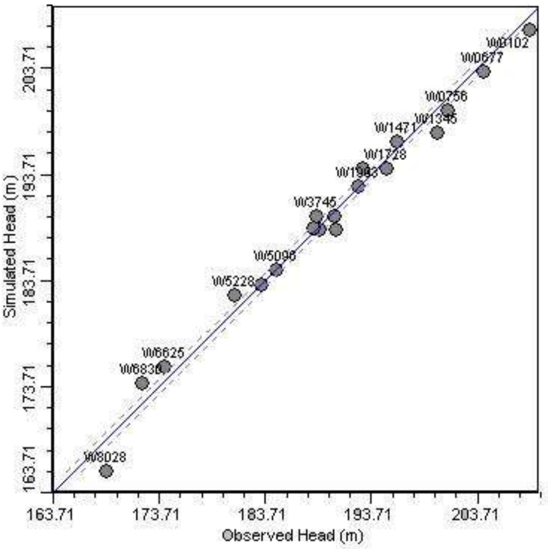


Figure – 4.11: Observed and simulated levels in groundwater observation wells in October, 1998

It is observed from the graph that for most of the wells, the observed and calculated levels match to a considerable extent. Some statistical estimates of the observed and simulated water levels are given in the following:

Minimum difference between observed and simulated (for W1993) = – 0.095 m
Maximum difference between observed and simulated (for W8028) = – 3.091 m
Residual mean = - 0.3 m
Standard error of estimate = 0.314 m
Root mean square error = 1.366 m

As the observed and simulated water levels match to a considerable extent, it can be concluded that the spatial distribution of pumping and recharge estimates provided by the scheme give a near-true representation of the actual occurrence in the command. Since the pumping and recharge values are directly related to the various components of the irrigation system, such as cropping pattern, soil water balance, irrigation demands, canal operation and seepage loss, groundwater withdrawal etc., it is therefore concluded that various components of irrigation system evaluated in the proposed scheme represent the near-true picture of the command.

* * *

CHAPTER – 5
CONCLUSIONS

Efficient operation and management of existing irrigation systems has become a major concern worldwide. This is especially true for developing countries, particularly in Asia, where the need to enhance the agricultural productivity is coupled with decreased availability of water for agriculture. It is reported by Tardieu (2000) that inappropriate irrigation water management practices around the world have converted 100 million hectare of arable land into unusable land because of waterlogging and salinity. Spatial heterogeneity within an agricultural command of an irrigation project may prevail in terms of topography, cropping pattern, soil type, meteorological conditions, agronomic and irrigation practices, groundwater conditions, water availability and utilization pattern etc. Often, gross simplifying assumptions, such as areal average cropping pattern, uniform physiographic and agro-climatic characteristics and average groundwater availability etc. over the command area are made in implementation and operation of irrigated agriculture systems leading to several managerial discrepancies with respect to ground situation.

A number of irrigation water delivery models (like SIMIS, OMIS, INCA, CAMSIS etc.) have been developed in the past with varying levels of sophistication. With modern tools of data acquisition, data management and analysis, it is now possible to develop a comprehensive model that integrates various processes of irrigated agriculture from micro-scale (field level) to macro-scale (overall command). The objective of this study is to develop a geo-simulation model that can integrate the spatial and temporal information on relevant variables and processes for analyzing the weekly operation of a canal network.

The developed geo-simulation model makes use of the satellite-derived spatially distributed information on cropping pattern and canal network layout and ground-collected inputs with respect to topography, soil, rainfall, groundwater surface, and irrigable area in GIS environment. The scheme incorporates spatial variability of different parameters and processes related to irrigation water distribution and utilizes the real-time information (rainfall, evapo-transpiration, canal operation etc.) coming from various sources to provide an integrated picture of the total system. ILWIS GIS system is used for input preparation and analysis of spatial data while ERDAS IMAGINE system is used for processing of satellite data.

The geo-simulation model consists of three main models: a) demand simulation model using the soil water balance approach, b) surface and groundwater allocation model using the canal network simulation approach, and c) groundwater behavior model using the aquifer simulation approach. Models for soil water balance (SWBM) and canal network simulation (CNSM) have been developed. For groundwater simulation, the model is linked to Visual MODFLOW. In addition, various modules have been developed for preparing the spatial database, increasing the computational efficiency of the model, and for linking various component models of the overall modeling framework. For the developed models, computer codes have been written in FORTRAN language. The scheme is linked to ILWIS GIS system for presentation of results in map form for easy comprehension and decision-making.

Application of the modeling scheme is presented for a case study of Lakhaoti command area under the Madhya Ganga Canal System in U.P. State, India. The 1956 sq. km of command area is simulated at a grid size of 24 m for the Kharif season (monsoon season) of the year 1998. Cropping pattern in the command is derived from four remote sensing images of LISS-III sensor (23.5 m spatial resolution) while the canal network layout is derived from PAN sensor (5.8 m spatial resolution) data. Intensive field investigations have been made and data have been collected with respect to daily rainfall, meteorological variables, groundwater levels, canal system characteristics, canal irrigable areas, crop characteristics etc. Soil samples have been collected and analyzed for deriving various parameters of interest such as field capacity, permanent wilting point, specific gravity, hydraulic conductivity etc. Various other information about the command area such as boundary, contours, spot levels etc. are obtained from Survey of India toposheets and digitized in GIS system. All spatial database have been imported/digitized in GIS system. Some data layers, such as grid-wise digital elevation model and groundwater depth are generated in GIS. All spatial database files are exported in ASCII format and processed with various database generation modules for input to the modeling scheme.

For validation purpose, the scheme is run with the database of Lakhaoti command for the Kharif season (wet season) of year 1998. Simulated groundwater levels in various observation wells have been found to match quite close to the observed levels at the end of the Kharif season.

5.1 POTENTIAL USE OF THE DEVELOPED MODEL

The model scheme can be used for: a) operational planning at the beginning of a cropping season, and b) real-time operation of the canal network.

Using the GIS for database management, it is possible to store, retrieve, or change voluminous data sets in a systematic manner. It is also possible to manipulate the spatial data, such as cropping pattern, canal irrigable area etc. and analyze the system for a variety of possible conditions. Representation of physical characteristics of command area in the scheme has been made realistic. The user-friendly presentation of model output can be used to bridge communication gap between the system analyst and irrigation managers. A record of canal water supply and groundwater withdrawal at the scale of canal segments can be maintained and used to evaluate spatially distributed performance measures. The record of canal water supply and groundwater withdrawal can also be used by the supplier to levy charges in a more rational manner.

With provision of a number of analysis options in different models, especially for demand estimation, prioritization of canal segments and augmentation supply, the representation of field conditions has been made more realistic leading to increased flexibility in the operation analysis. In addition to the water distribution planning, the developed scheme can also be used to design a canal network by simulating a number of canal configurations and comparing their performance.

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